A MANUAL PUMPING TEST METHOD FOR CHARACTERIZING THE PRODUCTIVITY OF DRILLED WELLS EQUIPPED WITH ROPE PUMPS

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Abstract

Since the introduction of the rope-pump in Nicaragua in the 1990s, the dependence on wells in rural areas has grown steadily. However, little or no attention is paid to rope-pump well performance after installation. Due to financial restraints, groundwater resource monitoring using conventional testing methods is too costly and out of reach of rural municipalities. Nonetheless, there is widespread agreement that without a way to quantify the changes in well performance over time, prioritizing regulatory actions is impossible. A manual pumping test method is presented, which at a fraction of the cost of a conventional pumping test, measures the specific capacity of rope-pump wells. The method requires only sight modifcations to the well and reasonable limitations on well useage prior to testing. The pumping test was performed a minimum of 33 times in three wells over an eight-month period in a small rural community in Chontales, Nicaragua. Data was used to measure seasonal variations in specific well capacity for three rope-pump wells completed in fractured crystalline basalt. Data collected from the tests were analyzed using four methods (equilibrium approximation, time-drawdown during pumping, time-drawdown during recovery, and time-drawdown during late-time recovery) to determine the best data-analyzing method. One conventional pumping test was performed to aid in evaluating the manual method. The equilibrim approximation can be performed while in the field with only a calculator and is the most technologically appropriate method for analyzing data. Results from this method overestimate specific capacity by 41% when compared to results from the conventional pumping test. The other analyes methods, requiring more sophisticated tools and higher-level interpretation skills, yielded results that agree to within 14% (pumping phase), 31% (recovery phase) and 133% (late-time recovery) of the conventional test productivity value. The wide variability in accuracy results principally from difficulties in achieving equilibrated pumping level and casing storage effects in the puping/recovery data. Decreases in well productivity resulting from naturally occuring seasonal water-table drops varied from insignificant in two wells to 80% in the third. Despite practical and theoretical limitations on the method, the collected data may be useful for municipal institutions to track changes in well behavior, eventually developing a database for planning future ground water development projects. Furthermore, the data could improve well-users' abilities to self regulate well usage without expensive aquifer characterization.

Table of Contents

List of Figures

List of Tables

Note on units

Unless otherwise noted, all equations use conventional units for the U.S. groundwater industry: gallons per minute (gpm) for flow (discharge or yield or capacity), feet (ft) for drawdown and depth, inches (in.) for diameter or radius, and gallons per day per foot (gpd/ft) for transmissivity. Conventional units are more intuitive to practitioners involved with groundwater supplies.

Acronyms

Acronym	Spanish	English
ASOCHOM	Asociación Chontaleña de Municipalidades	Association of Municipalities of Chontales
CAPS	Comité de Agua Potable y Saneamiento	Water and Sanitation Committee
CITA-INRA	Centro de Investigaciones del Instituto Nacional de Reforma Agraria	The National Agrarian Reform Institute Research Center
ENACAL	Empresa Nacional de Acueductos y Alcantarillas	Nicaraguan Regulatory Institution of Aqueducts and Sewers
CARUCA	Centro de Arquitectura y Urbanismo Centroamericano	Central American Center for Urban Development and Architecture
COSUDE	Agencia Suiza para el Desarrollo y la Cooperación	Swiss Agency for Development and Cooperation
FISE	Fondo de Inversión Social e Emergencia	Social Investment and Emergency Fund
INETER	Instituto Nicaragüense de Estudios Territoriales	Nicaraguan Institute of Earth Studies
INTA	Instituto Nicaragüense de Tecnología Agropecuaria	Nicaraguan Institute of Fishing and Agricultural Technology
IPRH	Inventario y Planeamiento de Recursos Hídricos	Water Resource Inventory and Planning
NGO		Non-Governmental Organization
SINIA	Sistema Nacional de Información Ambiental	National Environmental Information System
SNV		Dutch Development Organization

Acronym	Spanish	English
UNICEF		United Nations Children's Fund
UNOM	Unidad de Operación y Mantenimiento	Operation and Maintenance Unit
USAID		United States Agency for International Development

1 INTRODUCTION

Groundwater reserves, making up 97% of freshwater supplies found on Earth (Driscoll 1986), are becoming increasingly exploited to meet human needs as increasingly sophisticated exploration and drilling techniques are developed. Groundwater is commonly used in the developed world for drinking water supplies in large part because it is more economical than treating surface water for consumption. Moench (2005) claims that the number of water wells has increased exponentially in the past 50 years. Similarly, the use of groundwater is on the rise in the developing world as surface water becomes increasingly contaminated (increases in industry with loose environmental law) and scarce (changing ecosystems in response to over-exploitation of natural resources). Mark Rosegrant, director of the Environment and Production Division of the International Food Policy Research Institute predicts that between 1995 and 2025, water consumption in the developing world will increase by 27% (Rosegrant et al. 2002). It is only in the last 50 years that the awareness of the fragility of groundwater resources has heightened as more and more regions around the world realize their unchecked use is causing, or may lead to, serious consequences (Driscoll 1986).

Despite this rapid increase in groundwater use, rarely do countries invest in the type of hydrological information necessary to quantify sustained yields within aquifers unless they are already experiencing water-shortage issues (Moench 2005). Institutional weaknesses aside, the monitoring and management of the resource are difficult considering groundwater is hidden below the earth's surface. What research that is done on groundwater behavior has originated in first-world countries by universities and institutions with extensive financial resources, personnel and equipment. As a result, studies conducted to understand complete hydrogeological systems rely on advanced, expensive testing methods and models. Many studies use precipitation-, evaporation-, and climate databases that date back decades, well monitoring databases spanning nearly that same time, and comprehensive drilling logs. Furthermore, researchers are able to take advantage of data sharing between institutions.

On the other end of the spectrum, in the developing world these tools and technologies are not available. To highlight the wealth disparity between the industrialized and developing world, for example, the Netherlands spends five times the per capita income of the rural state of Gujarat, India on groundwater management alone (Moench 2005). The increased exploitation of groundwater reserves coupled with a lack of information on declining water tables, extraction estimates, and aquifer properties is of great concern from a sustainability standpoint.

Commonly in Nicaragua, and probably in the rest of the developing world, wells are evaluated via a rudimentary well test at the time of installation but accessing drilling logs is nearly impossible. To further complicate management and characterization plans, models are non-existent, little or no climatic information exists, well monitoring is sparse and reserved for wells serving large populations, and the drilling logs that are available are often incomplete. Moench et al. (2003) quote a Ministry of Water Report filed in 2001 claiming that in China,

Effective management [of groundwater] *is highly dependent on appropriate reliable and up-to-date information. Currently there are thousands of local and personal databases storing key technical and licensing data in a very unsatisfactory manner…The complete lack of a groundwater database is seriously constraining the formulation and implementation of effective groundwater management throughout China. The inability to access information, which at times is part of institutional secrecy, encourages inaction or incorrect decisions*.

Although the context is China, this statement is certainly applicable to Nicaragua and probably to less developed countries as well. Due to the nature of working in the developing world, where governmental institutions are strapped economically and most foreign aid is slated for building infrastructure, virtually no economic resources are allocated for improving knowledge of regional groundwater resources or assessing well performance. Studies of these types are normally costly and time consuming, and with a common "meet immediate needs" mentality, little emphasis is placed on planning and actions to ensure sustainability. Nonetheless, there is widespread agreement that without a way to quantify the changes in well performance over time, prioritizing regulatory actions is impossible (Kome 2007).

In the past 25 years, Nicaragua has experienced an increase in groundwater exploitation by the rural population. The rapidly diminishing and poor quality surface water resources have forced rural farmers to install relatively inexpensive shallow hand-dug wells. However, over the years, in many areas these wells tended to go dry during the critical summer months. In response, non-governmental organizations (NGOs) and government agencies have increased aid funding to install deeper *perforated*[*] wells equipped with manual pumps to serve small communities. To avoid the same fate of the hand-dug wells for the deeper wells, a monitoring program is imperative.

With the cooperation and support of an international NGO and several Nicaraguan ministries, this study was undertaken to develop a simple method to determine well productivity and monitor water table fluctuations in manually pumped wells. The development of an economical method for measuring well productivity would benefit municipal institutions in that they could track changes in well behavior, eventually leading to developing a database for planning future groundwater development projects. Furthermore, hydrogeological data could improve well-

[*] *Perforated* is the English translation of the common term (*perforado)* used to refer to a drilled well in Latin America.

users' abilities to self-regulate well usage without expensive aquifer characterization.

1.1 History and current status of wells in rural Nicaragua[†]

Gravity-driven aqueducts have been the preferred technology to bring water to homes in rural regions of Nicaragua located far from rivers and streams. These obviously are most useful in mountainous zones where a spring is found topographically higher than the community in need. However, over time, as springs became increasingly scarce, hand dug wells then became the next best option for populations lacking a nearby river.

Dug wells are appropriate in zones where the ground can be excavated with picks and shovels, and where the groundwater table is located within roughly 60 ft of the ground surface, though wells as deep as 160 ft have been achieved (Smet and van Wijk 2002). Though the hand-dug well is a viable option for rural citizens, several problems with hand-dug wells exist. First, hand-dug wells are susceptible to contamination from the surface unless the well head is completely sealed with a watertight slab and a pump is installed. This is particularly difficult in the developing world due to limited options for materials that are both watertight and removable to allow for maintenance and repair. Therefore water taken from these wells that is to be used for consumption should still be disinfected, such as by chlorination (Smet and van Wijk 2002). Secondly, much of the most populated areas of Nicaragua are underlain by volcanic basalt, which is difficult to dig into. With depth, bedrock fracture density decreases and the bedrock becomes increasingly harder to dig with manual tools, reducing the likelihood of excavating a sufficiently-productive well. Finally, hand-dug wells have a tendency to go dry, either temporarily or on a long-term scale. Commonly during the summer months in arid regions or in zones that have experienced extensive deforestation, wells dry up for a number of months. More seriously, the hand-dug well may not be useable if the groundwater table drops sufficiently and large-scale ecosystem changes affect precipitation and thus aquifer recharge. According to a Nicaraguan government document, 12% of the hand-dug wells in Nicaragua are not currently used because they have gone dry (GDN 2004).

Beginning in 1990, the technology of the down-hole hammer drill was made available to Nicaragua, and as of 2004, six such drills are available (in varying conditions of operability) (GDN 2004). Hammer drills make it possible to drill wells into hard rocks at rates of tens of feet per hour (Driscoll 1986), in comparison to percussion drilling, which is an older, more common method that

[†] *One of the biggest challenges of working in the developing world is finding reliable sources for current and historical information. Many reports reviewed for this section have conflicting numbers and dates, and studies quoted are often times not cited. All information, though at times conflicting, is presented here.*

can drill only tens of feet per day. These down-hole hammer drills are property of Nicaraguan Regulatory Institution of Aqueducts and Sewers (ENACAL), Care International, Save the Children, and an NGO called Central American Center for Urban Development and Architecture (CARUCA). These drills were donated by institutions such as United States Agency for International Development (USAID), Swiss Agency for Development and Cooperation (COSUDE), and United Nations Children's Fund (UNICEF). The operation and maintenance costs of wells managed by ENACAL are assumed by UNICEF and COSUDE.

The first drilled wells were equipped with imported hand pumps, however, the lack of replacement parts has rendered many pumps useless. Beginning in the 1980's the National Agrarian Reform Institute Research Center (CITA-INRA) began researching the rope-pump (GDN 2004) (Figure 1.1) in hopes of finding a more sustainable option. The rope pump is not a new technology as it dates back 2000 years ago (Harvey and Drouin 2006). However, in the past few decades it has come to the forefront as a solution to clean water access for rural communities in the developing world. The rope pump has been officially adopted as the solution to water supply in rural Nicaragua because of its simple design, low cost, reliability, ease of repairing, and higher discharge delivery rates than other manual pumps. Recently, almost all perforated and dug wells in Nicaragua have been equipped with rope pumps (Harvey and Drouin 2006). According to GDN (2004), in 2004 there were approximately 5,000 rope pumps in use in Nicaragua, and the various Nicaraguan manufacturers were exporting them to El Salvador and Honduras. Harvey and Drouin (2006) report that there were six times more rope-pump wells in 2006 than in 2004.

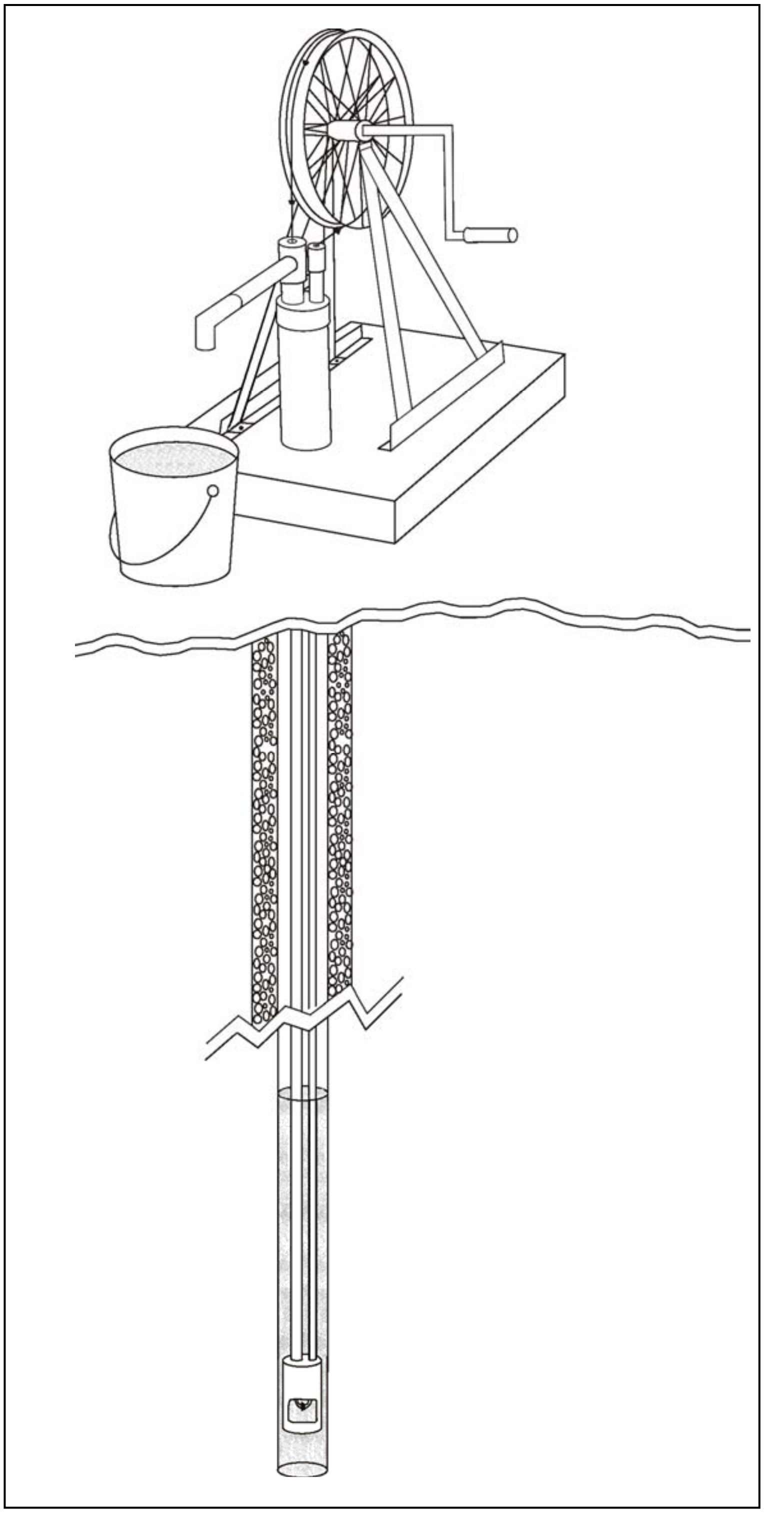

Figure 1.1 Schematic of rope pump in a drilled well.

The rope pump can be installed in both hand-dug and perforated wells, and in 2007 cost between US$50- US$100. Obviously hand-dug wells are much cheaper to install (US$85 – $140) (GDN 2004), while perforated wells are costly and typically only the economically advantaged are able to afford their own private perforated well. According to Engineer Milder Gutierrez, owner of a local well drilling company, *Perforaciones de Pozo,* located in Boaco, Nicaragua, the drilling of a 6-in diameter, 200 ft deep well in hard rock in Nicaragua cost about US$5000 in 2007 (Gutierrez 2008).

1.2 Research Project Development

In April 2006 the Nicaraguan Institute of Agriculture and Fishing (INTA), and the international NGO Dutch Development Agency (SNV Nicaragua) collaborated to lead a training workshop on Water Resource Inventory and Planning (IPRH) in a watershed (near Santa Rita, Figure 1.2) near the city of Juigalpa. The week-long project consisted of garnering local community support to aid in identifying and mapping water resources and, if possible, quantitatively describing these water resources and water-harnessing technologies in the community (hand dug wells, perforated wells, springs, stream flow, gravity-fed distribution systems). The inventory was purposely done at the height of the dry season to allow for a snapshot view of the community's water resources when least productive.

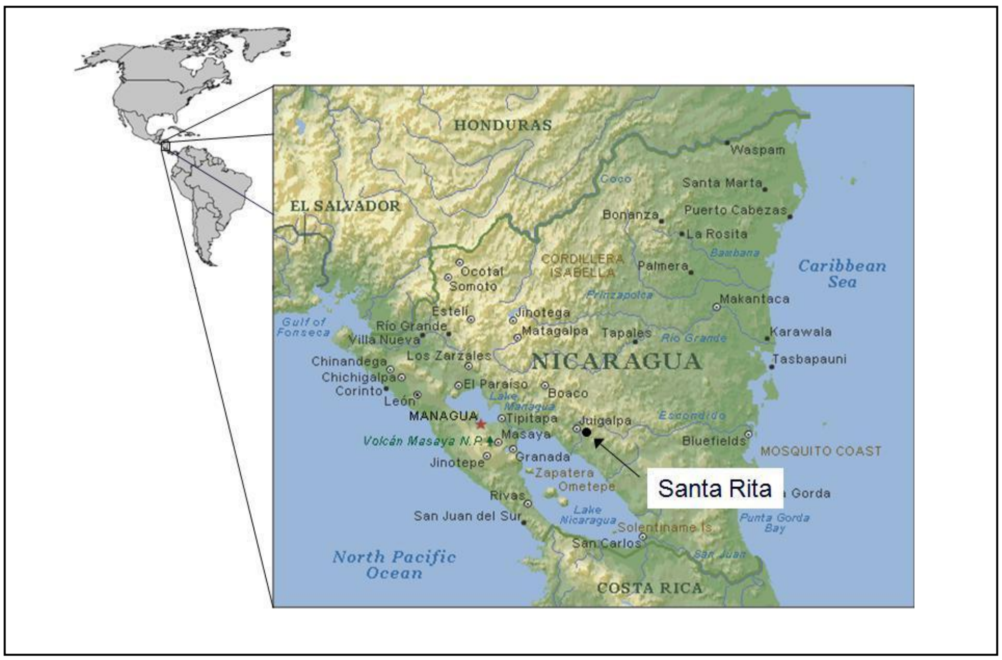

Figure 1.2 Map of Nicaragua (country map adapted from PDH 2008; Americas maps adapted from GGR 2008).

During the field work, measuring stream flow was easily done. Wanting to include the groundwater status in the inventory, the workshop participants attempted to take a measurement of depth to water table (also known as static water level) and well productivity of one perforated rope-pump well. While the hand-dug wells would have at the very least allowed for measurement of the depth to the water table, those wells were already dry at that time. The construction of the perforated rope-pump wells, however, did not allow for easy access into the well to take measurements and the idea of including groundwater/well data was abandoned for the workshop.

In light of the well construction limitations, it was necessary to develop a way in which well data could be more easily collected without significant cost or technical knowledge required. Pump modifications, pump-test equipment, and data analysis methods would all need to be economical and simple. Upon further inspection of the wells, it became apparent that a slight modification to the pumps' existing infrastructure would allow for 1) measurement of depth to groundwater, and 2) access to the well borehole enabling specific capacity to be determined via a manual pumping test. In addition to general characterization of the well for a water resources inventory, the specific capacity measured using the existing rope pump could be used to estimate the ultimate well capacity if the pumping capacity was increased by replacing the manual pump with a motorized one.

This study included triplicate manual pumping tests in three wells once a month for nine months. Four data-analysis methods were used in order to determine the simplest and most accurate manner to calculate well productivity. Comparing results to a conventional pumping test performed in one of the wells that had been tested with the manual pumping test revealed the representativeness of the manual tests. These manual pumping tests were performed monthly to observe possible changes in specific capacity resulting from the naturally occurring drop in static water level.

1.3 Research Objectives

Based on experience with rope-pump wells and some research on technologically appropriate well characterization methods for the developing world, the following two objectives were established for this study:

1. Develop and test a low-cost method for measuring static water level and specific capacity of a rope-pump well.

Determining well productivity is important not only for well users who want to maximize well use but also for long-term monitoring programs. Monitoring how well productivity changes with time provides conclusive evidence upon which policy makers can begin taking steps towards conserving watersheds and improving management practices. According to Luis Meza, an ENACAL hydrologist, actual pumping tests are not performed on wells perforated for rope-pumps during development. Instead, an air lift pump is used to determine if a sufficient amount of water (minimum of 5 gpm) to support a rope pump can be extracted from a well during approximately an hour-long period (Meza 2006).

In the industrialized world, pumping tests are done with electric pumps and other costly equipment that most developing countries do not have access to on a regular basis. The lack of an economical, simple method hinders the water utility and/or land management authorities' abilities to determine specific capacity of wells placed in rural areas. This study was designed to see if well productivity could be determined with only a manual pump and a *sounder*[‡].

