QUANTIFYING AVAILABLE WATER AT THE VILLAGE LEVEL: A CASE STUDY OF HORONGO, MALI, WEST AFRICA

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A REPORT

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This report, "Quantifying Available Water at the Village Level: A Case Study Horongo, Mali, West Africa," is hereby approved in partial fulfillment of the requirements for the degree of Masters of Science in the field of Civil Engineering.

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Data Sources

Source	Data
– Kita Meteorologist, Mamadou Keita	Average monthly precipitation and temperature for Kita, 2000-2007
– Kita, Department of Hydraulic Infrastructure (DNH)	Bore logs for the surrounding villages of, Kofeba Mansala, Kore, Banfarala, Kala and Douri
– Republique de Mali Ministre du Development Industriel Direction Nationale de la Geologie et des Mines (DIDNGM)	Geologic map

1 EXECUTIVE SUMMARY

Despite on-going efforts to develop adequate water supplies, only one in every five residents of the developing world currently has access to clean water (UNDP 2006). This means that 1.1 billion people have to travel more than 1 km from their home to access clean water and collect water from sources that may even contain pathogens and bacteria on a regular basis (UNDP 2006). Nevertheless, the statistics reflecting global water access are projected to become worse in the near future. Large areas of South America, Asia and Africa are threatened by increased temperatures and populations and decreased precipitation (Alcamo et. al 2000). In response to the potential negative effects from water scarcity, baseline hydrologic characterization of watersheds should be implemented as much as practical. Characterization of the hydrologic conditions of watersheds can help improve the effectiveness of water access projects, and anticipate risk of insufficient water supply in specific regions. To improve the accuracy of estimated hydrologic conditions, local climate data should be used as much as practical.

Horongo, a small rural village in the Kayes region of Mali, has experienced inadequate water supply at the end of the dry seasons for at least the past 2 generations (Traore 2006). Money-generating activities that occur during the rainy part of the year typically have to be suspended and women must spend exhausting hours of their day and night during the dry season to obtain enough water for their families. Current village activities that require water included domestic tasks, gardening, and drinking water for livestock. According to water use interviews conducted in 2008, village water use varied throughout three main seasons from approximately 10-40 Lpcd. The village water sources included 64 hand-dug wells and an ephemeral wetland/stream.

A simple watershed-scale water balance was used to estimate the amount of groundwater and surface water that was contributed by the up-slope watershed and eventually passes through the near-surface aquifer beneath the village. This water balance is a variation of the common Thornthwaite method and can easily be calculated using basic spreadsheet software. Collectively, groundwater and surface water supplies were estimated at 75 mm/year across the contributing basin (10 km^2), which translates to approximately 800,000 m^3/year or approximately 10% of average annual precipitation. All precipitation and temperature data used for the water balance evaluations were acquired from local records for the years 2000-2007.

The aquifer hydraulic conductivity was also determined from ten manual pumping tests performed in four hand-dug wells. The recovery curves of the tests were fit with the Papadopoulos-Cooper solution using the program AQTESOLVE. Hydraulic conductivity was estimated at 1 m/day and assumed consistent for the entire watershed.

To evaluate whether the estimates from the water balance and manual pumping tests were appropriate and to further explore water development, a watershed-scale groundwater model was created to simulate seasonal changes in the subsurface hydrology. The accuracy of the estimated hydrologic parameters was determined by comparing the simulated seasonal hydrology to observed groundwater levels in six wells. The results agreed to within an average of 1 m of the observed levels; therefore the estimated groundwater and surface flows and hydraulic conductivity were reasonable.

The model was used to explore groundwater development by drilled wells equipped with motorized pumps. The model suggests that if pumps extracted water throughout the village (0.38 km^2) approximately 420 m^3 of water could be accessed safely each day during the dry seasons. Realistically, for every well, up to a total of four, the village could access 80-100 m^3 of water daily. Water needs of the village as of 2008 could be safely produced by the installation of two wells.