The plan for this work included performing manual tests in each well a minimum of 33 times, ensuring that the method will be rigorously examined over a complete dry season and three months into the rainy season. Performing the tests over such a long time period may reveal changes in well productivity with change in depth to the water table. Well productivity is defined here as the yield (Q) per unit drawdown (s). As the static water level naturally declines over the course of the dry season, a drop in productivity is expected in an unconfined aquifer because the aquifer thickness decreases with a decreasing water table (Driscoll 1986). Because of the small volume of water abstracted by the well users, it is reasonable to assume that natural losses account for changes in static water level.

2. Determine if an adapted version of the empirical long-term field test to predict safe yield would be valid in rope-pump wells found in the rural areas of Nicaragua.

A study completed by Herbert et al. (1992), was performed to predict long-term (6 months) static water-level reductions over the course of a dry season for hand-dug wells in hard rock aquifers. Results were used to predict background drawdown that would occur throughout the entire dry season.

1.4 Previous work

The disparity between the amount of research conducted in alluvial systems compared to hard-rock aquifers is large because hard rock aquifers can be geologically complex and are not as often used for community supply wells due to their lower transmissivity. David Banks of the Geological Survey of Norway suggests the lack of published work on crystalline-rock aquifers may be attributable to 1) the complexity of fracture-flow systems, 2) the inability to collect necessary information, for logistical and economic reasons, for a well that will serve most likely an individual home or small town, and 3) poor predictive techniques (Banks 1992). He further states that what little research does exist on crystalline bedrock aquifers is related to contaminant dispersal in response to nuclear and hazardous waste disposal. Often these studies focus on individual fracture systems and in low-permeability terrain that are not particularly helpful to hydrogeologists looking for water-supply resources (Banks 1992).

[‡] A sounder is a probe connected to a measuring tape. When the probe is lowered into a well and becomes immersed in water, a buzzer is activated. At the sound, the tape is read to determine the depth to the water level.

It is understood that pumping tests are a well established practice, and while manual pumping tests may have been performed in the past, no research has been published on pumping tests in small-diameter wells in hard-rock aquifers using manual extraction methods. Most well performance studies in hard-rock aquifers are in either shallow hand-dug wells (Cimen 2001; Herbert et al. 1992; Rajagopalan 1983; Sammel 1974; Mishra and Chachadi 1985) or small diameter wells using motorized pumps (Reed et al. 1991; Smith 1984; Sanchez 2002; Summers 1972) or slug tests. As most research takes place in the industrialized world, researchers typically publish results acquired from implementing sophisticated tools and techniques only appropriate in affluent countries.

One rare set of studies on well productivity in hard-rock aquifers is reported by Barker and Herbert (1989) and Herbert et al. (1992). Their work at the British Geological Society has focused on performing aquifer tests in hand-dug wells to determine transmissivity and storativity values. While their pumping tests do rely on a motorized pump, they present several ways to use nomograms for data analysis of the recovery tests that liberate the hydrologist from computer modeling or advanced equipment typically lacking in developing countries.

Herbert et al. (1992) present several techniques for interpreting pumping tests in hand-dug wells in hard rock aquifers, two of which require computer analysis and two of which do not. The two latter tests can be used to assess aquifer properties in the field for routine hand-dug well pumping tests. Their research also includes a method to predict long-term (6 months) behavior of hand-dug wells in hard rock aquifers based on data collected from a series of 10-day pumping tests. In their study, they were interested in determining the long-term yield of a collector well (hand-dug wells with horizontal adits) during normal irrigation use.

While not widely used in hydrogeological studies, for this study the use of the equilibrium approximation would aid in developing an appropriate pumping test data interpretation method because of its simplicity. Misstear (2001) suggests this method for estimating well productivity, not necessarily only for use in the developing world but for hydrogeologists in general. He acknowledges that most interpretations of pumping test data is done by computer program analysis of pumping or recovery curves. However, using the non-equilibrium equations for recovery and pumping data is often misapplied and performed without attention to the underlying and limiting assumptions. Misstear (2001) encourages the use of the equilibrium approximation, not to replace computer analyzing programs, but says they are useful, *"(1) as an initial estimate of transmissivity in the absence of good test data, and (2) for comparison with, and therefore checking on, the results obtained from non-equilibrium analyses even where there are good time-drawdown data.*" If the values do not compare well, it may incite the hydrogeologist to think about issues such as leaky conditions or recharge boundaries; considerations that may be overlooked when implementing a prescriptive approach using standard methods.

Understanding that crystalline aquifers are important to large regions of the world, including many developing countries, northern Europe and North America, Banks (1992) proposed a tool to quantify bedrock aquifer characteristics from straightforward pumping tests in boreholes. His study was completed in several regions in Norway, and describes a simple method to calculate transmissivity of the hard-rock aquifer surrounding the borehole from the well's specific capacity. The specific capacity values he used were based on the simple equilibrium approximation method because standard methods typically used in analyzing pumping test data from alluvial aquifers (*i.e*., Cooper-Jacob analysis) in hard-rock aquifers are often dubious. (Banks 1992, Moench 2005). Moench (*Loc. Cit.* 2005) claims that the research on the quantification of available groundwater in hard-rock aquifers is questionable and quotes UC Berkley professor T.N. Narasimhan as saying, "*indiscriminate fitting of hydraulic test data to available mathematical solutions will but yield pseudo hydraulic parameters that are physically meaningless,*" and, "*a sound rational basis does not exist yet for quantifying resource availability and utilization*."

While broad regional characterization of hard-rock aquifers remains elusive, many studies have been done to determine individual well productivity of wells in crystalline aquifers. Aquifer transmissivity values range widely because essentially well productivity is dependent on the well borehole intersecting a water bearing fracture or fracture zone (see Section 1.6 for a discussion of hard-rock aquifers). In one low-productivity area, Summers (1972) reports that pumping tests performed the in Rothschild area in Wisconsin, underlain by syenites, granites and gabbro-diorites, yield values ranging between 0.02 and 0.6 gpm/ft. Granodiorite bedrock dominates the Narragansett basin in Hanover, Massachusetts and pumping tests reveal productivity values ranging from 2.6 gpm/ft to 4.3 gpm/ft (Reed et al. 1991). In an example of highly transmissive aquifers, pumping tests performed in marble bedrock in Pittsford, Vermont have determined specific capacity values ranging from 12 gpm/ft up to 34 gpm/ft (Smith 1984). A statistical study on the variability in specific capacity of 4,391 wells in fractured metamorphic and igneous rock in Pennsylvania, indicate that values normally range between 0.15 gpm/ft and 1.5 gpm/ft, but values as low as 0.01 gpm/ft and as high as around 60 gpm/ft have been recorded. Several wells also registered upwards of 100 gpm/ft, but those were rare (Knopman and Hollyday 1993). The most permeable basalt aquifer known is the Snake River Group in the Pacific Northwest of the United States where transmissivity values up to 15 million gpm/ft have been determined (Driscoll 1986).

1.5 Study Area

The small rural community of Santa Rita, located in the central part of Nicaragua (Figure 1.2), relies upon several community wells to meet water demands. These wells are located in the Apompuá watershed, which is located between 12º 02' 30" North and 85º 14' 58" West and is 52.91 km^2 in area (Figure 1.3).

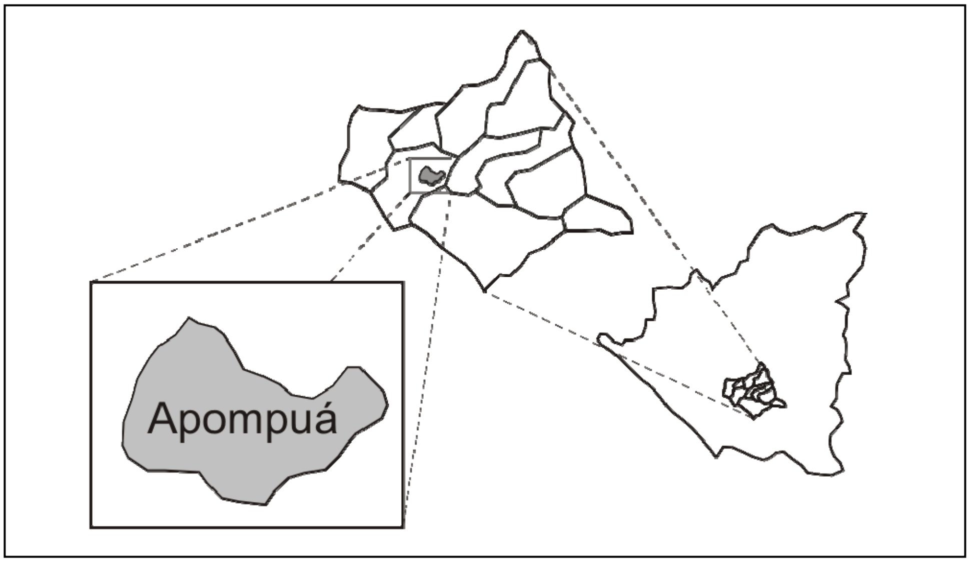

Figure 1.3 Location of the Apompuá watershed (12° 02’ 30” N and 85° 14’ 58” W) within the Department of Chontales, Nicaragua (INTA 2004).

The area is bordered by the foothills of the Amerrisque mountain range to the north east and plains to the southwest (Figure 1.4). Appendix A contains ancillary information on the region’s soils, vegetation, climate, and surface water.

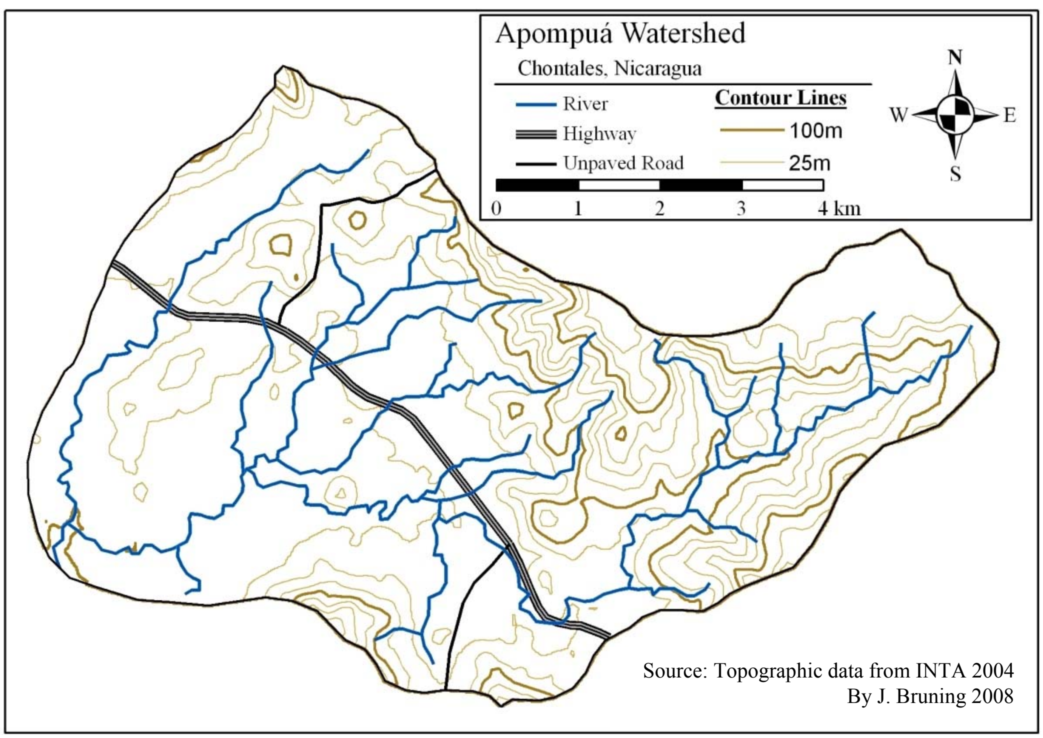

Figure 1.4 Topographic map of the Apompuá watershed. The Amerrisque Mountains are to the NE of the watershed and plains to the SW (Adapted from INTA 2004).

1.6 Regional Geology

The Apompuá watershed falls within the NW-SE trending volcanic belt called the Nicaraguan Depression or Graben. The depression was formed in the Quaternary period and includes the large lakes of Nicaragua and Managua (Figure 1.2). The graben spans entire length of the country parallel to the Pacific Coast. Geologically, Apompuá is composed of the 6400 - 1640 ft thick Pliocene-age Upper Coyol Group (Tpc). This formation consists of fractured ignimbrites (pumice-rich pyroclastic flow deposits), andesite, basalt, and conglomerates (Figures 1.5, 1.6). The Coyol group is not recognized as containing continuous or extensive aquifers, but rather one dominated by fissures, faults, and thin layers of decomposed or porous rock that could potentially supply enough water for small community use (INETER 2004). Though the well logs for the wells studied were not located by the local water authorities, it is assumed that the wells are located in hard rock aquifers because the well logs from other surrounding wells indicate such aquifers and because the wells are situated within the Upper Coyol group.

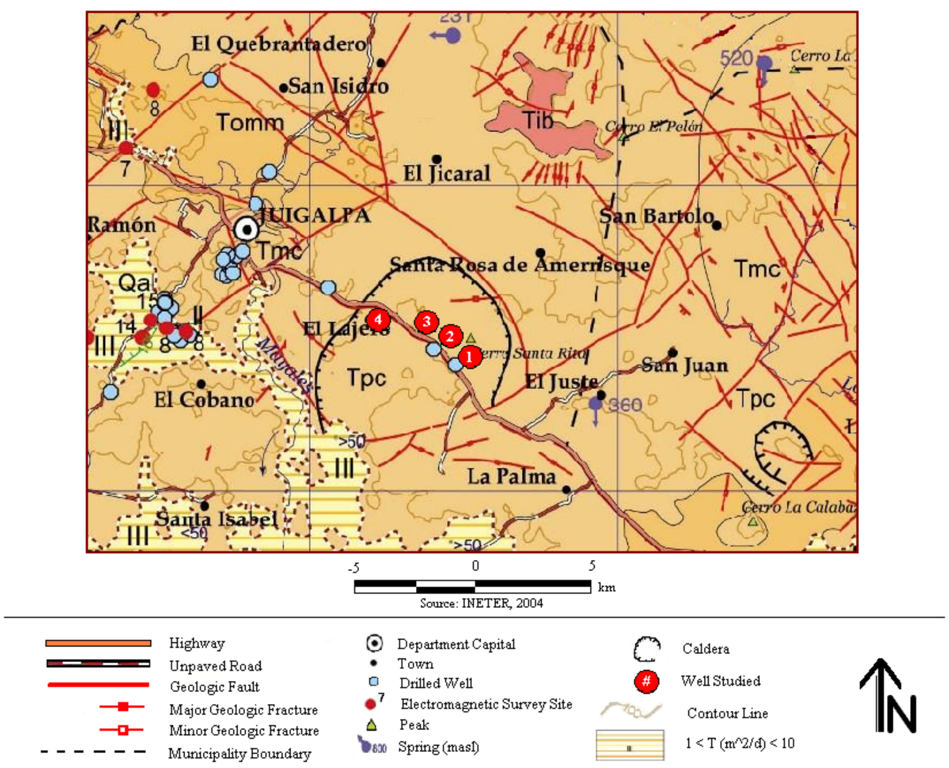

Figure 1.5 Hydrogeologic map of the Santa Rita area. Adapted from Mapa Hidrogeológico, Juigalpa NC 16-16, INETER, 2004. Note the Drilled Wells in Santa Rita area as identified by INETER. These wells are presumed to be the same as the Wells Studied, and their imprecise locations exemplify difficulties in attaining reliable information. (See legend Figure 1.6).

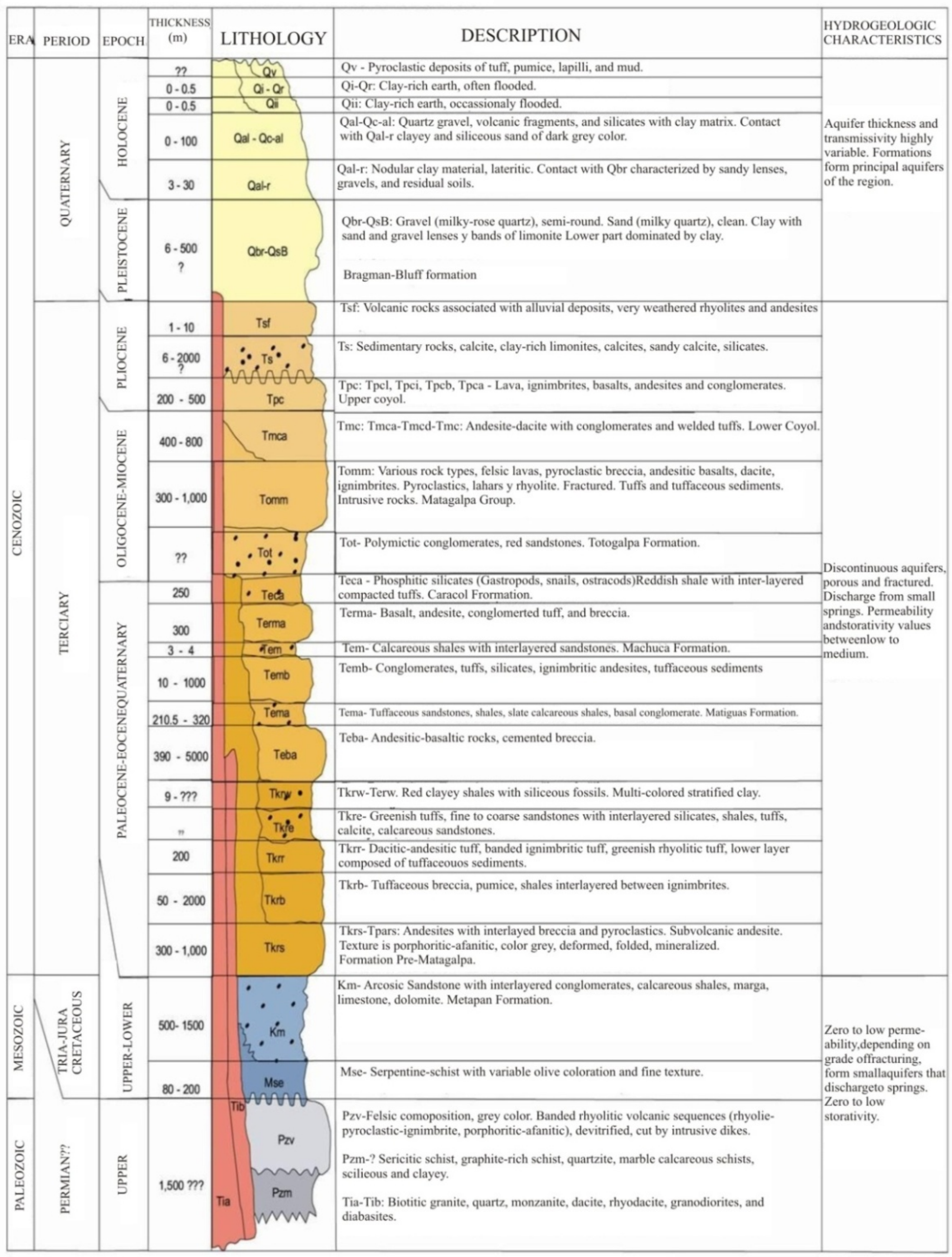

Figure 1.6 Legend for the hydrogeologic map (Figure 1.5) of the Santa Rita area. Adapted from Mapa Hidrogeológico, Juigalpa NC 16-16, INETER, 2004.

These types of extrusive igneous rock aquifers, while typically not as favorable for bearing water as sedimentary formations, may have sporadic features with high porosity and hydraulic conductivity that can provide high yielding wells (Driscoll 1986). These features may be a result of the way individual flows cooled, the length between flows, or post-emplacement structural and metamorphic changes. For example, primary porosity increases in empty lava tubes or with the presence of vesicles that form at the top of the flow. The interconnectedness of these vesicles, though, is necessary for higher hydraulic conductivities. Secondary porosity increases as cooling at the surface causes cracks to form in the upper crust of the flow, or with large-scale tectonic movements causing vertical fracturing. Also, with significant periods between flows, weathering, erosion, and deposition of alluvial sediments occur. These actions can significantly alter the capacity of the formation to store and transmit water. Weathering alone can transform a rock with virtually no porosity to one having over 30% porosity in the weathered zone (Driscoll 1986).

In crystalline rock aquifers, water is located primarily in joints and fractures. The water-bearing and water-yielding capacity of these types of aquifers depends on number, depth, size, and degree of interconnections of the fractures. Likewise, the yield of a well drilled into a crystalline rock aquifer depends on the number, depth, size, and degree of interconnections of the fractures penetrated by the borehole (Summers 1972). Lithological considerations aside, many factors influence the well yield in fractured rock aquifers. Some factors are fracture size and concentration, formation folding patterns, dip of the rock layers, depth to water, borehole depth/diameter, regolith/weathered rock thickness, altitude/topographic setting, and rainfall. However, each factor affects the well yield to different degrees (Fabbri 1997; Knopman and Hollyday 1993; Summers 1972). Many studies have shown that increasing the depth of a poorly-producing well in a hard rock aquifer does not significantly improve well yield (Fabbri 1997; Knopman and Hollyday 1993; Summers 1972; UNESCO 1984). This is due to the tightening of the joint and fracture systems with depth, which obviously reduces secondary porosity and hydraulic conductivity (Driscoll 1986).

1.7 Rope pump wells

Rope pump designs vary and many organizations have handbooks for their construction posted on the web (Bombas de Mecate 2008, Holstlag 2006, Practica Foundation 2006, WOT 2008). While the pump construction specifications are beyond the scope of this study, a description of the design representative of the rope pump wells used in this study follows.

As shown in Figure 1.1 and 1.7, the rope pump is a simple design consisting of a long rope loop with plastic pistons placed approximately a meter apart. The rope is looped over a large wheel at the well head and a small wheel inside the well. As the wheel turns, the rope descends into the well through a ¾-inch pipe and simultaneously ascends through a ½-inch pipe. The rope passes through the water column and is guided into the ascending pipe. Water trapped between the pistons is pushed to the surface.

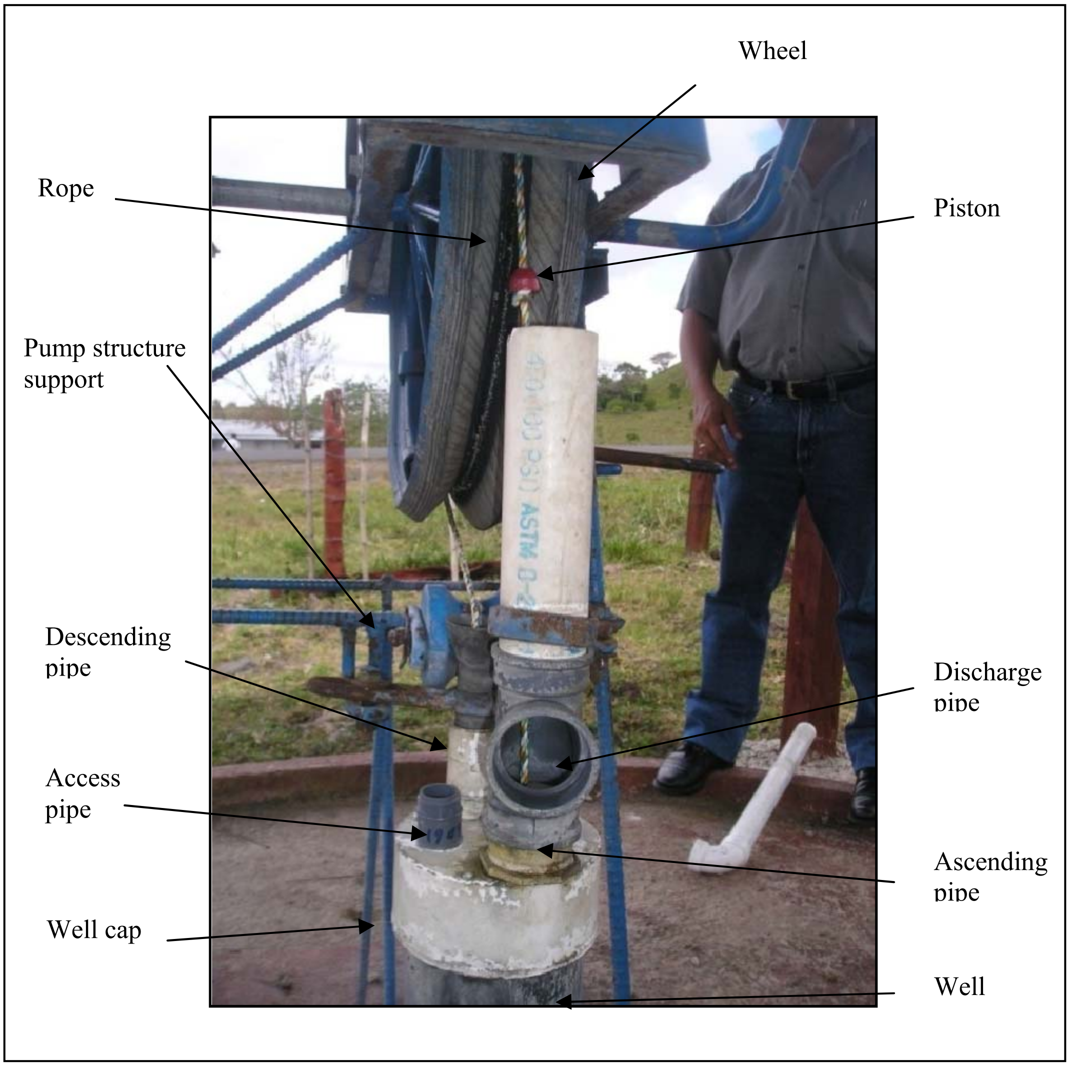

Figure 1.7 Front view of rope pump well. Photo by author.

Rope pumps configured as shown in Figure 1.1 and 1.7 operate at a maximum pumping rate of approximately 5 gpm. The delivery rate cannot be increased by simply pumping faster; excess water bypassing the delivery pipe will come out the top of the ascending pipe and cannot be captured. Table 1.1 lists basic specifications of perforated wells typically equipped with rope pumps in Nicaragua.

Table 1.1 Well and pump specifications based on field observations.

Pump part	Measurement	Comments
Well diameter	Average 6 ¼ in.	
Casing diameter	4¼ in. interior 4½ in. exterior	Cased down to bedrock, gravel pack usually in upper part.
Well depth	Approx 200 ft.	
PVC ascending and descending pipe length	60 ft.	Standard length, longer is more difficult to pump.
PVC descending pipe diameter	¾ in.	
PVC ascending pipe diameter	½ in.	
In-well guide diameter	3 in.	

2 METHODS

2.1 Well selection

The main factors determining well suitability for the study include: relative proximity to one another, number of well users at each well, and measurable drawdown observed at a 5 gpm pump rate. In general, perforated wells are located near major roads because the drilling equipment cannot access remote and poorly connected areas. To be able to test all the wells in one day traveling between wells on foot, it was necessary that they be near one another. The second most important criterion was the number of well users. At the time the study began it was believed that there would be a need to draw enough water for the entire community that the well served each day. The wells that were chosen serve communities that have less than twelve people using the well, which would have made it feasible to extract and store enough to serve the communities' daily water needs. Finally, the third criterion for well suitability for the study would not become apparent until a preliminary test was performed. This test would reveal if measurable drawdown could be achieved at the maximum pumping rate of 5 gpm. After interviewing the well users in Santa Rita, four wells were chosen for fitting of access pipes based on the first two criteria. The wells are located along a major highway within approximately 4 km of each other (Figure 1.5). Wells 1-3 serve small clusters of homes, and Well 4 is located at the local church.

The preliminary quick and simple "test" pumping tests done in all four wells revealed that wells 1, 2 and 4 met the third selection criteria and would accommodate a low-flow pumping test. However, the productivity of Well 3 was greater than 5 gpm per a few tenths of a foot of drawdown, making it impossible to achieve a measurable drawdown during manual pumping. Despite the inability to measure well productivity at that time, Well 3 was monitored throughout the study to determine if, with declining static water level, the productivity of the well would fall enough to allow for measurement using a manual test.

In addition to using Well 4 for pumping tests, it was also used for daily static water monitoring to gather data on seasonal water level changes. This well was chosen because the community claimed it is used less frequently than the other wells since there is only one home nearby (a small family that has a hand dug well), and people did not like the water's slightly salty taste (Appendix C lists water chemistry results). However, it was found that near the end of the dry season in May, that neighbors from up to a mile away came to get water for their homes, as their hand dug wells had gone dry and Well 4 was the next best option. Nonetheless, the well recuperated quickly enough after pumping to take reliable daily static water level measurements.

The most complete data (specific capacity as a function of static water drop/aquifer dewatering) would have been attained by including a well that had a history of going dry in the summertime. Unfortunately, no such well existed in this watershed.

2.2 Outfitting wells and test equipment

In November, with the assistance of an ENACAL technician, the wells were outfitted with access pipes (Figure 1.7) so that the water-level measuring probes would not become entangled in the PVC pipes that protect and guide the rope. Well 1 had a 1/2-in. diameter access pipe installed, which allowed for passage of the sounder probe. Wells 2-4 had 3/4-in. diameter pipes installed, which also accommodated the Levelogger probe. Access pipes were tightly capped when not in use to prevent unnecessary exposure to airborne contaminants. A 290-gallon storage tank was installed near the well to store the water extracted from the well during the pumping tests.

Equipment used during the pumping tests, some of which appears in Figure 2.1, includes:

- Model 101 Water Level Meter, (Commonly referred to as a sounder) manufactured by Solonist, Canada (US$ 757 for 300 ft model). A sounder consists of an electronic probe attached to a measuring tape. A buzzer and light on the reel are activated when the probe makes contact with water. The user can read the water level directly from the tape at the top of the well casing. It is powered by a 9-volt battery.
- LT3001 Levelogger Junior, manufactured by Solonist, Canada. (US$ 385). This probe consists of data logger, temperature sensor, and pressure transducer and can store 32,000 sets of temperature and water level data points. It can be programmed to take measurements anywhere between 0.5 seconds and 99 hours. A PC Interface Cable connects it to a PC where the instrument can be programmed and/ or data downloaded for export. A 5-year battery is installed in the housing.
- 290-gallon storage tank, manufactured by Rotoplast. This is not necessary for pumping tests if homes are nearby and can fill their buckets with water extracted during the test or if the area is not sensitive to discharging water on the ground. However, it was offered to the well users as an incentive for participating in the study.
- 2 5-gallon buckets. The pump rate was measured volumetrically by tracking the number of buckets filled and dividing that volume by the pumping time.
- Stopwatch.

Figure 2.1 Photo Rope pump well and equipment set-up. Photo by author.

2.3 <u>Manual pumping test</u>

Pumping tests are typically done to determine well performance to ensure selection of the correct pumping equipment. The data from the pumping tests is used to calculate the specific capacity (Q/s where Q = yield and s = drawdown) of the well. When conducting a pumping test, certain criteria must be met. Table 2.1 outlines these criteria and how each point was addressed in the manual pumping test.

Table 2.1 Criteria for validity of different pumping test analysis methods.

Criterion	Applicable to Analysis Method	Underlying Reasoning
Well must be at static water level before test	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Well allowed to sit a minimum of 4 hours before pumping. In most instances, wells at rest for previous 12 hours of test.

Criterion	Applicable to Analysis Method	Underlying Reasoning
Constant pumping rate maintained during pumping	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Every attempt was made to ensure as constant a rate as possible. Nevertheless, it is a valid concern in a manual pumping test, as those pumping tire or become distracted over the course of the test, altering the rate. To determine an average pumping rate, the volume of water was divided by the time pumped.
Achieves equilibrium pumping water level	Equilibrium Drawdown	Measurements taken late in pumping time best approximate equilibrium pumping level.
Laminar flow, 100% well efficiency	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Valid due to low pumping rate.
Aquifer uniform in character, homogenous hydraulic conductivity	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Not critical for this approach since low pumping rates were used and data only from the pumping well were analyzed
Aquifer uniform in thickness and areal extent	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Short-duration, low pumping rate tests affect only the nearby aquifer region.

Criterion	Applicable to Analysis Method	Underlying Reasoning
No aquifer recharge	Recovery Test Constant-Rate Pumping Test	Pumping and recovery periods were of short duration, tests conducted during dry season, water pumped was stored in a tank.
Pumped well penetrates, and receives water from full thickness of water-bearing formation	Recovery Test Constant-Rate Pumping Test	Presumably wells were open boreholes in bedrock, but lacked drillers' logs to confirm.
Water removed comes from aquifer storage	Recovery Test Constant-Rate Pumping Test	Only data beyond where casing storage is significant was analyzed.
Water table has no slope	Equilibrium Drawdown Recovery Test Constant-Rate Pumping Test	Short-duration, low pumping rate tests affect only the nearby aquifer region.

A constant-rate pumping test basically entails the pumping of a well until it reaches an equilibrated pumping drawdown and then allowing it to fully recover to the initial water level. The equilibrated pumping drawdown refers to the time when the pumping water level does not vary at the constant pumping rate the well is being subjected to. Typically during pumping the water level decreases relatively quickly when pumping at a constant rate begins. Depending on the aquifer and the pump rate, with time the water level will "stabilize" at a certain pumping water level, as the aquifer is providing water to the well at the same rate the pump is extracting it. Depth-to-water-level data is collected throughout the test and then analyzed to determine well productivity. The following steps were performed to obtain a single manual pumping test. The process was repeated three times for each well and then the results from each data analysis were averaged:

The steps followed for conducting the pumping tests include:

1. Measure the static water level. The well must not be pumped for a minimum of four hours (for these wells, because their recovery was fast (< 2 hrs); shallower wells and wells in low-transmissivity aquifers may have to rest

longer, typically 24-48 hrs) before the pumping test is conducted. Agreement on the part of the well users is necessary to ensure accurate static water level measurements.

2. Lower the Levelogger (programmed to take measurements every ten seconds) into the access pipe several minutes before pumping starts to establish the static water level. Lower sounder probe into access pipe. Note the static water level indicated by the sounder.
3. Pump the well until an apparent equilibrium pumping level is established. Record pumping time start. Take water level measurements with the sounder approximately every minute during pumping.
4. Record the time pumping ceases.
5. Measurement the depth to water level with the sounder: lift the tape approximately 0.3 ft from where water was when pumping was stopped. Record water level and time when the water level reaches the sounder probe, then lift another 0.3 ft, again recording the water level and time. Repeat until static water level is reached. In this study, normally between 10 and 20 data points from the sounder were recorded for each test, while the Levelogger collected 200 to 400 data points depending on the length of the test.

As an example of the data collected during a set of triplicate pumping tests, Figure 2.2 depicts the typical observed drawdown for the various stages during a set of three pumping tests.

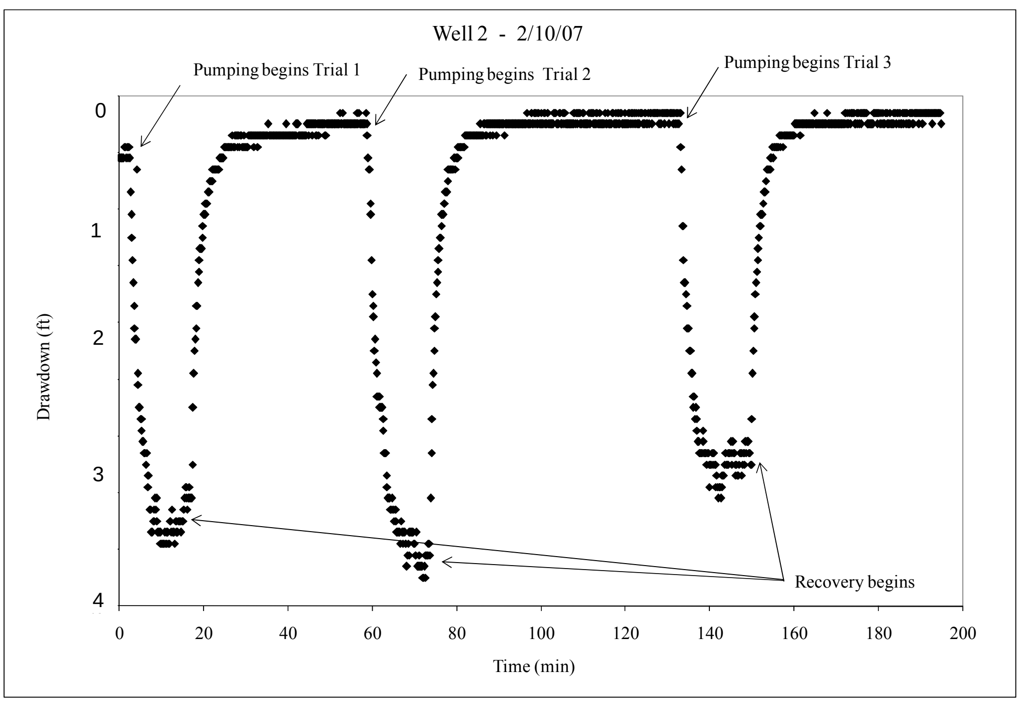

Figure 2.2 Example of pumping test time-drawdown for 3 replicate trials, including pump and recovery. Data from Well 2, 2/10/07.

Pumping was first commenced at approximately 250 sec. after lowering the Levelogger. The effects of pumping are observed as the water level drops precipitously. The same pumping rate is maintained through approximately 900 sec., though at approximately 600 sec., the drawdown reaches about 3.4 ft and seemingly remains stable. This indicates maximum drawdown at that pumping rate (average 3.8 gpm for that test). Then at 900 sec., pumping is stopped and recovery can be observed until 3520 sec., when pumping begins again for the second test. In this case, the pumping time was as follows: Trial 1- 00:14:50, Trial 2 - 00:14:30, Trial 3 - 00:16:50. The longer pumping time for the third trial is reflected in the drawdown achieved being less than those of first two trials: an average 3.04 ft compared to averages of 3.26 ft and 3.69 ft in the first two. The same volume of water was pumped in each test, it just took longer for Trial 3, presumably because those pumping had tired. Over the course of the study, the importance of maintaining a steady rate was communicated to those pumping, and the majority of tests experienced fairly similar rates, less than 10% variation on a given day.

2.4 Monthly monitoring and manual pumping tests

Once per month between December 2006 and August 2007, three manual pumping tests were performed in Wells 1, 2, and 4. In December 2006 and April 2007, back-to-back testing was performed, making each well tested at least 33 times during the study. Each set of pumping test data was analyzed four ways (equilibrium approximation, time-drawdown during pumping, time-drawdown during recovery, and time-drawdown during late-time recovery) to compare specific capacity values determined by each method at that particular starting (static) water table depth. This ensured rigorous testing of the manual pumping test method and allowed observation of potential changes in well productivity over the course of the dry season. Obviously static water levels for all four wells were measured once a month between December 2006 and August 2007, but to observe daily static water level fluctuations the Levelogger was installed in Well 4 between January and October 2007. It was programmed to take measurements at least twice a day.

Having determined well specific capacity over a range of static water levels then made for easy comparison of data from the manual tests with data from a conventional pumping test. With this comparison, the accuracy of the manual pumping tests could be determined.

2.5 Conventional pumping test

To evaluate the representativeness of the manual pumping test method, a conventional pumping test was performed at a higher rate in Well 4 on September 25, 2007. The test was donated by the ENACAL-Juigalpa office, and required a team of four technicians working two and a half days. A step-drawdown test was chosen to see if well productivity varied with pumping rates. This would either confirm or reject the hypothesis that the relatively low pumping rate of 5 gpm during the manual pumping tests would reflect the ultimate well capacity.

Well 4 was chosen for the conventional pumping test. The well was not pumped for 24 hours prior to the test. A Franklin Electric 1.5-hp submersible pump was placed in the well at 181.5 ft below ground level, about 20-ft above the well bottom. The well was pumped approximately two hours each at 5, 15, 25, and 36.9 gpm, which was the maximum rate for this pump for the well drawdown conditions. Recovery time was one hour after the 5 gpm test, and 12 hours after the 36.9 gpm pumping test. A valve was used to adjust the pumping rate, and the rate was determined volumetrically by timing the filling of a 5-gallon bucket. Water was discharged into an adjoining field that sloped away from the well approximately 10 ft from the well for the 5 gpm test, 20 ft away for about half of the 15 gpm test, and 30 ft away for the remainder of the test.

Reading the time-drawdown history shown in Figure 2.3 from left to right, a rapid drop and recovery in the water level occurring at about one hour is observed. This is a result of beginning the pumping test with a faulty valve. Once it was determined it would be difficult to maintain a steady pumping rate, the pump was turned off and a new valve was installed. The well was allowed to recover for 53 minutes, at which time a new static water level measurement was taken – reading 0.5 ft lower than before, indicating that the well had not fully recuperated. Nonetheless, the pumping test continued as planned.

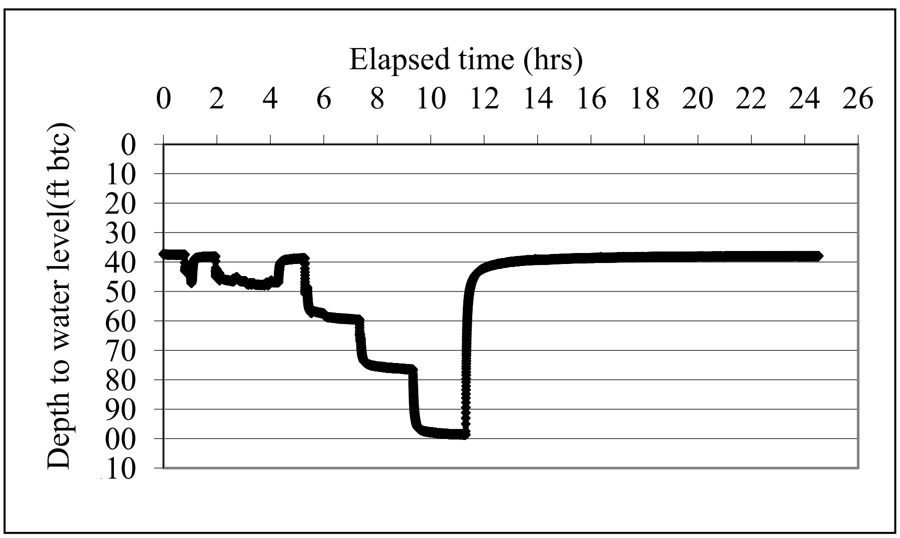

Figure 2.3 Well 4 pumping test time-drawdown graph from ENACAL conventional test on 9/25/07. The well was pumped for 2 hours at 5, 15, 25, and 36.9 gpm. The well was allowed to recover for 1 hour after the 5 gpm test, and 12 hours after the 36.9 gpm pumping test.

Figure 2.4 shows that adjustments made to achieve the desired pumping rate caused unsteadiness in the pumping water level during approximately the first 10 minutes of pump rate change in all but the 36.9 gpm step. Furthermore, it can be seen that the pump did not maintain a steady rate during the 5 gpm step, making for data to be less reliable. However, the data became increasingly more stable as the pumping rate increased.