2 INTRODUCTION

To sustain and improve water access for the world's population, it is necessary to characterize water resources (WWAP 2003). In 1995, 25% of the earth's land surface (excluding Antarctica and Greenland) was already experiencing severe water stress (more than 40% of available water is being withdrawn) due to climate change and increased demand by industry, municipalities and agriculture (Alcamo et. al 2000). The symptoms of water stress include: decreasing groundwater levels, desiccation of rivers and the drying of lakes and inland water bodies (UNDP 2006). The areas affected include large parts of Asia, Europe, Central North America and Northern Africa (Figure 2.1).

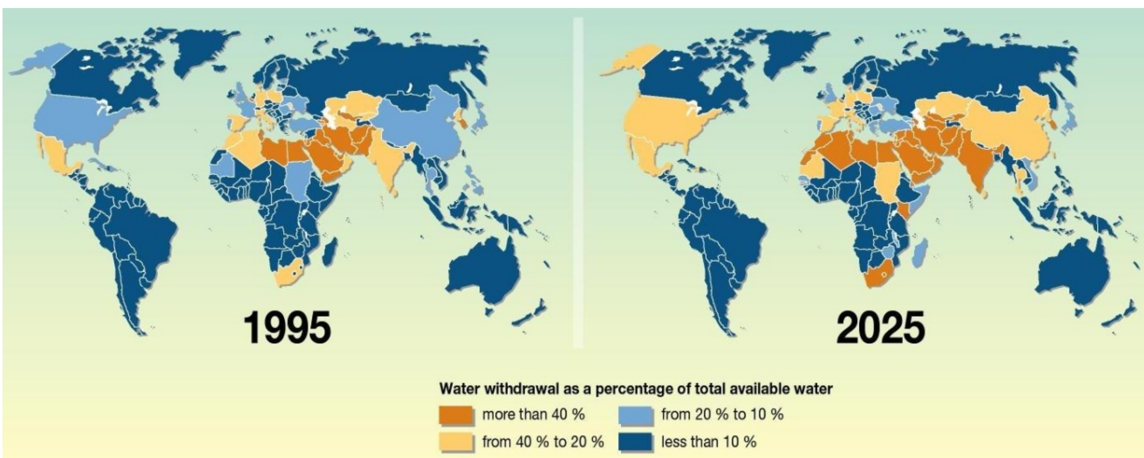

Figure 2.1, Increased global water stress (UNEP/GRID-Arendal 2009)

The world's population, already at 6 billion people in 1995, is projected to increase to 8 billion by the year 2025, creating pressure from inadequate water supplies for 60% of the worlds land surface (Alcamo et. al 2000). However, some developing countries, such as areas of Latin America and Sub-Saharan Africa will feel more of this pressure from lack of infrastructure than lack of availability. Even now, one out of every five people in these areas does not have adequate access to clean water (UNDP 2006).

In the last two decades, a large commitment has been made on the African continent to the development of water access, but monitoring and planning of water resources have not received commensurate attention to sustain and improve these investments. The Sub-Saharan region of Africa alone is projected to increase in temperature by 0.2-0.5 ^{o}C, and experience a 10% decrease in precipitation by 2025; exacerbating already variable conditions. The current problems in these areas could potentially become emergencies in the near future due to the large percent of the population that is dependent on rain-fed agriculture (UNDP 2006).

In response to a need for improved planning and monitoring for the continent of Africa, climate scientists, water managers and policy makers from 23 African countries and 14 other countries came together for the 2008 Kampala Conference in Uganda. A variety of speakers presented their current strategies for water resource monitoring and focused their content on the main conference theme; climate variability and its effect on groundwater. Groundwater currently supports 75% of Africa's population and will be more resilient to change than surface water flows within a changing climate (UNESCO 2008).

Many of the methods presented in the conference for characterizing and predicting the behavior of water resources are consistent with what is used in the developed world, but Sullivan et al (2003) point out that most of these strategies use aggregated data from nationwide statistics. Aggregated data is used to characterize water resources because adequate funding and qualified staff are unavailable to support data collection at a local level. Analysis of water resources using aggregated data is better than no analysis, but it ignores the spatial variability of groundwater resources and exploitation. To accurately characterize groundwater resources, local data must be collected (Sullivan et al 2003).