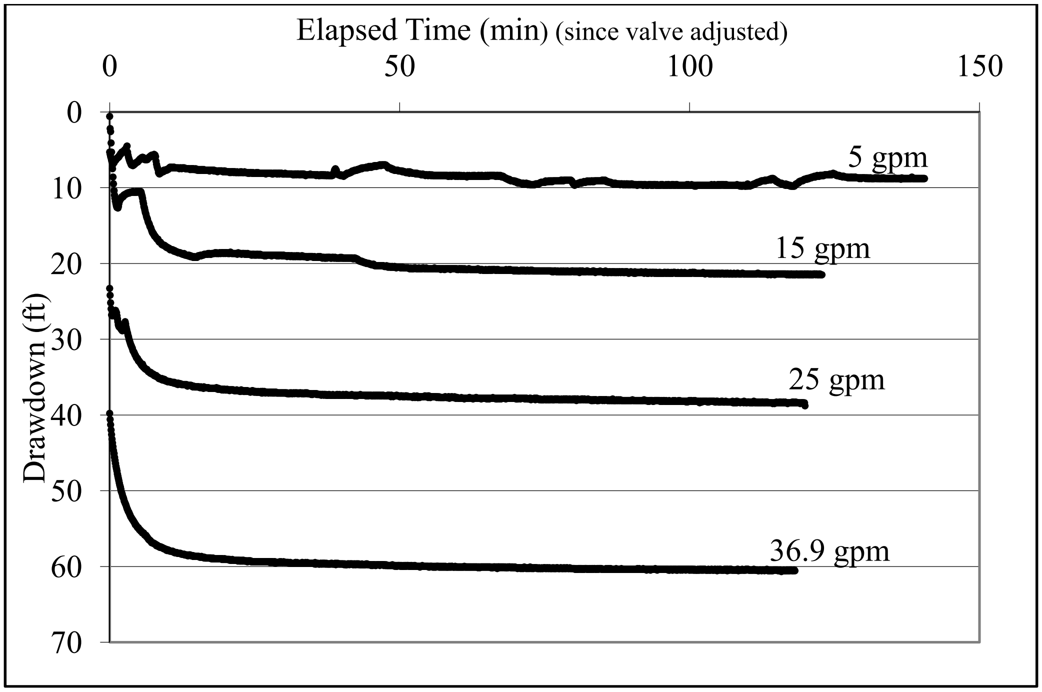

Figure 2.4 Observed drawdowns for 5, 15, 25, and 36.9 gpm pumping rates during conventional test, Well 4, 9/25/07.

The time-drawdown pumping test data from all manual tests and the conventional pumping test were analyzed to determine the well's specific capacity. Many methods exist depending on well or pump type, aquifer lithology and conditions, pump-test type, and presence of observation wells. The following methods were chosen and results compared.

2.5.1 Data Processing[§]

2.5.1.1 Equilibrium approximation method

The equilibrium approximation method is preferred for determining specific capacity in the developing world because the simple data processing does not require the use of a computer or other expensive equipment; a calculator suffices. Furthermore, it does not require the need to use assumed values for immeasurable

[§] Note: With no driller's logs available, it is unknown whether these wells are in confined or unconfined aquifers. For analysis purposes, assumed variables for unconfined aquifers are used.

variables as in the other analyses that follow. The simplest method to determine specific capacity uses data acquired during the pumping equilibrium phase:

$$\text{Specific Capacity} = \frac{Q}{s} \qquad \text{(Eq. 1)}$$

Q = Total yield of the well
s = Average equilibrium pumping level

Figure 2.5 is an example of drawdown during the pumping period of the test for three replicates that are re-zeroed at the start of each test. For these tests, some time beyond 320 seconds after pumping started, an equilibrated pumping level was achieved. An average equilibrated pumping drawdown was calculated by averaging drawdown measurements taken every ten seconds from 320 sec. into the test to the end of the pumping period.

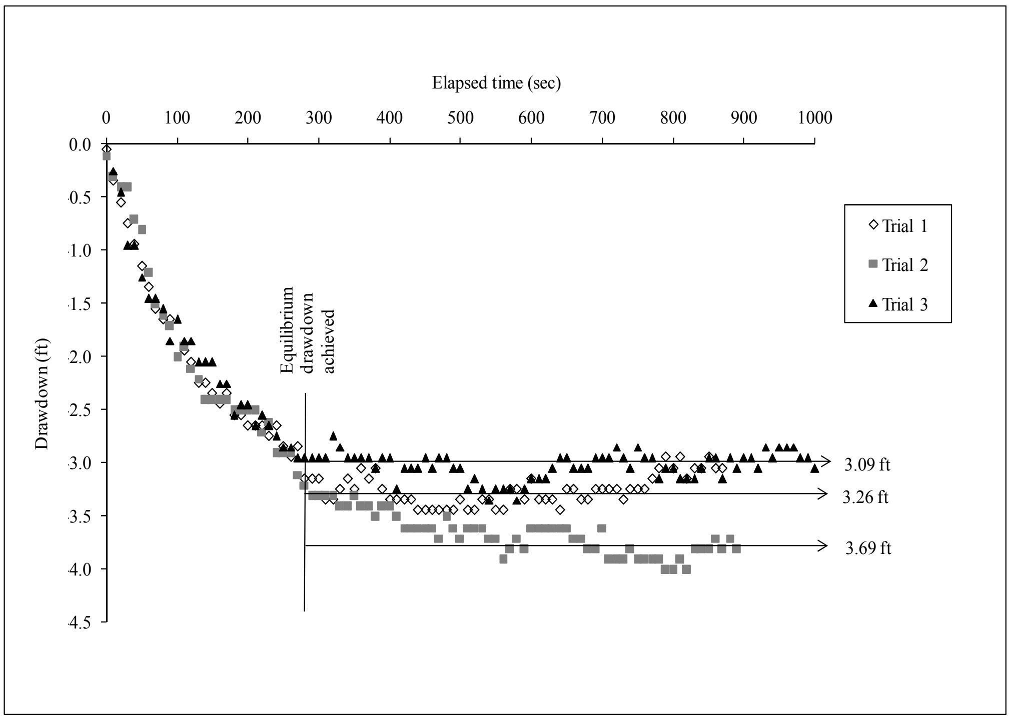

Figure 2.5 Example of equilibrium approximation method. Average pumping rates for each trial are 1) 3.78 gpm; 2)3.75 gpm; and 3) 3.28 gpm. Data taken from Well 2 2/10/07.

Each pumping period was carefully timed, as was the quantity of water measured for each test. Dividing the volume of water extracted by the time pumped determines the yield in gallons per minute. Then the specific capacity for the well was calculated by dividing the yield by the equilibrated pumping drawdown. The specific capacity values from the three trials were averaged, determining the well productivity at that depth to water level.

2.5.1.2 Pumping curve analysis

The pump curve of a pumping test can be used to determine specific capacity using the Jacob's Straight-Line method and the Jacob's modified non-equilibrium equation (Driscoll 1986) .This method uses pumping data when the dummy variable, *u*, of the Theis well function, *W(u)*, is less than 0.05 (which translates to a maximum error in using the approximation of 5%):

$$u = \frac{1.87r^2S}{Tt} \qquad \text{(Eq. 2)}$$

r = Distance from the center of the pumping well to the point where *s* is measured (ft)
S = Aquifer storativity (unitless)[**]
T = Aquifer transmissivity (gpd/ft)
t = Time since pumping started (days)

Several trials were used to determine that the *u* values were sufficiently small to use the modified non-equilibrium equation to determine the coefficient of transmissivity.

The pumping curves were plotted drawdown as a function of the logarithm of elapsed time since pumping started. Employing the Jacob's Straight-Line method requires fitting a straight line through the straight section of the graph (Figure 2.6).

[**] While using drawdown observed in pumping wells to estimate storativity (*S*) is not recommended (Driscoll 1986) nor necessary for determining well productivity, it was attempted using the Jacob's Straight-Line method on Well 2 trial 1 test data. A value of 0.51 was calculated. As expected, this is an unreasonable value, even for unconfined aquifers. Instead, the assumed value of 0.075 was used (Driscoll (1986)), which is a typical value for an unconfined aquifer.

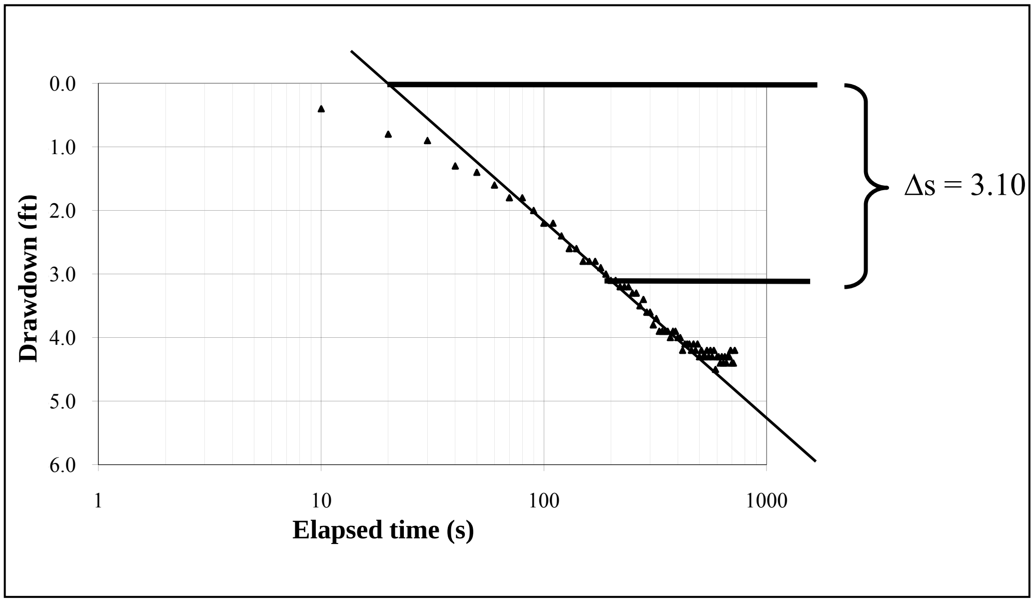

Figure 2.6 Example of Jacob's Straight-Line for pump curve analysis, from Well 2, trial 3 pumping data 4/15/07.

A Δs value was determined from the slope over one complete log cycle (e.g., 20 to 200 sec.). The known values were then used in Eq. 3 (derived from the Jacob's modified non-equilibrium equation) to estimate transmissivity (Driscoll 1986).

$$T = \frac{264\,Q}{\Delta s} \qquad \text{(Eq. 3)}$$

Where
Δs = Slope of the straight part of the drawdown on a semi-logarithmic graph (ft)

Once transmissivity was determined, the Cooper-Jacob's modified non-equilibrium equation (Driscoll 1986) was used to estimate the specific capacity. No well losses during the pumping test were assumed. The non-equilibrium equation was used because: 1) only one well was available for measurement, whereas application of the equilibrium equations requires data from two observation wells, and 2) for analysis with pumping data, the equilibrium equations require stable pumping rates, which were difficult to achieve with a manual pump. The non-equilibrium equation allows for the variables to be determined at any point during pumping or recovery:

$$\frac{Q}{s} = \frac{T}{264 log\frac{0.3Tt}{r^2S}} \qquad \text{(Eq. 4)}$$

The specific capacity values for the three tests were averaged.

2.5.1.3 *Recovery curve analysis*

Analysis of recovery data is the best to use when no observation well is available and measurements are taken in the pumping well. Data analysis is similar to that of pumping curve analysis, with one difference. The recovery curves were plotted as residual (i.e., remaining) drawdown as a function of the ratio of the time since pumping started (*t*) to the time since pumping stopped (*t'*).

The Δs value over one log cycle was measured after drawing a straight line through the data as shown in Figure 2.7. This slope and the other known variables were necessary to apply Eqs. 3 and 4 as shown above in the pumping curve analysis to attain specific capacity values.

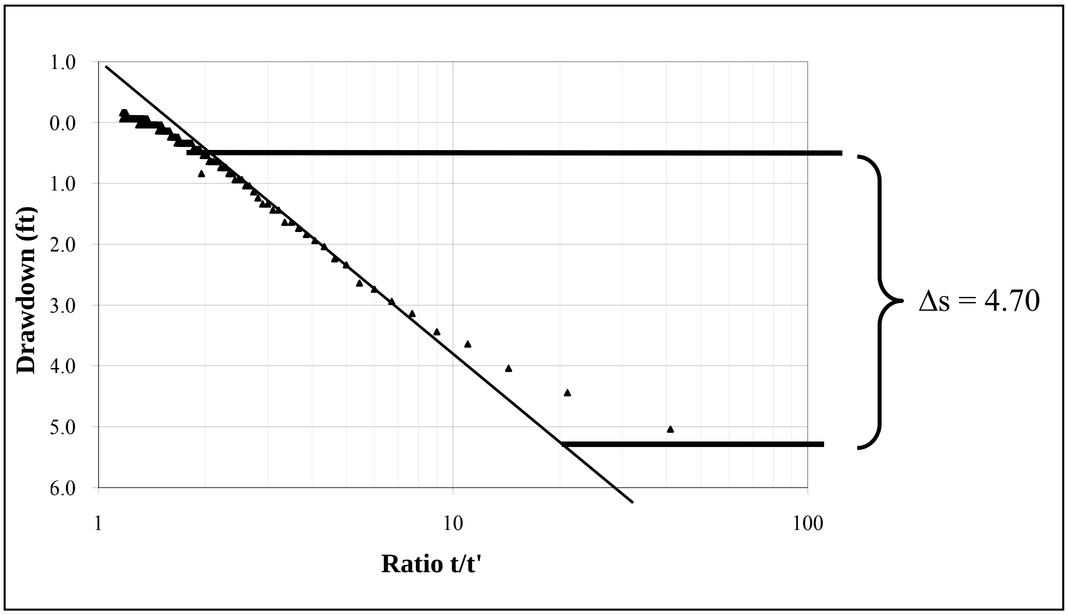

Figure 2.7 Example of Jacob's Straight-Line for recovery curve analysis, from Well 4, trial 1, 5/05/07.

2.5.1.4 *Late-time recovery curve analysis*

The late-time recovery curve data (Figure 2.8) was analyzed in light of results comparing the specific capacity values calculated using the Jacob's Straight-line modified non-equilibration equation method used in this study and values attained using several other analysis methods including the Papadopulos-Cooper solution using the AQTESOLV program and GMS models (Myre 2008).

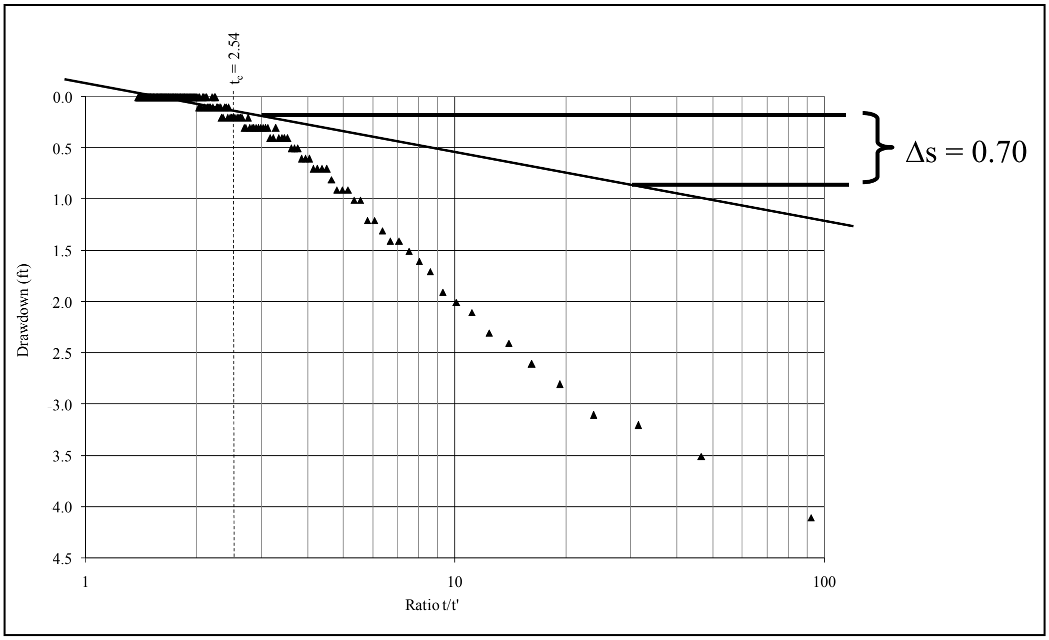

Figure 2.8 Example of Jacob's Straight-Line for late-time recovery analysis from Well 2, trial 3, 8/6/07. Note late time data is to the left of the graph. The x-axis is the ratio time since pump started to time since pump stopped.

Myre's results suggest that using the Jacob's modified non-equilibrium equation to analyze manual pump data leads to underestimations of well capacity. This is because the equation does not take into account casing storage. Typically, casing storage is not an issue in wells of small diameter during conventional pumping tests. But conventional pumping tests are run at much higher pumping rates than the 5 gpm that the manual pumps are capable of. When pumping begins, water in the casing is removed first, and data recorded during this period (termed "early-time data") will not yield a true measurement of the well's productivity. As pumping continues and the water level in the casing falls, water from the surrounding formation enters the well. Therefore it is necessary to analyze the "late-time data" (Myre 2008). The transition between the early and late time is called the critical time (t_c). Calculating the t_c for both pumping and recovery curves is described in Myre 2008.

2.6 Empirical long-term field-test to predict safe yield

A study completed by Herbert et al. (1992) was performed to predict long-term (6 months) static water level reductions over the course of a dry season for hand-dug wells in hard rock aquifers. The study was performed in Malawi in a collector well with adits. At the end of the rainy season the well was tested by pumping for two hours 63.5 gpm three times a day for an eight-day period. The depth to the water table was measured before and after each pumping period and plotted as water level depth over test time (Figure 2.9).

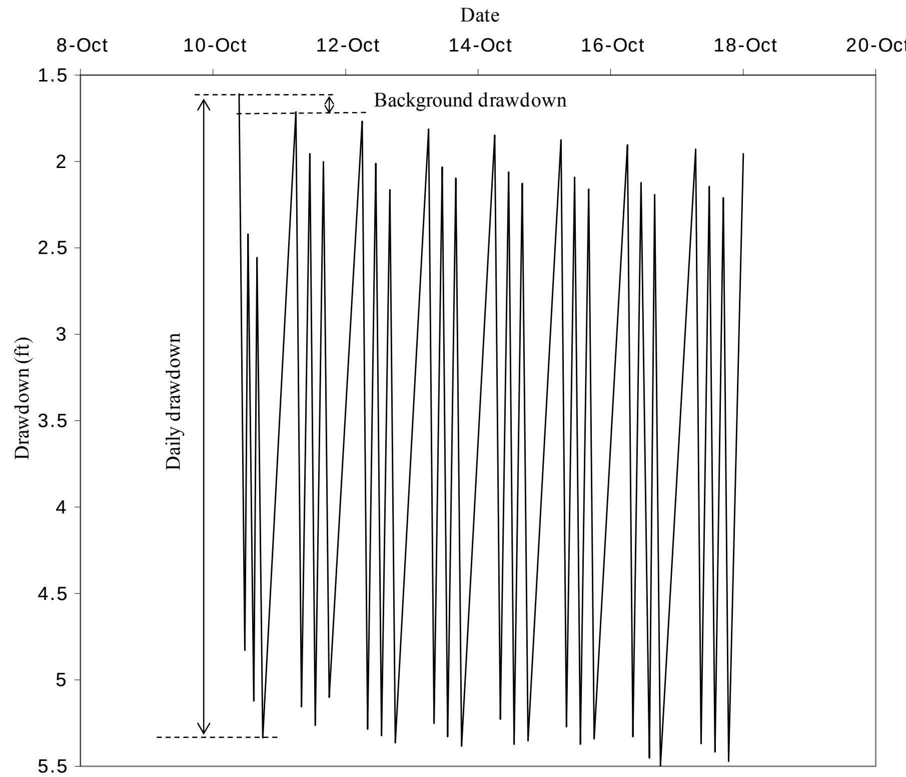

Figure 2.9 Drawdown of long-term pumping test in a large diameter hand-dug well (adapted from Herbert et al. 1992).

They found that the total drawdown could be divided into two different parts: the constant daily change from start to end of each pumping day and an apparent background-level drawdown (static water level changes) resulting from the natural decline in the water table. The observed gradual fall in static water level over the eight-day pumping test was used to predict background drawdown that would occur throughout the entire dry season. For a hydraulically efficient well, there is a roughly proportional relationship between pumping drawdown per unit discharge (specific capacity) and the saturated thickness in the aquifer. They proposed that their test could be used to calculate a safe discharge rate that could be maintained over the course of the dry season. For example, if a well with 50 ft of water column in the well, pumped at 10 gpm achieves a drawdown of 10 ft, the specific capacity is 1 gpm/ft. Assuming that specific capacity does not change significantly as drawdown increases, this well could be pumped safely at 40 gpm, which would draw the well down to 40 ft, leaving the remaining 10 feet of water in which to submerge the pump.

An adapted version of the Herbert et al. (1992) approach was assessed using the small diameter wells equipped with a rope pump. The main differences between the Herbert et al. (1992) study and this one are well size, pumping capacity, and pumping regime. Though Herbert et al. (1992) do not describe the hand-dug wells used in much detail, they are probably relatively shallow with a diameter of about 3-6 ft. In contrast, the wells used in this study are 4.25 in. in diameter and probably at least 2-4 times deeper than the hand-dug wells. The pump used in the Herbert et al. (1992) study is capable of sustaining a rate of 63.5 gpm for two hours, while with the manual pump, the maximum pump rate is 5 gpm and can only be sustained as long as those pumping do not tire (usually about 30 mins).

Using the Herbert et al. (1992) approach as a guide, the original plan was to do a 10-day series of pumping tests at the end of the rainy season. It was necessary that water was pumped only during the pumping test, thus well users would not be allowed to access their pump during that 10-day period. Therefore, it would be necessary to pump enough water during each day's test to meet their daily needs. This amount, which determined the amount of water to be extracted during the pumping tests, was established by estimating the well users' daily demand through well user surveys and then direct observation (Appendix B). Table B.3 lists estimated and observed values.

The pumping test consists of measuring the well's static water level, then pumping a specified volume at the most constant rate possible. Maximum pumping drawdown is recorded. When pumping ceases, the well is allowed to recover and the level at which the water recovers is recorded. This process is repeated twice more for a total of three tests per day.

The pumping test steps include:

1. Insert Levelogger and sounder probes in well. Allow Levelogger to measure pressure and temperature for at least 5 minutes to establish the static water level in the well.
2. Record static water level with the sounder.
3. Pump specified amount. Record the maximum (equilibrium) drawdown.
4. Allow well to recover, record recovery level.

The 10-day long tests were planned to be completed December 4 - 13, 2006. The measured data was to be used to extrapolate a static water level curve for the duration of the dry season, as done in the Herbert et al. (1992) study. Static water level measurements taken on a monthly basis through October 2007 would be used to determine the validity of the projected static water level.

3 RESULTS

The two main objectives of this study are: 1) Develop and test a manual pumping test for rope-pump wells, and 2) Evaluate empirical long-term manual pumping tests in rope pump wells. The results of the field work and data analysis are now presented and evaluated. Following that, discussions of potential error sources in the work and recommendations on the manual rope pumping test procedures are offered. Finally, a collaborative effort between SNV and the author to implement a well monitoring program in the department of Chontales is described. The raw data and all analyses are available in the attached CD.

3.1 Objective 1: Development and Testing of Manual Pumping test

Specific capacity values determined by all interpretation methods of all manual and conventional pumping tests are listed in Table 3.1. Figures 3.1, 3.2, and 3.3 compare the specific capacity calculations based on the four different methods as a function of static water level for each well. In general, values from the late-time recovery data, while not as consistent as the other results, are higher than all other values. The equilibrium approximation method generally yields specific capacity values roughly twice those as calculated by the pump and recovery curves analyses. Overall, there are striking similarities between the values attained from application of the four different methods in each well.

Table 3.1 Summary of specific capacity values for all wells as attained from manual and conventional pumping tests.

Date	Depth to water	Average specific capacity equilibrium approximation (gpm/ft)	standard deviation	Average specific capacity recovery curve Levelogger (gpm/ft)	standard deviation	Average specific capacity recovery curve sounder (gpm/ft)	standard deviation	Average specific capacity pump curve (gpm/ft)	standard deviation	Average specific capacity from late-time recovery (gpm/ft)	standard deviation
Well 1											
12/4/2006	36.7	-	-	-	-	1.11	0.12	-	-	-	-
12/5/2006	36.75	-	-	-	-	0.80	0.07	-	-	-	-
1/11/2007	38.15	-	-	-	-	1.13	0.03	-	-	-	-
2/10/2007	39.2	-	-	-	-	1.04	0.29	-	-	-	-
3/7/2007	39.98	-	-	-	-	0.80	0.25	-	-	-	-
4/14/2007	40.89	-	-	-	-	1.07	0.18	-	-	-	-
4/15/2007	40.91	-	-	-	-	0.72	0.05	-	-	-	-
5/5/2007	41.4	-	-	-	-	0.75	0.04	-	-	-	-
6/2/2007	43.25	1.96	0.08	-	-	0.89	0.10	-	-	14.18	2.19
7/3/2007	40.42	1.89	0.02	-	-	0.59	0.10	-	-	-	-
8/6/2007	37.2	-	-	-	-	0.79	0.08	-	-	-	-
Well 2											
12/4/2006	26	1.12	0.03	0.55	0.03	0.54	0.04	0.56	0.04	2.18	0.03
12/5/2006	25.98	1.26	0.03	0.68	0.02	0.51	0.01	0.72	0.04	1.44	0.31
1/11/2007	27.1	1.24	0.07	0.62	0.19	0.60	0.05	0.58	0.02	1.64	0.28
2/10/2007	27.91	1.08	0.06	0.62	0.05	0.65	0.07	0.54	0.02	2.15	0.27
3/7/2007	28.41	1.11	0.01	0.45	0.06	0.57	0.03	0.64	0.05	1.73	0.23
4/14/2007	29.15	0.97	0.02	0.47	0.03	0.50	0.01	0.56	0.05	1.91	0.18
4/15/2007	29.15	1.05	0.03	0.59	0.04	0.51	0.03	0.60	0.03	1.90	0.63
5/5/2007	29.59	1.12	0.02	0.52	0.02	0.54	0.04	0.74	0.02	-	-
6/2/2007	30.19	1.00	0.04	0.46	0.01	0.52	0.01	0.53	0.06	1.13	0.02
7/3/2007	30.4	0.92	0.02	0.45	0.02	0.47	0.02	0.43	0.05	1.89	0.25
8/6/2007	30.23	1.03	0.01	0.48	0.03	0.51	0.03	0.57	0.04	1.92	0.17
Well 4											
12/4/2006	35.35	2.90	0.34	1.02	0.24	1.57	0.01	1.39	0.27	-	-
12/5/2006	35.39	3.44	0.15	1.83	0.12	0.93	0.13	1.21	0.11	2.53	0.28
1/11/2007	36.5	3.25	0.25	1.12	0.15	1.10	0.15	1.31	0.18	4.17	0.77
2/10/2007	37.41	3.01	0.32	1.41	0.09	0.95	0.21	1.20	0.02	3.11	0.23
3/7/2007	38.15	2.34	0.26	1.18	0.27	0.67	0.09	1.11	0.04	3.32	0.16
4/14/2007	39.7	0.84	0.04	0.45	0.02	0.42	0.01	0.47	0.05	2.00	0.37
4/15/2007	39.8	0.94	0.00	0.49	0.00	0.40	0.02	0.54	0.05	1.63	0.47
5/5/2007	41.35	0.82	0.04	0.43	0.01	0.33	0.01	0.53	0.07	1.11	0.11
6/2/2007	43.25	0.59	0.00	0.30	0.00	0.29	0.00	0.35	0.01	1.02	0.10
7/3/2007	42.25	0.62	0.01	0.35	0.02	0.33	0.01	0.38	0.03	0.74	0.28
8/6/2007	42.25	0.79	0.06	0.45	0.02	0.41	0.01	0.53	0.03	1.42	0.12
9/22/2007	41.2	0.86	0.02	0.41	0.01	-	-	0.52	0.05	1.43	0.05

Well 4 Conventional Pump test results, SWL = 41.8 ft

Date	Q	Specific capacity Equilibrium approximation (gpm/ft)	Papadopoulos and Cooper AQTESOLV
9/25/2007	5 gpm	0.58	
9/25/2007	15 gpm	0.71	
9/25/2007	25 gpm	0.66	
9/25/2007	36.9 gpm	0.61	0.61

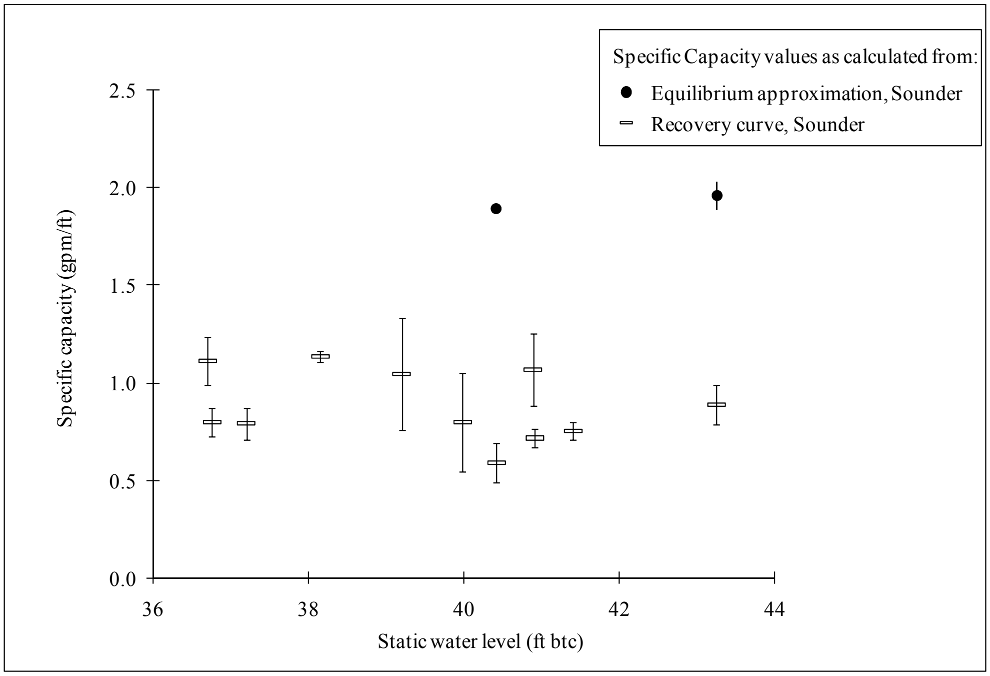

Figure 3.1 Well 1 specific capacity values with changing depth to water level. Equilibrium approximation data set is complete. Recovery curve data compared where available. One late-time recovery curve analysis was performed on June 2, 2007 data (Table 3.1) and indicated a specific capacity of 14.18 ± 2.19 gpm/ft (not shown). (btc=below top of casing).

Well 1 was outfitted to allow passage of only the sounder probe, thus the data is not as complete as the other two wells. Change in static water level for Well 1 was 6.5 ft. Due to rapid recuperation rates noted while in the field, very little late-time data was available for analysis. The one late-time recovery curve analysis performed on the June 2007 data suggests a value of 14.18 ± 2.19 gpm/ft (Table 3.1). Compared to results from Wells 2 and 4, this seems uncharacteristically high, though recovery time in this well was much quicker than in Wells 2 and 4. The few equilibrium approximation values place the specific capacity as slightly more than twice the values from the pump and recovery curve data. The Recovery curve analysis yields consistent results averaging 0.88 ± 0.17 gpm/ft.

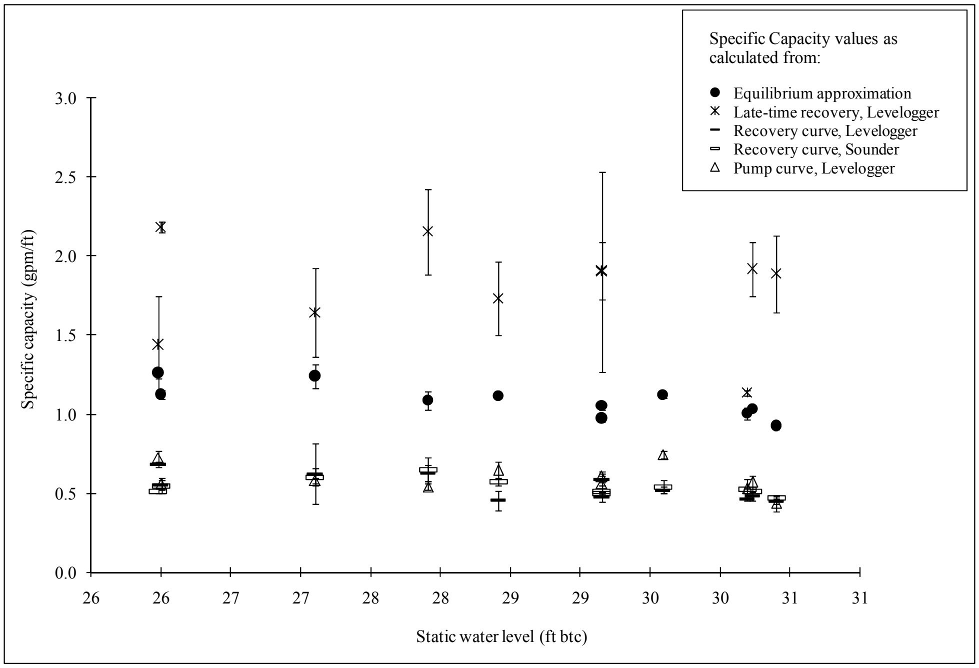

Figure 3.2 Well 2 specific capacity values with changing depth to water level. All four interpretation methods are compared.

The static water level in Well 2 dropped only 4.4 ft from December 2006 to June 2007. Taking the equilibrium approximation data as best representative of the specific capacities over the nine-month period, values range between 0.92 ± 0.02 gpm/ft and 1.26 ± 0.03 gpm/ft, and variation is minimal. As in Well 1, equilibrium approximation values, averaging 1.08 gpm/ft, appear about twice the average values determined by the pump and recovery curves analysis. The late-time recovery curve data follows the same trend as seen in Well 1 as values from this method are about three times those calculated by the pump and recovery curves.

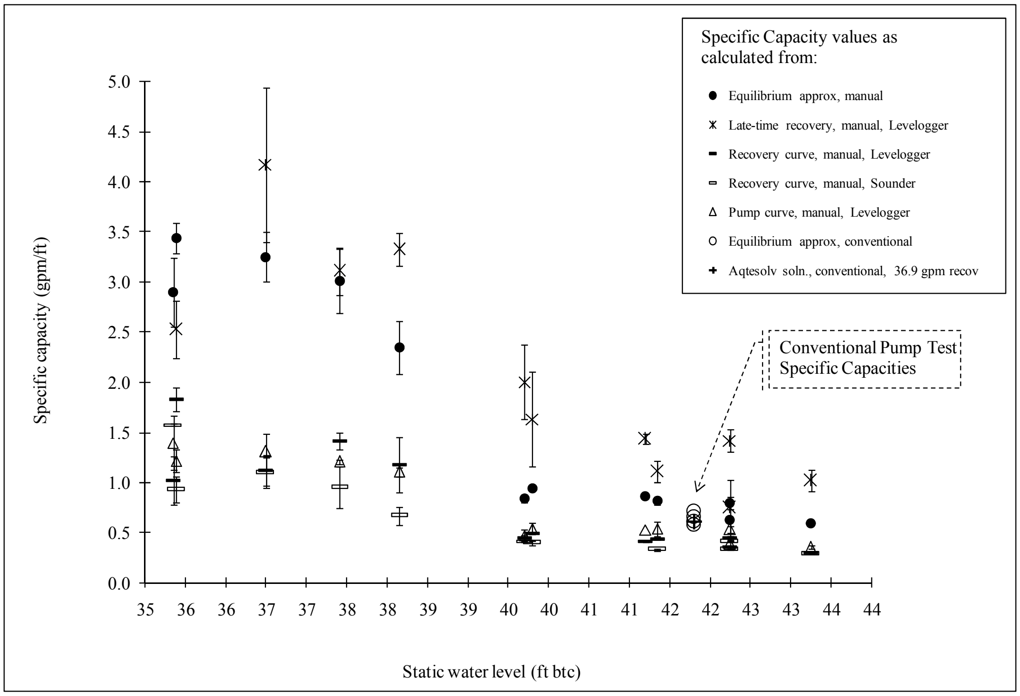

Figure 3.3 Well 4 manual and conventional pumping test specific capacity values with changing depth to water level. All four interpretation methods are compared.

Trends between data analysis methods for Well 4 are similar to those noted in Wells 1 and 2. Well 4 experienced an almost 8 ft drop in static water level over the summer, the greatest of all the wells. The equilibrium approximation values range is greater than the other wells; values fell between 0.59 ± 0.004 gpm/ft and 3.44 ± 0.15 gpm/ft. Just as in Well 2, the late-time recovery data analyses place the specific capacity higher than the equilibrium approximation values. However, the difference is smaller, averaging 20%. The pump and recovery curves analyses, again, estimate specific capacity values lower than the other two analyses methods.

Explanations for differences in the values calculated by the four methods involve casing-storage considerations. As discussed in Section 2.5.1.4 , the equilibrium approximation and late-time recovery curve analyses methods account for casing storage effects, however, Jacob's non-equilibrium equation, which was used to analyze the pump and recovery curves, does not. The results suggest that casing storage causes an underestimation of the actual specific capacities.

Though well productivity can vary widely in crystalline bedrock aquifers, they appear reasonable when comparing to other published values (Section 1.4). Higher standard deviations are associated with higher specific capacity values. Nonetheless, with only three exceptions, errors for the data with the highest standard deviations (late-time recovery curve) are less than 20%.

As mentioned in Well Selection (Section 2.1), Well 3 was monitored monthly to determine if the seasonal drop in water level would allow for the manual pumping test to estimate the well's specific capacity. Unfortunately the observed drop in static water level was only 6.25 ft and not sufficient to cause a significant decrease in specific capacity. Nonetheless, monitoring was still important as maximum pumping capacities can still be estimated. For example, if a 0.1 ft drawdown is assumed when pumping at 5 gpm, the well could sustain pumping at approximately 800 gpm assuming 160 ft available head and no significant decrease in well productivity with drop in head.

3.1.1 *Comparison of manual test results with conventional test results*

The conventional test 36.9 gpm recovery curve was analyzed with the Papadopulos-Cooper solution using the computer program AQTESOLV (Figure 3.4). Details on the application of the solution are described in Myre (2008). This analysis yielded a specific capacity value of 0.61 gpm/ft, and is assumed to best represent well specific capacity. The equilibrium approximation method was also applied to all four pump curves from the conventional pumping test. This analysis yielded values of 0.58, 0.71, 0.66, and 0.61 gpm/ft for 5, 15, 25, and 36.9 gpm pumping rates respectively. Confidence is placed in the higher, more stable, pump rates of 25 gpm and greater. Figure 3.3 shows the manual test results from the study and the conventional pumping test results plotted together.

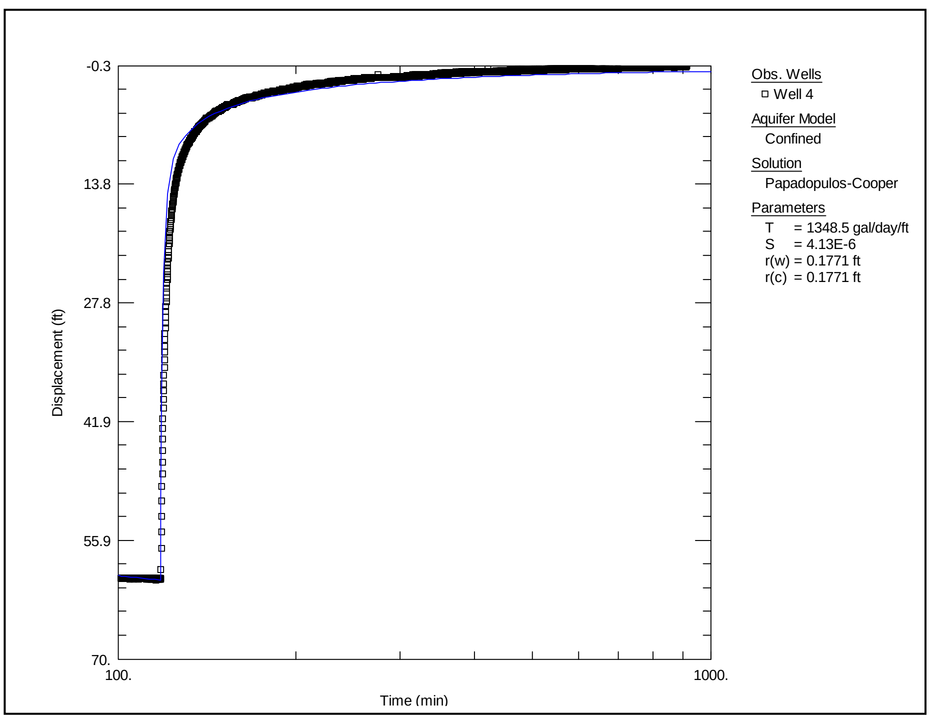

Figure 3.4 Papadopulos-Cooper solution using AQTESOLV program for 36.9 recovery curve. Curve matching for the pump down part (not shown) was not as precise as the recovery. *T* and *S* values taken from the analysis using the Cooper-Jacob's non-equilibrium equation (Eq. 4) yielded a specific capacity value of 0.61 gpm/ft.

A comparison of specific capacity values yielded from the manual pumping test performed three days prior to the conventional test and the specific capacity value from the Papodopolous-Cooper solution of the conventional pumping test 36.9 gpm recovery curve reveals the accuracy of the different analyses methods. The manual test pumping and recovery curves analyses methods underestimate the actual specific capacity by 14% and 33% respectively. The equilibrium drawdown and the late-time recovery curve data methods overestimate by 41% and 133% respectively. Variability in the pumping and recovery analyses is attributable to difficulties in maintaining constant pump rates and casing storage effects. The equilibrium drawdown method typically overestimates specific capacity because the true equilibrated pumping level is often not attained during pumping tests.

In addition to providing a specific capacity value for the well, the conventional test allowed for the testing of other hypotheses as well. There was concern that with the low pumping rate of the manual pumps a true specific capacity value would not be attained. This is because pumping tests are usually performed at high pumping rates to try and achieve the maximum drawdown so ultimate capacity can be calculated. The step-drawdown data provided a manner to compare the low-flow pumping test estimations of well capacity to those attained through more traditional methods. Evidently this is not a concern in light of the conventional test data. Additionally, head losses due to well inefficiencies, or well loss, were assumed to be zero for the manual pumping tests. The conventional test results confirmed the validity of that assumption as shown in Figure 3.5 which shows the yield as a function of drawdown. The linear nature of the trendline indicates that well losses are indeed negligible.

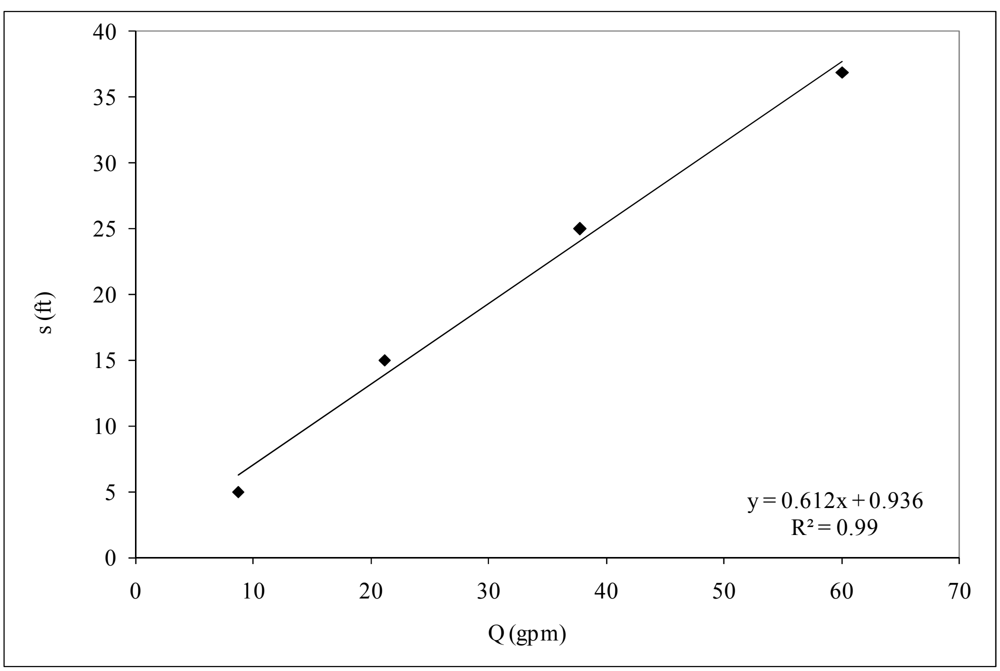

Figure 3.5 Yield (Q) as a function of drawdown (s) for the conventional step-drawdown pumping test.