This report explains a method to characterize available water resources in a developing community setting. Similar considerations could be incorporated by the existing governmental and non-governmental organizations (NGO) that work with the development of water supplies in countries around the world. If these organizations used such a method they could not only improve their immediate project results, but also better understand the nature of their current water shortages and identify areas at risk. Efficient identification of at-risk areas could result in the implementation of water access and conservation programs to sustain and improve the quality of life.

2.1 PROJECT MOTIVATION

The initial motivation to develop an appropriate method for water supply characterization in a developing country setting came from my service as a Peace Corps water and sanitation volunteer in the village of Horongo, Mali. I was asked to live and work with the village of Horongo because of their need for increased water access. Although I was told that the community had a "need" for water, I was not informed of specific "needs," and there were no data upon which to inventory the current water supply conditions.

Initial, informal interviews determined that the villagers of Horongo experience insufficient water levels in their hand dug wells during the latter part of the hot dry season. Water collection becomes stressful for the women because they must rise 3 or 4 times at night to take advantage of the freshly recharged wells next to their house and/or must walk longer distances past the perimeter of the village to supplement their need from garden wells. Water can still be found for most domestic and agricultural needs, but when water cannot be supplemented from other sources, personal gardens get smaller and laundry is washed less often, reducing the overall nutrition and hygiene in the village.

Examples of water access projects in the area included: the enlargement/extension of existing wells, digging new wells, installing hand pumps, and damming of ephemeral streams. However, many of these projects were non-functional or provided less water than was intended at the time of observation. Factors that could have contributed to the early failure or less than desired production of water include the exclusion of village water needs and proper estimation of hydrologic parameters for the communities' contributing watersheds. Before I could ethically ask the village of Horongo to contribute to the construction of a water access system, I felt compelled to quantitatively evaluate the water resource conditions.

2.2 OBJECTIVES

Objective 1: Quantitatively determine the hydrologic conditions of the Horongo watershed to analyze water development and management options that will increase or sustain water supplies.

Characterizing hydrologic conditions of watersheds is increasingly important to provide sustainable water supply for all communities, especially those in the developing world. Many countries are struggling to provide adequate water supply to their current population and climate change threatens existing water supply investments. Characterization of the hydrologic conditions of watersheds can help improve the effectiveness of water access projects, and anticipate risk of insufficient water supply in specific regions.

Objective 2: Demonstrate the applicability of various data-gathering and quantitative approaches to estimate hydrological parameters and watershed-scale, seasonally variable components of the water cycle.

To accurately characterize watershed hydrology, data should be acquired from local organizations or measured locally by methods that incorporate readily available resources. All data gathered for this study and estimations of watershed hydrologic parameters were done so using resources that could be easily accessed by a local water development NGO. The appropriateness of the data and estimation methods must be determined to validate the claims of hydrologic conditions made by the study.

3 PROJECT SITE: HORONGO, MALI (N 13^{O}02', W 9^{O}36')

Horongo is located in the Kayes region of Mali on the Manatali Road, 14-km west of the cercle[1] capital of Kita. Kayes is the western-most region in the country and third largest after the Tombouctou and Gao regions that stretch up into the Sahara Desert. Horongo's commune[2] is defined as Kita West, and the commune seat is located in the village of Kofe Ba, 3-km east of Horongo.

Figure 3.1 Map of Mali, West Africa (adapted from Map Library 2009)

Horongo is considered a mid-size village in the Kayes region and has an estimated population of about 1200 people. This population estimate was obtained from informal interviews conducted for this research in 2008. Plan International [3] also reported a population of 1105 in 2005 (46% adult and 47% female) in their document "Plan de Development du Village de Horongo." On the basis of the two latest population estimates in 2005 and 2008, the population seems to be growing 3% annually. For a more detailed cultural description of the project site please refer to Appendix A.

[1] Political division of Mali's eight regions, administered by a prefet or commandant (USDS 2009).

[2] Political division of Mali's cercle, the commune is further divided into villages or quarters (USDS 2009).

[3] Plan International works in 49 developing countries with children, their families, communities, organizations, and local government to implement programs at grassroots level in health, education, water and sanitation, income generation and cross cultural communication (Plan Int. 2009).