The need to compare results from analyses of the data attained from the manual pumping tests and conventional test is obvious. However, a cost comparison is worth noting as part of the objective is to create an economical method accessible to financial strapped institutions and/or municipalities. The cost of the conventional test performed for the study was approximately $700. This fee included rental of the water utility's equipment, gasoline, and 2.5 days of labor. In contrast, once a sounder is obtained, the cost of the manual pump tests depends essentially only on the cost of labor. As discussed later in Recommended Manual Pumping Test Procedures (Section 3.1.6), the pumping test can be performed without installing probe access pipe, negating the need to buy materials to retrofit the wells.

3.1.2 Sounder and Levelogger data comparison

Both sounder and Levelogger instruments were used to measure the depth to water table during the pumping tests. While the Levelogger higher temporal resolution data and is more convenient to use in the field, the sounder is an established and acceptable way to collect measurements as well. Both instruments were used to determine if the data collected varied considerably and to determine if the sounder would provide accurate enough results to be appropriate as a standalone data collection tool. Most of the time, sounders are used for monitoring observation wells and pumping well data are not used because it is difficult to measure a falling water level in a pumping well. In rural settings there are no observation wells, so it is necessary to conduct the tests in pumping wells. To make that assessment, the specific capacity values as calculated from the recovery curves measured by both instruments from each pumping test were compared. The recovery curve data was analyzed because it is the easiest data to collect manually during the pumping test.

Figure 3.6 shows both sounder and Levelogger pumping test data taken during the June 2, 2007 pumping tests. This is representative of all curves and they appear to match quite well.

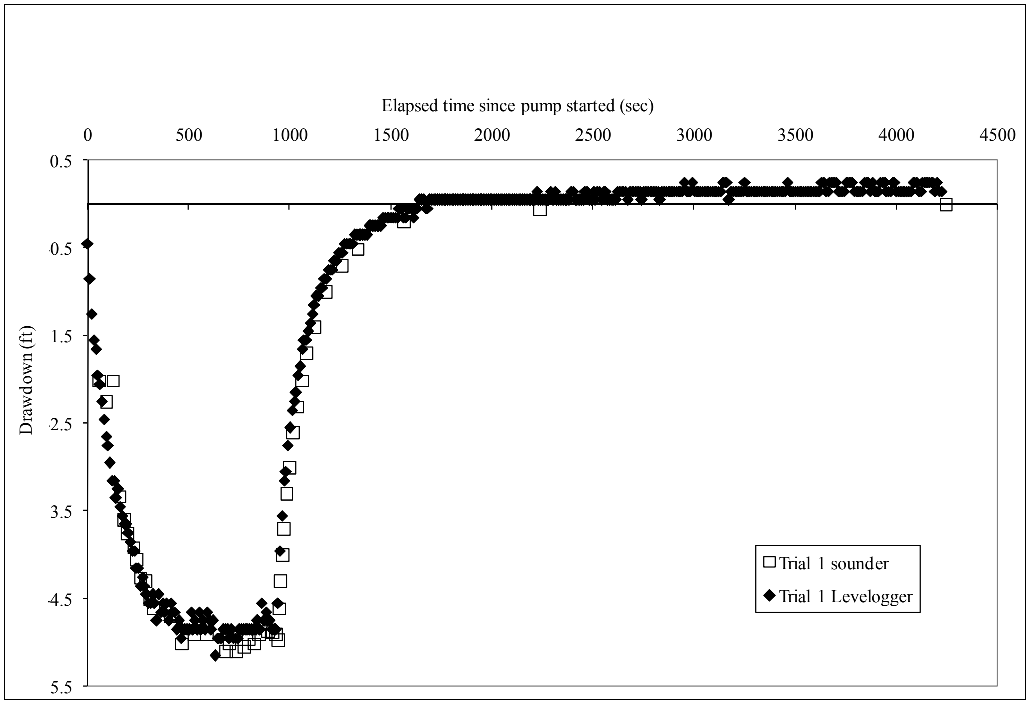

Figure 3.6 A comparison of sounder and Levelogger data taken from a pumping test on Well 2, 6/2/07.

Comparing the average percent difference of all tests (Table 3.2), a discrepancy of 9.9% for Well 2 and 31.4% for Well 4 is observed. Noting the generally elevated percent difference between the Levelogger and sounder values for Well 4's December 2006 – March 2007 data, it appears that higher discrepancy between measurement methods is related to higher specific capacity values. Nonetheless, for field studies, it is not uncommon for aquifer properties derived from idealized characterization methods to vary this significantly.

Table 3.2 Comparison of recovery curve data collected by sounder and Levelogger instruments for Wells 2 and 4.

Date	Specific Capacity calculated using Levelogger data (gpm/ft)	Specific Capacity calculated using sounder data (gpm/ft)	% Difference
Well 2			
12/4/06	0.55 ± 0.03	0.54 ± 0.04	2.1
12/5/06	0.68 ± 0.02	0.51 ± 0.01	32.6
1/11/07	0.62 ± 0.19	0.60 ± 0.05	3.6
2/10/07	0.63 ± 0.05	0.65 ± 0.08	3.7
3/7/07	0.45 ±0.06	0.57 ±0.03	20.6
4/14/07	0.47 ± 0.03	0.50 ±0.01	4.9
4/15/07	0.59 ±0.04	0.51 ± 0.03	14.4
5/5/07	0.52 ± 0.02	0.54 ± 0.04	4.0
6/2/07	0.46 ± 0.01	0.52 ± 0.01	12.0
7/3/07	0.45 ± 0.02	0.47 ± 0.02	4.3
8/6/07	0.48 ± 0.03	0.51 ± 0.03	6.5
Average			9.9
Well 4			
12/4/06	1.02 ± 0.24	1.57 ± 0.01	35.3
12/5/06	1.83 ± 0.12	0.93 ± 0.13	96.8
1/11/07	1.12 ± 0.15	1.10 ± 0.15	2.0
2/10/07	1.41 ± 0.09	0.95 ± 0.21	48.8
3/7/07	1.18 ±0.27	0.67 ± 0.09	76.8
4/14/07	0.45 ± 0.02	0.42 ± 0.01	7.9
4/15/07	0.49 ±0.01	0.40 ± 0.03	23.7
5/5/07	0.44 ± 0.01	0.33 ± 0.01	33.3
6/2/07	0.30 ± 0.01	0.29 ± 0.01	4.5
7/3/07	0.35 ± 0.02	0.33 ± 0.01	6.6
8/6/07	0.45 ± 0.02	0.41 ± 0.01	9.7
Average			31.4

3.1.3 Monthly Pumping tests

Figure 3.7 compares 2006 and Jan-Oct 2007 precipitation measured to average precipitation recorded between 1960 and 2005. Less than average rainfall occurred in 2006 while opposite is true for 2007.

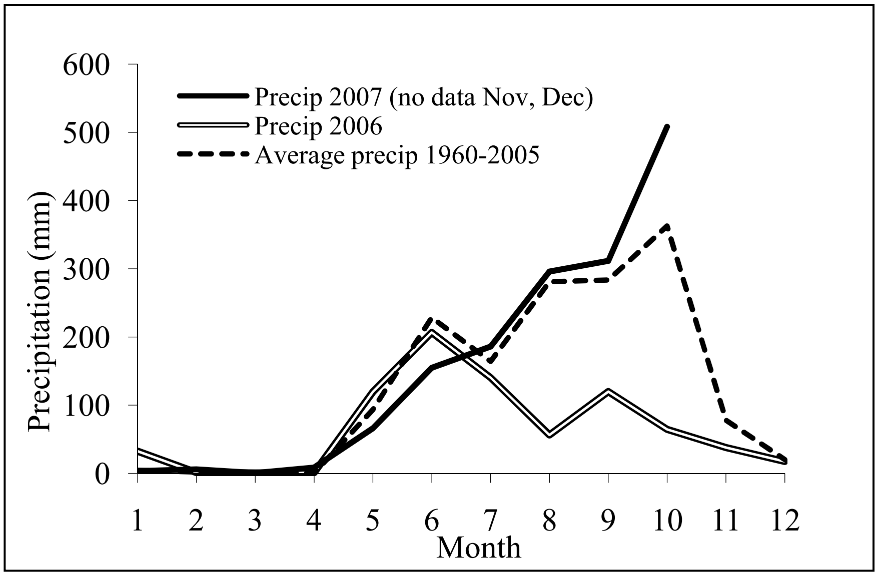

Figure 3.7 A comparison of the average precipitation per month (1960-2005) to precipitation that occurred in 2006 and Jan-Oct 2007. 2006 experienced significantly lower rainfall than the average, while the data for 2007 show higher than average values. 1960-2006 data from INETER (2007). 2007 data taken from Levelogger placed in well 4.

The effects of variable monthly precipitation were observed as monthly variations of the depths to water level, as shown in Figure 3.8. Each of the wells was utilized differently. Well 1 served principally only one household and had no gardens needing watering, while Wells 2 and 3 served either multiple homes or more water was used to water a small family garden. Well 4 was used the least of all the wells, as discussed in Well Selection (Section 2.1). Despite these differences in use, the extraction is so low that changes in water level are attributable only to natural seasonal variability.

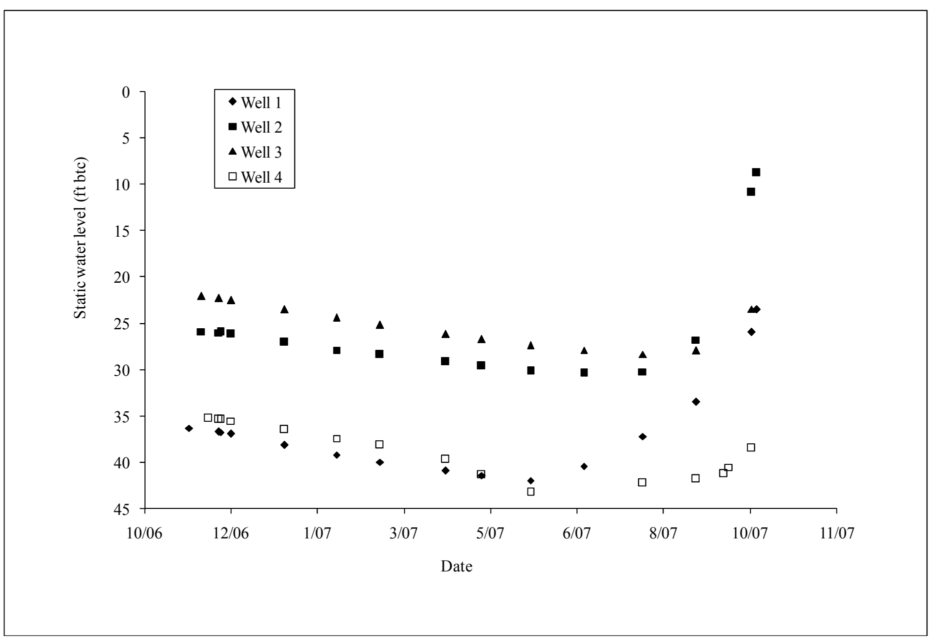

Figure 3.8 Static water changes with time (December 2006 – September 2007) for all wells.

In the most extreme example, Well 2, December 2006, the depth to water level was measured at 25.9 ft, and by the end of October 2007, the level had risen to 8.8 ft, a difference of 17.1 ft. The other three wells experienced increases in the water table, but not as great as in Well 2. During the dry season (December 2006 – April 2007) the wells all show comparable differences in magnitude of static water level drop, but with the recharge of the aquifer, the well's static water levels recuperated at varying rates. The graph shows that recuperation in Well 1 began almost a full three months earlier than the other wells, perhaps because the water level is lower than the other wells, and/or because topographically the well site is lower than the other wells. However, this is based solely on field observations as no reliable elevation data on the wells is available.

Plotting the rainfall data for 2007 and depth to water level in Well 4 as shown in Figure 3.9 shows a dry-season drop of 7.91 ft from the first measurement taken November 27, 2006 and the lowest depth to water level measured on March, 31, 2007. Beginning in June, the water level begins to rise and heavy rains in October eventually cause the water level to surpass the initial measurement taken in November 2006.

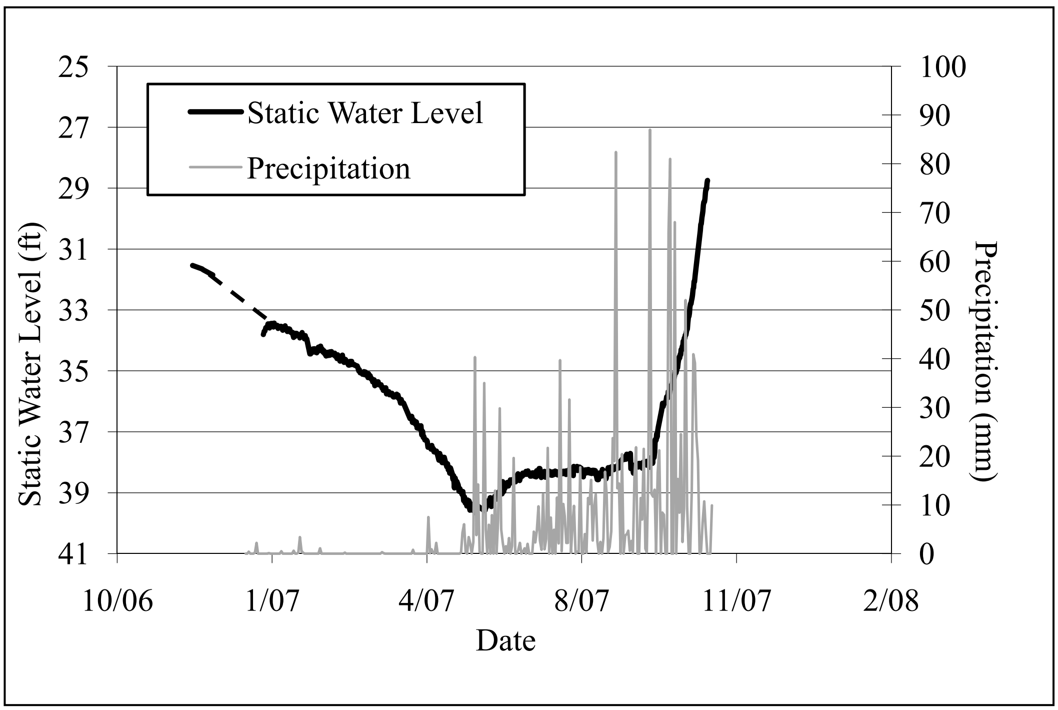

Figure 3.9 Static water level of Well 4 and precipitation between 11/27/06 and 10/26/07. Static water level measurements were taken with Levelogger programmed to collect a data point every 8 or 12 hours. Dashed line indicates projected trend when levelogger was not available. Precipitation data taken from Juigalpa meteorological station, located approximately 8 miles NW of well.

Although it is clear that the water table is rising in response to precipitation, there is not a direct correlation to the rate of rise and the amount of precipitation observed at the meteorological station as shown in Figure 3.9. It is plausible that the precipitation amounts in the recharge areas of the wells are different than what was observed in Juigalpa. Moreover, it appears that the recharge areas for each of the wells may differ. Wells 1 and 2 appear to be closer to the topographically higher areas, where presumably the majority of the precipitation occurs (Figure 3.10), and Wells 3 and 4 appear to be located in different subcatchments that are farther from the higher terrain.

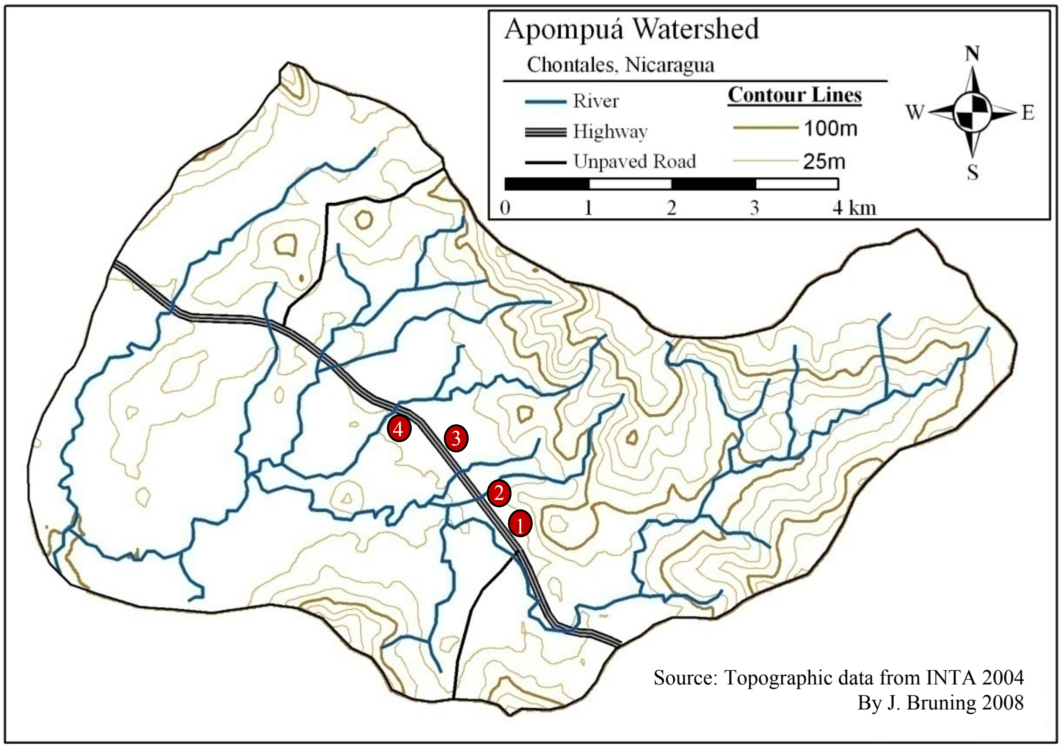

Figure 3.10 Topographic map of Apompuá Watershed with well locations.

Figure 3.11 shows that the changes in well productivity with changing static water level in Wells 1 and 2 are insignificant. In theory, for a fully penetrated unconfined aquifer a 100% drawdown would yield a 50% drop in specific capacity (Driscoll 1986). In Wells 1 and 2 drops in static water levels were only 3.6 and 2.7% of the available water column (assuming well depths of 200 ft). If the theoretical relationship holds true for the wells studied, the changes in specific capacities for these minute drops in water level are so small that it is impossible to confidently identify the aquifer as confined.

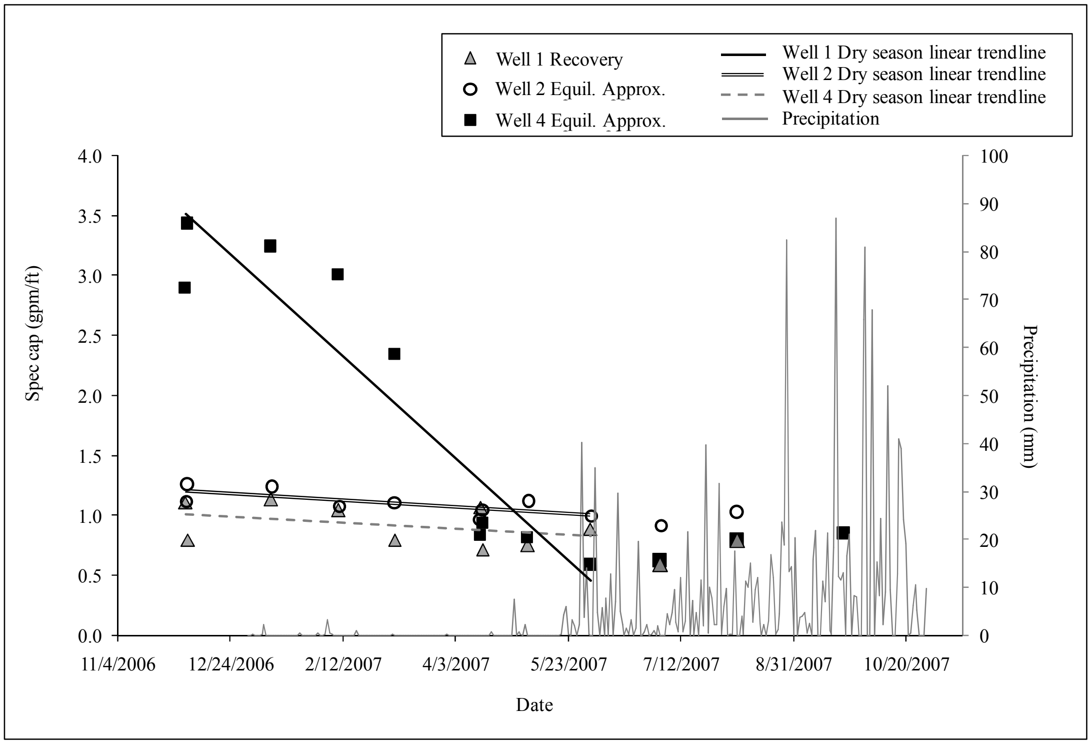

Figure 3.11 Changes in specific capacity with static water levels over the dry season (Dec. 2006 – May 2007). Precipitation data taken from Juigalpa meteorological station, located approximately 8 miles NW of well.

In contrast, Well 4 experiences a marked decrease of 80% in specific capacity while exhibiting the greatest change in static water level over the summer. In Figure 3.3, it appears that Well 4 data taken between December 2006 and April 2007 specific capacity values were almost unchanging. The same occurred for April 2007 to September 2007, but at a lesser specific capacity value. This may suggest that a feeder-fracture/fracture zone near the surface had gone dry around April. Without this contribution, the well productivity declined notably and remained at this level throughout the study.

3.1.4 Sources of Error

3.1.4.1 Instrument

Small error may be due to inaccuracies in the Levelogger measurements. Depth to water measurements are calculated internally by the datalogger based on the pressure of the water column in which it is placed and is accurate to 0.1% full scale, which for this instrument is 300 ft. The larger standard deviations of the late-time data compared to the other analysis methods may be a result of the Levelogger's limitations.

The sounder is a simple instrument yet some complications can arise with its use. In the case of Well 4, the water had a comparatively higher $CaCO_3$ and sulfate concentration than the other wells (Appendix C), which may decrease the sensitivity of the probe. Since the salts in the water are more conductive than pure water, they maintained the closed circuit completed by contact with water, activating the buzzer and light even after removal from submersion underwater. A sensitivity adjustment knob is located on the housing of the sounder, nonetheless difficulties were encountered.

3.1.4.2 During Data Collection

Possible errors during the pumping tests may involve counting and recording errors. For example, 5-gallon buckets were used to transfer water from the well to the storage tank, and it is possible that the number of buckets was miscounted, which would lead to an error in average pumping rate. Additionally, it was impossible to collect every drop of water that came out of the well. A small amount of water was also lost (less than 10 %) due to the water that was entrained in the rope and was sprayed out as the rope traveled around the wheel. Moreover, if the well was pumped too fast, water would bypass the horizontal delivery pipe, travel up the ascending pipe and spill out. All efforts were made to ensure this did not happen, and most errors of these types were probably concentrated in the first few months of data collection, as after that, a reliable way of counting was established, and the people pumping had a better feel for an appropriate pumping rate. Other error includes not maintaining a steady enough pumping rate.

Particularly when a well was rapidly recuperating (in the first minute after pumping stops) there was a higher probability that incorrect measurements and/or times were made and/or recorded. However, plots of the data made it easy to identify serious mistakes, as they do not fall well along the curves. Outliers were not included in the visual fitting of the Jacob's Straight-Line test.

3.1.4.3 During Data Analysis

During data analysis, potential error is attributed to the researcher's judgment in curve fitting, the assumed values for storativity, and not complying with the assumptions listed in Table 2.1 when applying the Jacob's modified non-equilibrium equation. Because these methods were all applied manually (not using a modeling program except in the case of the conventional pumping test data), errors on the part of data interpreter were inherent. For example, in applying the Jacob's Straight-line method, the line is drawn manually, making the results contingent upon the interpreter's estimations. The method is easier to apply when there is rapid change in drawdown with time (i.e., recovery curve analysis), but more difficult when change in drawdown is more subtle (i.e., late-time recovery curve analysis). For the equilibrium approximation, the point at which apparent equilibrium status was achieved during the pumping test is also dependent on the interpreter's opinion. This affects specific capacity values most when a relatively small amount of drawdown has been attained.

As mentioned earlier, the storativity was an assumed value of 0.075, suggested by Driscoll (1986) as a typical value for unconfined aquifers. There is no way to properly estimate the storativity value from empirical data because 1) no observation wells were available and 2) fractured rock aquifers do not meet the assumptions required to apply the non-equilibrium equation with confidence. A comparison of the data using 0.075 and the typical assumed value for confined aquifers of 0.001 yields a difference in specific capacity of approximately 35%. Due to the uncertainty in assumptions needed to apply the non-equilibrium equation, analysis using this approach is not recommended.

3.1.5 Limitations of the manual test

Field experience has shown that the single most limiting factor on the application of the manual rope pumping test is well productivity. If the well is too productive, the pump cannot drawdown the water level sufficiently. Nonetheless, the "test" does provide valuable information as an estimation of pumping capacity can be made as done for Well 3 (Section 3.1). On the other hand, in the case of the very low productive well, the water level drops until it reaches the bottom of the pumping mechanism and never approaches equilibrium. Obviously then the equilibrium approximation is impossible to apply. In that case, the late-time recovery curve analysis should be applied.

As with any pumping test performed in a fractured bedrock aquifer, it is possible that after pumping what appears to be a productive zone in the aquifer, production rapidly declines. This is a result of the well being placed in a fractured zone with limited connection to recharge sources or minimal aquifer storage (Sanchez 2002). While this occurs among conventional step drawdown and constant rate tests, since the manual pumping test is so short it is possible that the manual pumping tests may not yield reliable minimum specific capacity results. Rather, the values reflect maximum specific capacity. Nonetheless, as the conventional pumping test results confirm, productivity values really did not change significantly with increased drawdown.

In any case, determining the maximum specific capacity is important if determining the maximum capacity pump for a well is desired. But for monitoring purposes, the rope-pump most likely does not pump enough water for limited connection to recharge source or minimal aquifer storage to be of much concern.

3.1.6 Recommended manual pumping test procedure

It would most likely benefit a municipality or community to attain well information when the well is least productive. While the variability may not be great (as observed in Wells 1 and 2), it would be best to perform the pump tests at the end of the dry season when groundwater tables are at their lowest. Generally, it is not necessary to perform tests every month, however if a drop or increase in static water level greater than 10% of the available water column is observed, determining well productivity at that water level is advisable.

The following steps outline the field-data collection and analysis procedures:

- Measure the static water level. The well must not be pumped for a minimum of four hours (for these wells, because their recovery was fast (< 2 hrs); shallower wells and wells in low-transmissivity aquifers may have to rest longer, typically 24-48 hrs) before the pumping test is conducted. Agreement on the part of the well users is necessary to ensure accurate static water level measurements.
- Lower sounder probe into access pipe. Note the static water level indicated by the sounder.
- Record pumping time start. Track the volume of water extracted. Pump the well until an apparent equilibrium pumping level is established and maintain several minutes. Take water level measurements with the sounder at least every minute during pumping.
- Record the time pumping ceases.
- Measurement the depth to water level with the sounder: lift the tape approximately 0.3 ft from where water was when pumping was stopped. Record water level and time when the water level reaches the sounder probe, then lift another 0.3 ft, again recording the water level and time. Repeat until static water level is reached.
- If possible use the equilibrium approximation to determine specific capacity by dividing the volume of water extracted by the "equilibrated" pumping drawdown (Section 2.5.1.1).
- If an equilibrated pumping level is not attained due to a very low-productive well, use the late-time recovery curve analyses procedures outlined in Section 2.5.1.4.

It is probably not necessary to install access pipes if the test will be performed infrequently in the same well. In that case, simply gaining access by detaching the pump from the cement apron and elevating the pump on several bricks provides sufficient room for removal of the well cap and insertion of the probe(s). The sounder is the preferred instrument for data collection due to its simplicity.

3.2 Objective 2: Test empirical long-term pumping test in rope pump wells

It appears that an adapted version of the long-term field test to predict safe yield, from Herbert et al. (1992), is not applicable in the wells in this region due to the lack of a measurable "background" drawdown observed over the two days the test was performed. As shown in Figure 3.12, after six tests there is no appreciable drop in "background" drawdown either between tests or between adjacent test days (compare to Figure 2.9).

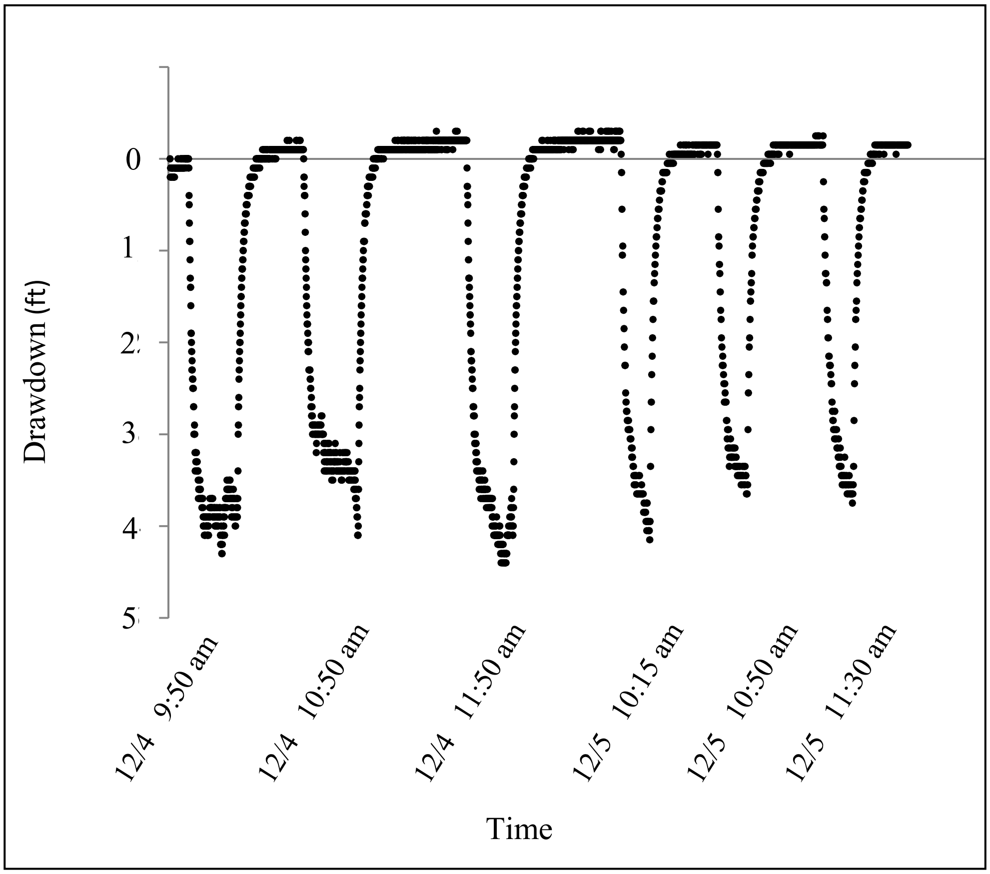

Figure 3.12 Well 2 drawdown during long-term-pumping test performed on 12/4/06 and 12/5/06.

The fact that the wells behaved much differently that what Herbert et al. (1992) observed in their study could be because:

- well productivity is higher than anticipated and there is little stress placed on well by manually pumping
- the extraction rate (5 gpm) is too low
- The wells are located in the middle region of the Apompuá watershed. The aquifer was probably replenished by recharge from the mountainous Amerrisque range to the northeast. Perhaps if the wells had been higher in the watershed, recharge would have been negligible. The hydrogeologic setting in the area of Malawi studied by Herbert et al. (1992) was not described, so no hydrogeological comparisons can be made.

If pursuing this experiment further, the study area would need to be thoroughly researched and an attempt to best match their pumping regime with longer pumping periods using a higher-capacity pump should be made.

4 AN EXPERIMENT IN IMPLEMENTING A WELL MONITORING PROGRAM IN NICARAGUA

While the focus of this study is technological in nature, it is well understood that in the developing world, groundwater management progress is not necessarily severely hindered by technological limitations, but rather by underlying social, political and administrative problems and inefficiencies. The quality of the analyses and conclusions on groundwater status from the developing world are questionable in part because of lack of understanding of techniques employed, but also because of sensitive political issues. One example is the altering of data to attract financial awards allocated to areas underlain by aquifers qualified for groundwater development (Moench et al. 2003). While discussing solutions to the social issues are beyond the scope of this study, it is worth noting the larger-scale issues surrounding resource management.

Countries often employ large-scale extraction-recharge balances to determine groundwater conditions and potential for development. However, while difficult enough in the industrialized world, this process is nearly impossible in developing countries due to the lack of basic scientific and monitoring equipment and data processing required. Thus Moench (2005) suggests simplifying the process to be most meaningful to a country’s citizens. Declining water levels directly affect energy requirements for pumping and the cost of establishing wells and have a great impact on visible environmental degradation, such as reduced baseflows in streams, poor wetland health, and receding lake boundaries. Also, acceptable water quality is imperative to people’s health which translates to a more productive working population and decreased health care costs. Therefore, rather than focusing on large scale studies with significant inherent error, more attention should be paid to simply monitoring depth to ground water and basic water quality.

This became the focus of a project undertaken with Antoinette Kome starting in March 2007. Combining the access pipe modification used in this study with a simple way to measure static water level and knowledge on well disinfection from one of the participants, a simple regional groundwater monitoring program was developed and presented to the local mayors. It was well accepted, particularly because the department of Chontales borders Lake Nicaragua. This lake ranks as the 20th largest lake in the world, and aside from being a source of pride for Nicaraguans, it is also an economic hub and may become the source of various cities’ water supply in the near future. Therefore, water management has its place on every mayor’s agenda.

4.1 Regional Groundwater Monitoring Program

During the summer 2007, a network of UNOMs (*Unidad de Operacaión y Mantenimiento* (operation and maintenance unit) was created to generate rural well status data and promote sharing between municipalities in Chontales (Figure 4.1).

UNOMs are technicians, employed by the mayor, whose main responsibility is to ensure sustainability of rural wells and water distribution systems. The network was principally created to monitor groundwater (depth to groundwater and quality) in rural areas since no monitoring program existed.

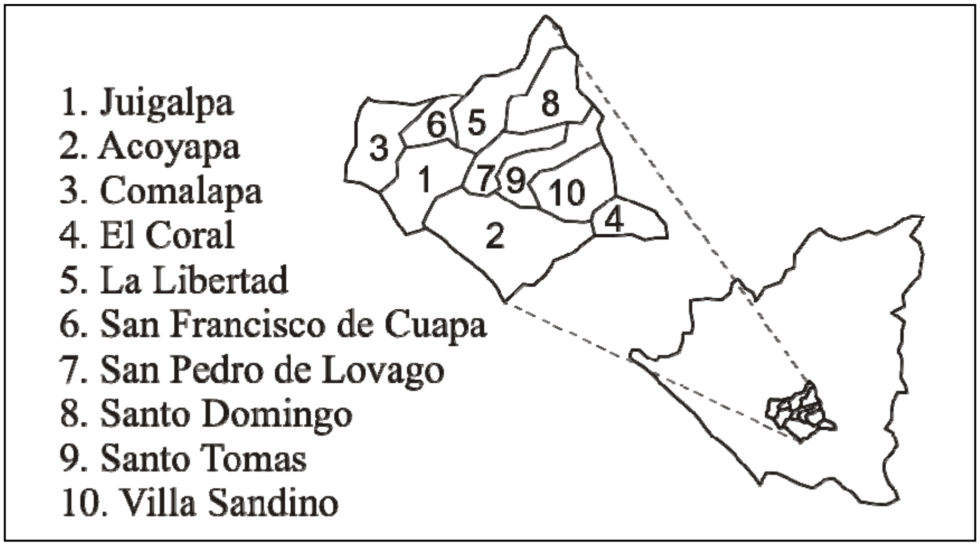

Figure 4.1 Municipalities of the department of Chontales. Adapted from INTA 2004.

4.2 Method

In March and April 2007, several training sessions were planned for UNOMs to learn how to choose and equip monitoring wells, measure static water levels in rural wells, and input data into an Excel spreadsheet. Responsibilities for each leader are as follows: Antoinette Kome of SNV: project oversight; Luis Meza of ENACAL: topographic maps and locating wells; UNOM Walter Garcia well disinfection; and the author; static water level monitoring using a measuring tape and water-soluble chalk (Figure 4.2). Ten UNOM technicians were invited to attend. Three opportunities were presented over the course of six weeks. Of these training sessions, two were consolidated meetings in or near Juigalpa, and one was a visit by the author to each municipality to work with the UNOM one-on-one in the field. UNOMs were encouraged to install the access pipe themselves, as well as take measurements and fill out the paperwork. All efforts were made that the training sessions be as participatory as possible.

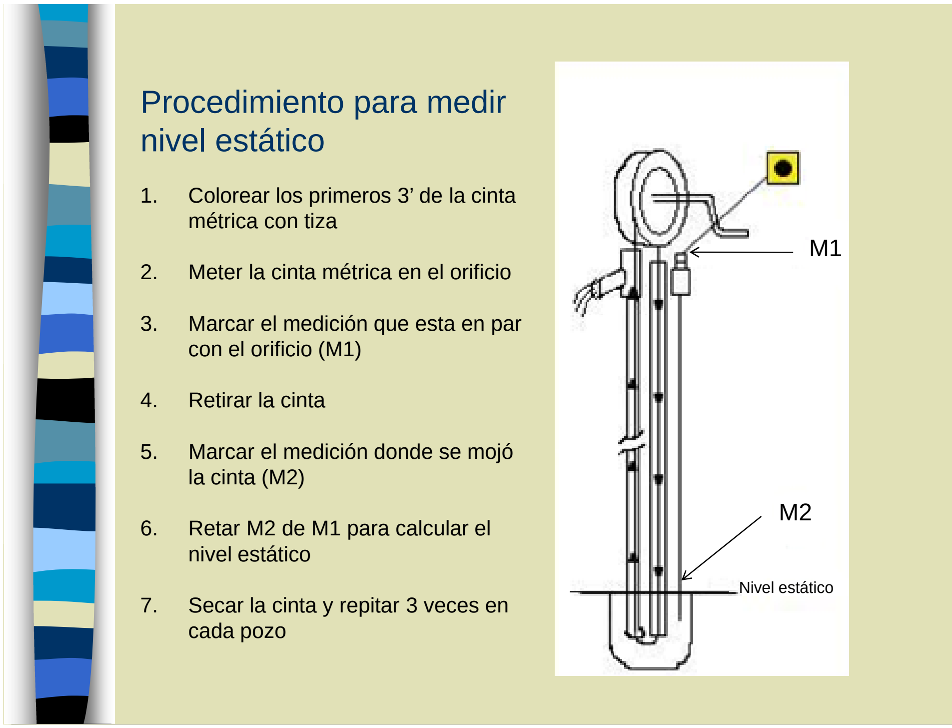

Figure 4.2 Slide from presentation given to UNOMs on how to measure depth to water level

The training sessions included a discussion of how their data would fit into the larger plan of beginning a groundwater monitoring program as each UNOM shared data with other municipalities. The data would eventually be inputted into a database management program and mapped, depending on the advances of ENACAL or FISE in developing a program for well/watershed information dispersal.

Once trained, the technicians were to choose several wells in their municipality and measure the static water levels of those wells at least once before the rainy season began (approximately June).

4.3 Results

Of the ten municipalities, eight chose to participate (Juigalpa and La Libertad declined). Seven UNOMs showed up to the first meeting, and four to the second. Seven site visits were completed, with Santo Tomas having to cancel the scheduled visit.

In the May 31, 2007 meeting, at which time the technicians were to bring their data sheets and enter them into an Excel spreadsheet, none of the UNOMs brought data. In subsequent meetings, data was still not presented for review. Finally at a meeting in September 2007, UNOM’s provided data showing that nine wells in three of the municipalities in Chontales (five in Acoyapa, three in Santo Tomas, one in Villa Sandino) had at least one static water measurement taken (all taken between April and June). The success of these three neighboring municipalities (Figure 4.1) could be because the especially energetic UNOM stationed in Acoyapa helped out in nearby municipalities. Acoyapa's UNOM also improved the monitoring technique by substituting instant coffee paste for the hard-to-see chalk for marking the measuring tape. An example of the form filled out can be found in Table 4.1.

Table 4.1 Example of well registration from the municipality of Santo Tomas, Chontales, Nicaragua.

WELL REGISTRATION - BASIC INFORMATION

		1	2	3	4	Notes
Technician		Emilio Orozco	Emilio Orozco	Emilio Orozco	Emilio Orozco	
Municipality		Santo Tomás	Santo Tomás	Santo Tomás	Santo Tomás	
Community		Tierra Blanca	Tierra Blanca	Atillas	Las Mesas	
Sector		Los Galeanos	Los Massis	San José	La Pita	
GPS X					12.3.43N	
GPS Y					85.3.6,4O	
Date		6/5/2007	4/27/2007	4/26/2007	3/7/2007	
Time		9:40 AM	4:00 PM	12:25 PM		
Well number		3	1	1	2	
Well name		Los Galeanos	La Polvora	San José	La Pita	
Name of property owner well on which well is located		Galeano	Massis	Miranda	Atayo	
Well type (drilled, hand dug)		drilled	drilled	drilled	drilled	
pump type		rope pump	rope pump	rope pump	rope pump	
Private or Communal?		communal	communal	communal	communal	
Financed by		ENACAL-UNICEF	ENACAL-UNICEF	ENACAL-UNICEF	ENACAL-UNICEF	
Year of construction		2002	2002	2005	2005	
Well depth (ft)		200	200	75 meters	200	
Water uses	**options**					
School?	yes-no	no	no	no	yes	
Number of students		0	0	0	38	
Number of families		4	5	4	5	
Number of people		32	40	28	27	
Other source of water used?	yes-no	no	no		no	
Consumption	yes-no	yes	yes	yes	yes	
Wash dishes	yes-no	yes	yes	yes	yes	
Wash clothes	yes-no	yes	yes	yes	yes	
Personal higene	yes-no	yes	yes	yes	yes	
Clean house/kitchen	yes-no	yes	yes	yes	yes	
Water livestock	yes-no	no	no	no	no	
Water plants	yes-no	no	no	no	no	
Time of pathoscreen test		16:15	9:00 AM	10:30 AM	10:14 AM	
Time of pathoscreen test		16:50	12:00 PM	12:00 PM	10:35 AM	
Pathoscreen result		negative	negative	negative	positive	
Average SWL		**-18.4**	**-34.8**	**-6.0**	**0.0**	
Measurement of top of access pipe		25	30	10		
Measurement of stained tape mark		6.5	0	4		
SWL calculated by tech.		18.5	30	6		
SWL calculated by spreadsheet		-18.5	discard	-6	0	
Measurement of top of access pipe		20	40	8		
Measurement of stained tape mark		1.9	4	2		
SWL calculated by tech.		18.1	36	6		
SWL calculated by spreadsheet		-18.1	-36	-6	0	
Measurement of top of access pipe		19.50	36			
Measurement of stained tape mark		1	2.5			
SWL calculated by tech.		18.5	33.5			
SWL calculated by spreadsheet		-18.5	-33.5	discard	0	

Further advances of the network included a two-day workshop in September 2007 at Juigalpa's National Environmental Information System (SINIA) office to learn how to work with GPS and GIS. The members have also presented the network program to the Association of Municipalities of Chontales (ASOCHOM) in order to gain financial support from the mayors and formalize the organization to justify time spent working on achieving its objectives. A small budget was approved by ASOCHOM to support the group's activities. With the help of the SNV and varying levels of support by the municipality mayors, the network has since broadened its functions to include: assessing water and sanitation needs of communities, map construction, identifying well users' demands, reactivation of well committees, leading trainings in hygiene and sanitation for committees, and monitoring well water quality.