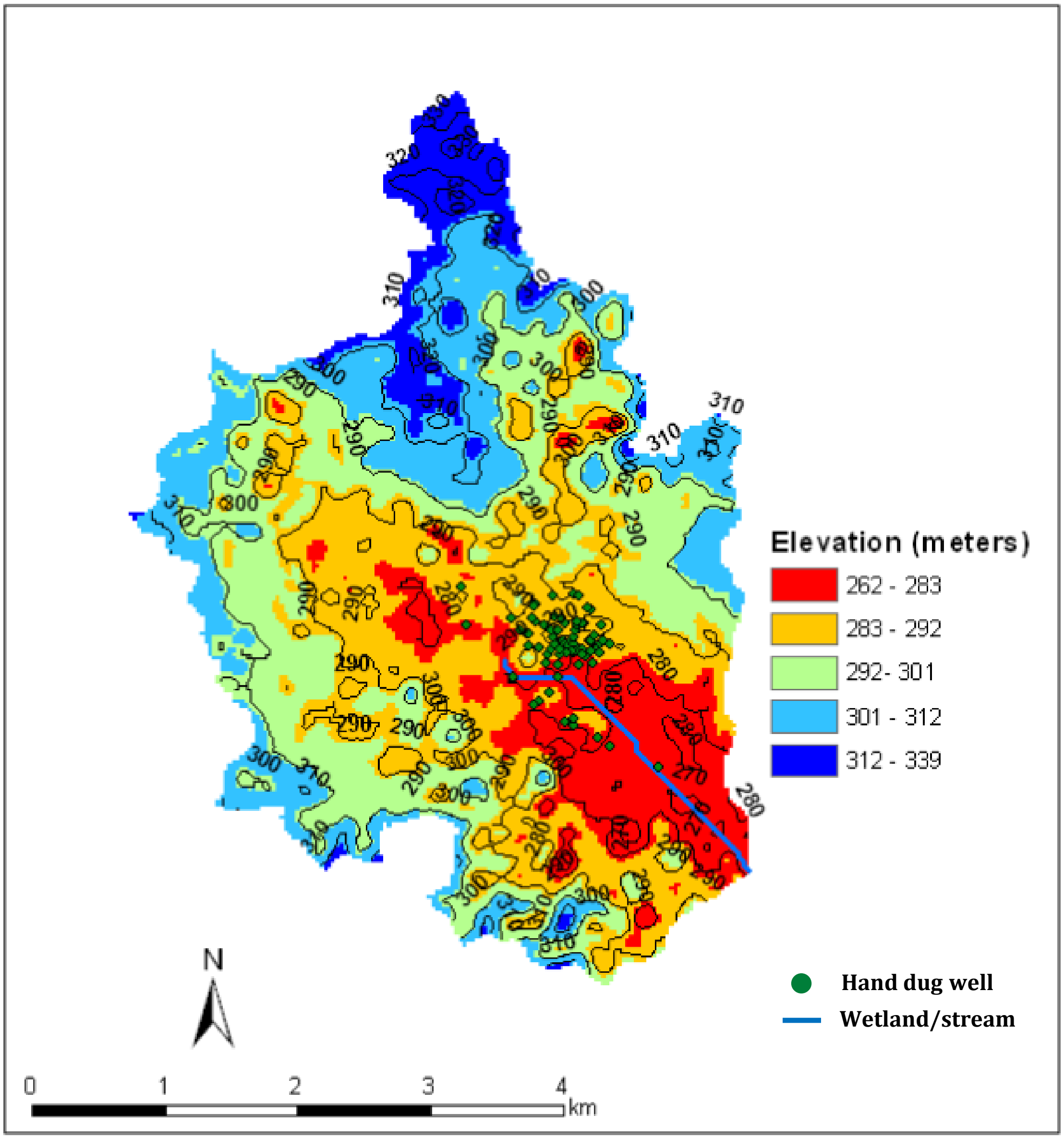

Figure 3.2 The Horongo watershed (ASTER DEM image. Source LPDAAC 2008)

Figures 3.2 is a 30-m resolution, advanced spaceborne thermal emission and reflection radiometer (ASTER), Level-1A images, generated using bands 3N (nadir-viewing) and 3B (backward-viewing) that has been imported into a geographic information system (GIS) program. The images have been clipped and all background area that contains "no data" has been removed from the original ASTER DEM file using ArcMap. The watershed boundary and ephemeral wetland/stream was delineated by applying ARC Hydro 1.2, display package for ArcGIS 9.2. The images were taken Dec. 10, 2004 and contain no cloud cover. The entire watershed area is estimated at 17.6 km^2, and the contributing watershed for Horongo is approximately 10.8 km^2. The wells of Horongo in Figure 3.2 were imported as scatter points using global positioning system (GPS) coordinates.