4.4 Challenges

Problems on various levels led to the network's low-productivity beginnings. These ranged from the more obvious problems of the UNOMs reluctance or inability to actually take static water level measurements, to larger scale problems with little or no follow through on the part of the town halls due to weak institutional goals. Challenges include:

- Finding correct type of well to be able to do measurements. Some older well designs have cement caps rather than PVC ones, making the installation of an access pipe impossible.
- Filling out paperwork (i.e., not noting times, too few measurements).
- Measuring with a resolution of feet, rather than inches.
- Technician pumping well just before taking measurements to see if water level could be estimated by popular farmers' method of counting number of wheel turns.
- Miscommunication about meeting times.

On a larger scale, some of the difficulties encountered in past attempts to start a monitoring program, and which may contribute to difficulties for this network, include:

- The many projects town halls undertake at one time makes follow-through with long-term plans difficult.
- Use of UNOMs for many different tasks, not just work with rural water projects. UNOMs are supported by a renewable two year contract from UNICEF, who also provides them with a motorcycle and some basic tools. As part of the agreement with UNICEF, the Town Hall provides the UNOM's salary. It appears to be the case that UNOMs have come to use technicians to support other areas of the government's responsibilities.
- No UNICEF evaluation of UNOMs work.
- Regulation by ENACAL of rural water projects difficult because many groups do their own projects without notifying ENACAL.

- ENACAL’s inventory database of all wells in holding pattern for at least two years.

5 FUTURE WORK

Future work in improving the methodology of the manual pumping test is necessary to further identify the potential and limitations the manual pumping test has over other more conventional ways of determining well productivity. Possibilities include:

1. More pumping tests to better determine range of applicability of this test:
   a. In similarly configured wells but varying hydrogeologic environments.
   b. Wells of varying configurations including hand-dug, wells of varying depths, and variations on the rope-pump mechanism (i.e.: windmill, bicycle-pump, animal powered).
   c. Wells with higher usages (i.e.: field irrigation or livestock watering). Wells in this study were for home water supply and watering of small gardens only.
   d. Wells in areas that experience different seasonal settings. This part of Nicaragua experiences stark contrasts in wet and dry seasons.

2. Geophysical/geological investigations to identify why varying responses of well productivity with seasonal water fluctuations are observed.
3. Further testing of analyses methods using analytical solutions and numerical models. This would be particularly interesting in determining the rigidness the rule of thumb that Myre (2008) has established for identifying critical time in recovery curves.

6 CONCLUSIONS

Determining the productivity of wells in a determined region is necessary to complete a comprehensive regional water resource management program. However, municipalities in the developing world often times cannot afford conventional pumping tests to attain productivity measurements on a wide geographic scale. Therefore, this manual pumping test method was developed based on the need to determine well productivity in drilled wells equipped with rope pumps in a simple, economical and relatively quick manner. Approximately 100 manual pump tests were performed over an eight month period (beginning in the dry season and extending three months into the rainy season) to rigorously test the procedure. Manual pumping tests using the pumps' existing infrastructure can be performed in a half day and in a cost effective manner.

Tests were performed in triplicate once a month in three wells in a small rural community in Chontales, Nicaragua, and from these data, two objectives were addressed: 1) Develop and test manual pumping test, and 2) Test empirical long-term pumping test in rope pump wells.

Data collected from the tests were analyzed using four methods (equilibrium approximation, time-drawdown during pumping, time-drawdown during recovery, and time-drawdown during late-time recovery) to determine the best data-analyzing method. The ability to apply the equilibrim approximation analysis while in the field with only a calculator makes it the preferred method to estimate well productivity. Results from this method agree to within 41% of results from a conventional pumping test in one of the wells. The other analyes methods, requiring more sophisticated tools and higher-level interpretation skills, yielded results that agree to within 14% (pumping phase), 33% (recovery phase) and 133% (late-time recovery) of the conventional test productivity value. The wide variability in accuracy results principally difficulties in reaching an equilibrated pumping level during the pumping test and from casing storage effects in the pumping/recovery data. Furthermore, the pumping curve analysis method is subject to more variability due to difficuties maintaining constant pump rates. While the manual pumping tests can determine if wells can support higher capacity pumps, a comprehensive aquifer study would need to be undertaken to ensure sustainability of the increased abstraction.

The results indicate that the empirical long-term pumping test for rope pump wells in the study area is not applicable. This is probably due to a markedly distinct hydrogeological environment that that where the study was initially undertaken by Herbert et al. (1992) and that the low-flow manual pumps did not sufficiently stress the wells.

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APPENDICIES

Appendix A: Watershed characteristics

Soils

The soils in Santa Rita are composted of clays including inceptisols, molisols, and vertisols (Figure A.1).

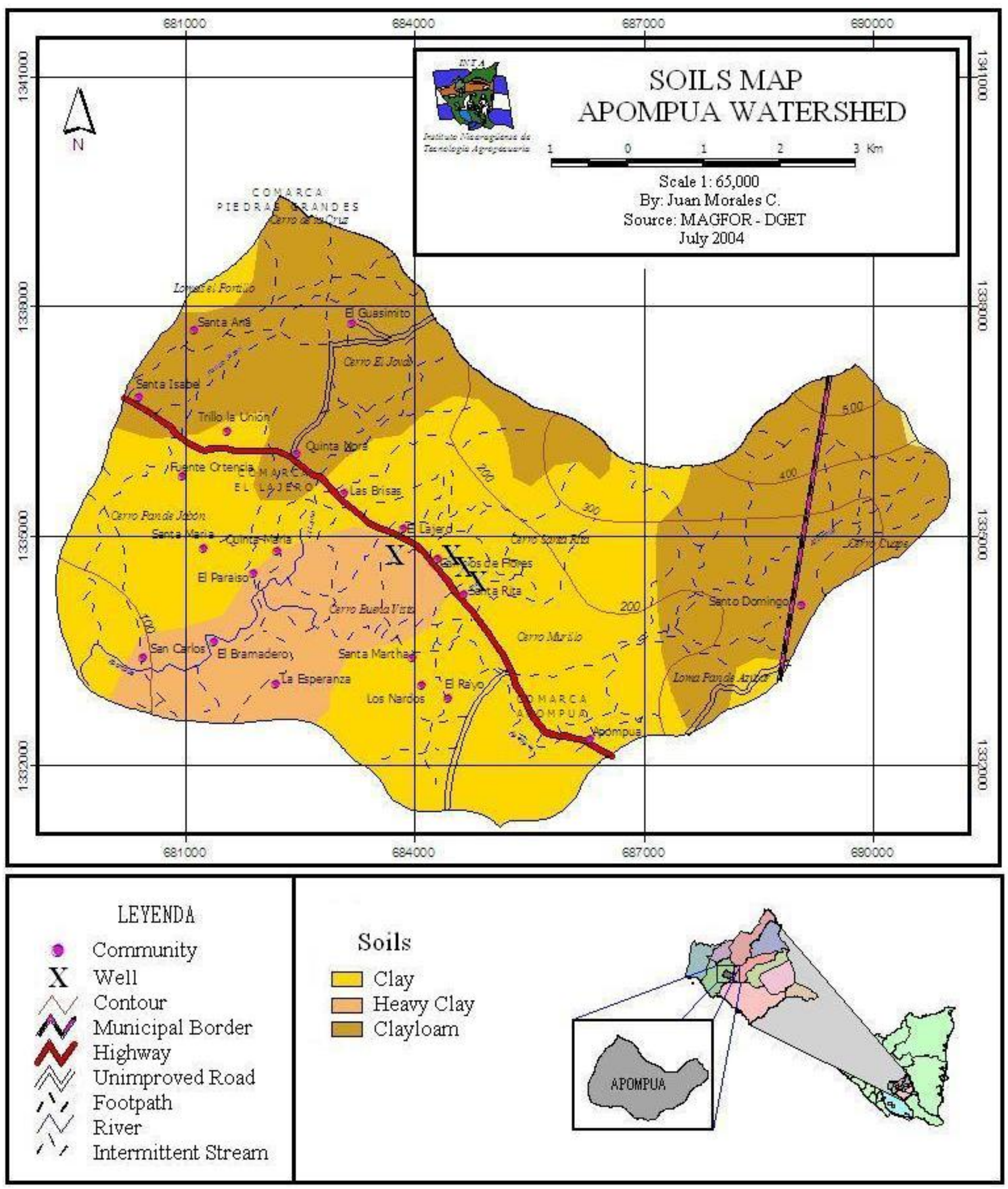

Figure A.1 Soils of the Apompuá watershed. Adapted from INTA 2004.

Vegetation

According to Holdridge, vegetation of the Apompuá watershed is Dry Tropical Forest. Figure A.2 shows forest coverage and indicates that few forested areas remain as much land has been cleared for agricultural activity.

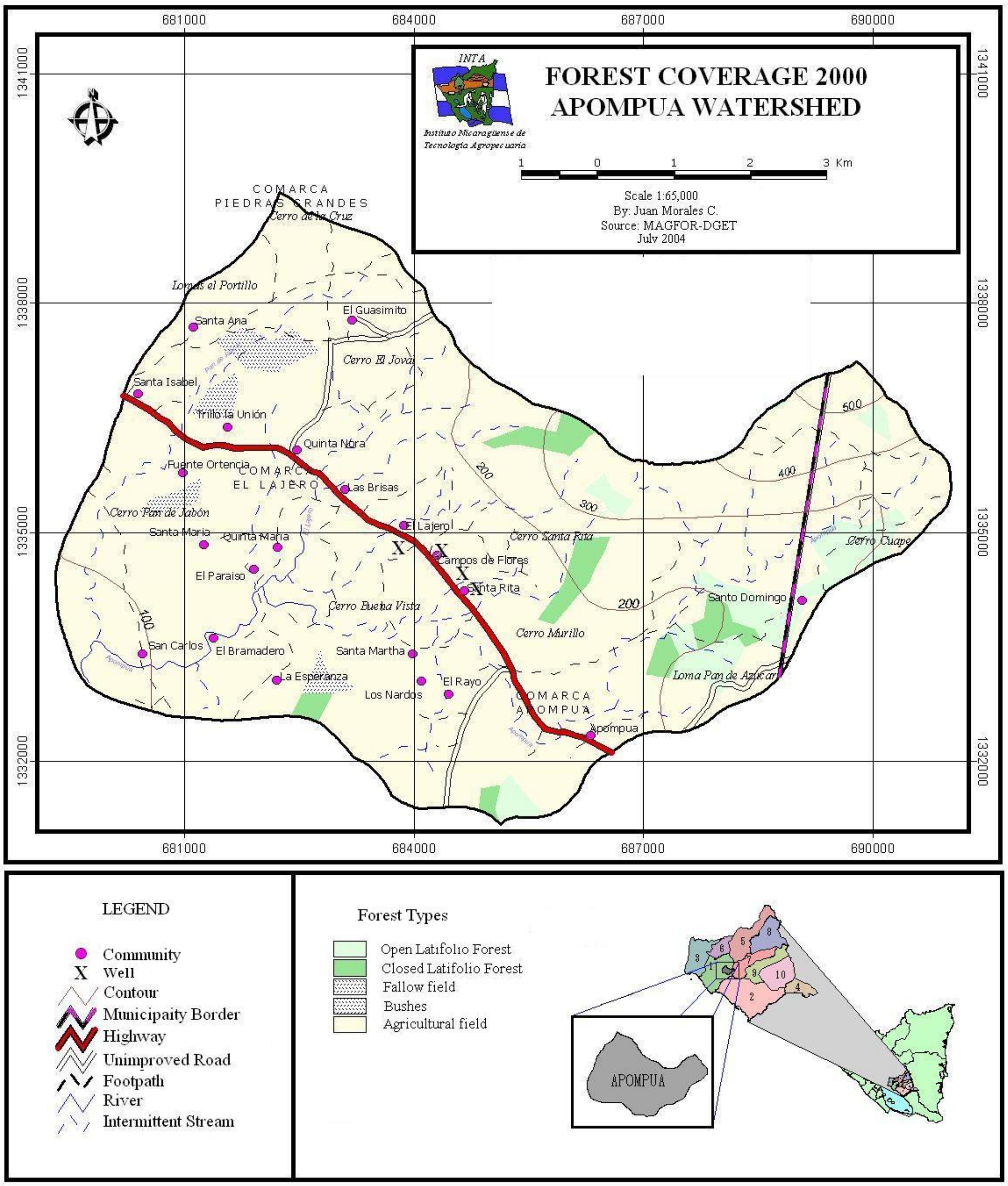

Figure A.2 Vegetation of Apompuá watershed. Adapted from INTA 2004.

There is growing concern over Nicaragua's rapid deforestation trend and it's affect on climate, water resources, and ecosystems. Many Nicaraguans claim that temperatures in the past decade are higher than temperatures in the past and attribute the change to deforestation. Trees play in integral part in the water cycle, as they draw water from the ground, and through transpiration, release water molecules that eventually combine and form rain-producing clouds. Without trees to shade and protect surface water from evaporation, rivers and streams dry up. Furthermore, trees retain water in their leaves, trunk, and roots, slowing the movement of water through the watershed. The slower movement of water allows for more infiltration into the soil, eventually recharging aquifers. Without the trees, precipitation leaves the watershed rapidly through surface channels, and less recharge is achieved.

Climate

The average annual temperature is 80°F (26°C) with highest temperatures coinciding with the dry season between November and April (Figure A.3). The average annual precipitation is 49 inches (1250 mm) with an average annual humidity of 78% (INTA 2004).

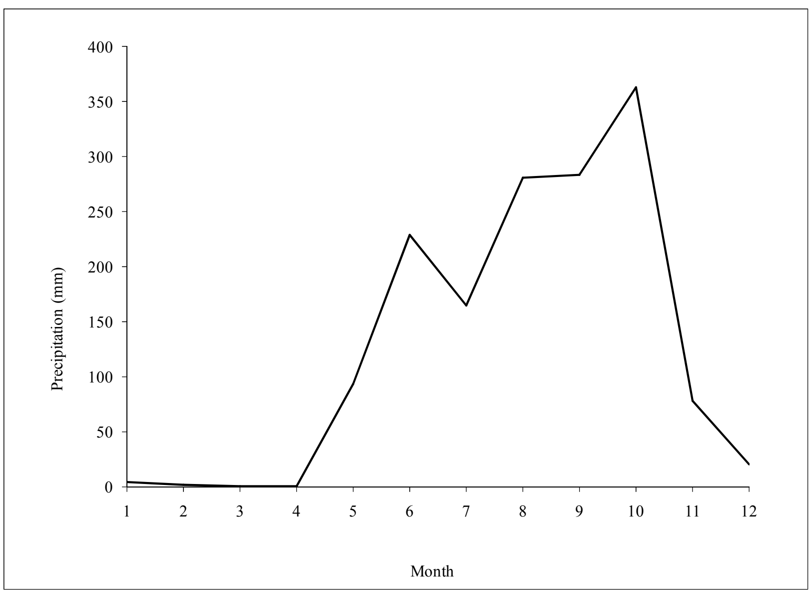

Figure A.3 Average precipitation per month taken at the Juigalpa Meteorological station; 1960-2005 (INETER 2007).

Surface water

The main river in the watershed, fed by El Lajero river, Pan de Jabon river, and many unnamed intermittent tributaries, is the Apompua. This river feeds the Mayales river which then drains into Lake Nicaragua.

According to the IPRH done in April 2006, long stretches of the rivers and streams were dry with the points shown in Figure A.4 having sufficient flow to measure.

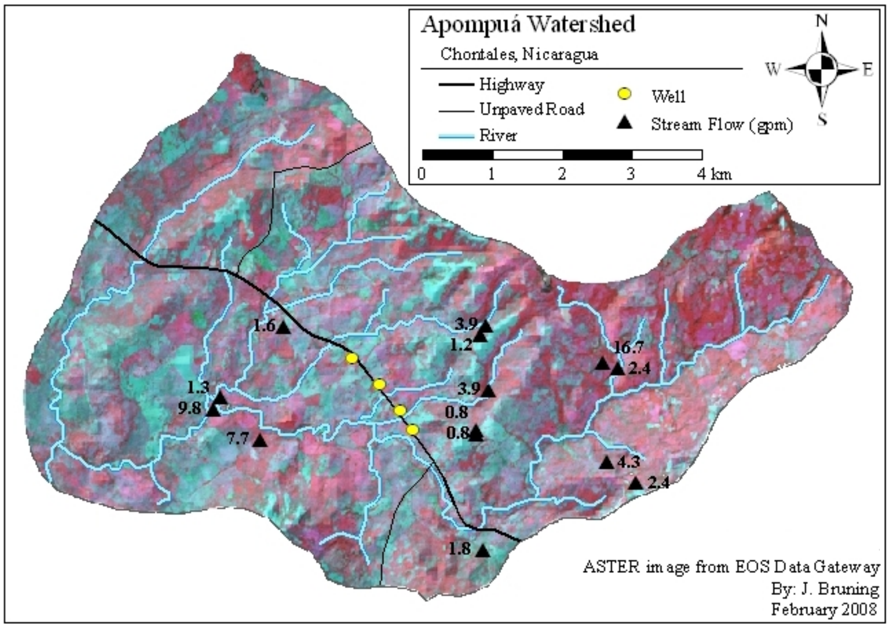

Figure A.4 Streamflow measurements from IPRH study completed in April 2006.

Appendix B: Well user survey results

To ensure pumping test accuracy, it was necessary that there be no pumping of the well except for during the pumping tests, therefore the amount of water that would be pumped for the test was determined on how much water the users needed on a daily basis.

Table B.1 shows the results of the surveys given to the well's selected.

Table B.1 Estimated values of well users' consumption

House	Number of people	Activity	Gallons used	No times activity done per week	Gallons/week
1	7	Laundry	55	7	385
		Drinking/cooking	25	7	175
		Bathing	35	7	245
		Cleaning	25	7	175
					Total 980
2	3	Laundry	55	2	110
		Drinking/cooking	25	7	175
		Bathing	15	7	105
		Cleaning	40	7	280
		Garden	40	2	80
		Cleaning animal pens	40	7	280
					Total 1030
3	3	Laundry	165	1	165
		Drinking/cooking	15	7	105
		Bathing	20	7	140
					Total 410
					Total all houses 2420 gallons

One well was constantly watched for two days to validate the well users' estimates, and estimated versus observed water use differed markedly (Table B.2).

Table B.2 Observed well users' consumption

House	Day 1 (wash day for 1 and 2) (gallons)	Day 2 (gallons)
1	155	35
2	140	65
3	65	10

Extrapolating the observed volumes of water extracted to estimate weekly extraction values, House 1 would consume 400 gallons; House 2, 595 gallons; and House 3, 525 gallons. Table B.3 compares weekly estimated and observed values. Houses 1 and 2 overestimated their water use by 41% and 58% respectively, while house 3 underestimated by 22%.

Table B.3 Estimated weekly water consumption based on surveys and observed values.

House	Estimated (gallons/week)	Observed (gallons/week)
1	980	400
2	1030	595
3	410	525

Difficulties in the survey include:

- Identifying number of family members served: Defining the number of members in a household is very difficult with members leaving home for weeks at a time for either studying or working, some returning on weekends or for extended visits. In some cases, it appeared that the interviewee would have difficulty determining family size at first, subsequently they would forget, recalculate, and provide a different number.
- Estimating water use: Especially difficult where use changes with seasons. For example, extended family members (not living in the home) would come wash their clothes in the summertime at the wells because of water scarcity in city. Also, in the summertime, strangers would arrive from the city to fill barrels of water in the middle of the night.
- Validity of responses: It seemed that in some instances interviewees simply offered a number for the sake of answering without really making an educated guess. Similarly, on occasions a neighbor would lead participant to say a certain value.

Appendix C: Water chemistry results

Table C.1 Water quality results for well water tested 1/17/07 at the Michigan Department of Community Health Upper Peninsula Laboratory.

Constituent	**Well 1**	**Well 2**	**Well 3**	**Well 4**	**W.H.O drinking water guideline** (WHO 2006)
Coliform organisms (per 100 mL)†	positive	positive	positive	positive	No presence of E. Coli or thermotolerant coliform bacteria
Chloride (mg/L)	8	16	11	7	n.a.
Fluoride (mg/L)	0.2	n.d.	0.1	0.2	1.5
Hardness as CaCO3 (mg/L)	1035*	272	219	208	n.a.
Iron (mg/L)	n.d.	n.d.	0.1	n.d.	n.a.
Nitrate (mg/L)	n.d.	n.d.	n.d.	n.d.	50
Sodium (mg/L)	139	18	22	19	n.a.
Sulfate (mg/L)	1133*	n.d.	n.d.	n.d.	n.a.

†Samples were taken 1/11/07. The lab requires the sample be taken within 48 hours of testing for coliform testing. Obviously this limit was exceeded. However, the fact that the coliform tested positive despite the 6-day lapse between sampling and testing indicates that coliform organisms are present in the well.
*Hardness and sulfate quality control results were outside allowed limits due to matrix interferences.
n.d. = not detected; n.a. = no guideline available