Watershed Surface

The climate in this area of Mali is classified as tropical savanna [4] by Peel et al. (2007). The year is divided into three main seasons that are referred to locally as rainy, hot dry and cold dry. The rainy season spans from approximately July through October, during which an average of 800 mm of rain is accumulated and temperatures range from 20-30^{o}C. The cold dry season follows from November through February, with little or no precipitation and a temperature range of 15-35 ^{o}C. The rest of the year (March-June) is the hot dry season, with little or no precipitation and temperatures range from 20-40 ^{o}C. These temperatures and precipitation amounts are a summary of the average monthly temperature and cumulative monthly precipitation data acquired from a meteorologist in Kita, Mamadou Keita, for the years 2000-2007. The data was acquired in May 2008 by copying the handwritten records provided by Mr. Keita.

The natural terrain is rolling grassland, dotted with trees, on a slope no more than 10 m/km (Figure 3.2). Tree types that were observed in the village of Horongo include nere, karate, cailcedra, kapioka, and baobab, which is consistent with the vegetation description provided by Cleavland (2007) for a tropical, savanna. Beneath the trees are hyparrheni "elephant" grass that reaches 2 to 3 meters tall, shrubs and herbaceous plants.

Watershed Subsurface

A map acquired from the DIDNGM (1982)classifies the underlying bedrock in the watershed as hematite, ferruginous siltstone and heterogranular sandstone. Sandstone and siltstone are types of sedimentary formations and therefore have a high potential for groundwater development, but can be non-renewable in arid regions (MacDonald and Davies 2000). Borehole logs, acquired from the DNH in Kita, estimate that the top of the underlying bedrock layer is approximately 5-30 m below the ground surface for areas surrounding the Horongo watershed. The same range of depth has been applied to the watershed for this research.

[4] Precipitation of the driest month < (100mm - the mean annual precipitation); temperature of the coldest month $\geq$ 18^{o}C (Peel et al. 2007)

The top 15 m of soil above the bedrock was identified as sandy silt loam or loamy sand when a hand dug well was excavated in April 2008 by a village resident (Appendix B). The excavated material was classified using the "Guide to Soil Identification" in Davis and Lambert (2002). Hydraulic conductivities for these soils are approximately 1.56 m/day for loam sand and 0.007 m/day for silt loam (Dingman 2002).

To confirm the soil classifications made in the field, the Global Soils 3.6 map from the Food and Agriculture Organization of the United Nations (FAO) was referenced (Map Journey 2008). However, this map classifies the area as a Regasol soil, which does not help further estimate the properties of the soil. Regosol are all soils that could not be placed in any other soils group. They are mineral soils that are very weakly developed in unconsolidated materials and do not contain much gravel, sand or fluvic material. They are very similar to what the United States classification of an Entisol, which are commonly found in arid, semi-arid and mountainous areas that are prone to erosion (FAO 2006).

3.2 WATER ACCESS OUTSIDE THE HORONGO WATERSHED

The Kayes region of Mali reported potable water access for 64% of the population as of 1995 (N'Djim and Doumbia 1998). From observations made while living and traveling in the area, specific examples of general water access projects include:

- **Well improvement** – An upgrade from the basic well-head reinforcement material of logs can be the addition of one or a combination of: well-head concrete reinforcement; covers; pulleys; interior, concrete sealant; and width and depth expansion. Some of these additions are specifically constructed to improve water quality, but most of the village populations do not effectively take advantage of these improvements. Examples of misuse include: leaving well covers off after use, water bags are left on the ground and then placed into the well, and pulleys are disregarded shortly after installation.

- **Small concrete dams** –Ephemeral streams have been dammed to extend higher groundwater levels further into the dry season and increase surface water access for irrigation. Many of the dams, however, fail soon after completion because of poor design. Undercutting, scouring and overtopping of the dam are common failures due to the lack of knowledge in hydrogeology and geology. Dam gates also have a tendency to break due to the poor quality of metal used during fabrication.

- **India-Mali hand pumps** – The India-Mali hand pump was widely used in water access projects throughout Kayes because it was the only pump manufactured in Mali (Parker 1997). Placement of a pump is accompanied by the construction of a drilled bore hole, a concrete pad and concrete walls to protect the above surface well head. The majority of the villages that surround Horongo have at least one India-Mali pump. Most of the pumps are still working at the time of this writing, but some are locked from use because of political turmoil or are broken. Most current pump installation opportunities require a community contribution of around $1000 USD. The full cost of drilling a bore hole, placing pipe, setting the pump head and constructing a concrete pad and barrier around the pump can be as much as $14,000 USD (Coulibaly 2008). A series of programs starting in 1974 has made the installation of this technology possible:

I. With the help of the Franc Communaute Financiere Africaine (FCFA), the Malian government placed pumps in 1974 to help relieve drought conditions. During placement local populations were not taught how to manage the pumps, no sanitation animations were performed, no village contribution was requested, no water committees were formed, no mechanics were trained, the state could not efficiently fix the pumps themselves, and no spare part shops were supported. Many of the pumps are not working today (WorldAid 1995).

II. From 1983 to 1992 the World Bank contributed funds for the placement of pumps in 215 villages around Kita and 15 villages around Bafoulabe and Kenieba. Village water committee formation and committee contribution was required. The DNHE trained 300 villagers on purchasing of quality parts and 50 artisans in pump repair. The DNHE also bought a large stock of parts and employed two hand pump specialists. Villagers were responsible for the maintenance and upkeep. As of 1996, 90% of the pumps were still operating (Parker 1997).

III. Franc Communaute Financiere Africaine (FCFA) again provided funding in 2005-2006 to improve the original pumps placed in the 1970's.

3.3 WATER ACCESS IN THE HORONGO WATERSHED

The village of Horongo was the only community accessing water within the watershed. Access was provided by two types of sources: hand-dug wells and a wetland area that was available during the rainy and cold dry season. The water from these sources was used for the support of domestic and basic agricultural activities (livestock and garden watering). It was very turbid at most times of the year, suggesting the presence of disease causing organisms such as viruses, parasites and bacteria (USEPA 2009). Locations of the wetland and wells are shown in both Figure 3.2 and Figure 3.3.

Horongo had an opportunity to install a pump during the World Bank project in the early 1990's, but did not take advantage of the funding and pump placement offered by the project because the village chief at the time advised against it. At the time they were not experiencing water shortages as they are now, so he thought they should not waste their money by fixing a problem that had not occurred yet (Traore 2006). The village has since understood their monumental mistake, but again has not taken advantage of supplementary offers made by other organizations because village funds as of 2004 have been funneled into the construction of a new school with Plan International. By the middle of the rainy season in 2008, pumps were still absent from Horongo's water sources.

Wells

There were approximately 64 hand dug wells located in or around the living compounds[5] and gardens. Gardens were not more than a five minute walk from the compounds; therefore all 64 wells were relatively close to the main living areas. The wells located in the interior of the village mainly provided water for domestic use, while the out-lying wells were used for garden irrigation. As the hot season progressed the women accessed more of their water from the out-lying wells because demand was too large for the interior wells' abilities to recharge during the lower water tables. At the wells, water was pulled by hand using a rubber bladder and a rope. It was then transported to home, carried on a person's head, in 15-20 L buckets or 40-50 L basins made of plastic or steel.

At the time of original construction well diameters can range from 0.7-0.9 m, but erosion has increased some diameters to as large as 1.2 m. Most of the wells have a well-head reinforcement of logs, but a project in 2000 by Plan International improved 11 of the wells with covers and concrete well-head reinforcement. Since then, other families have mimicked the original Plan International well-improvement project and added tires or concrete. One other improved well exists as a gift from a family member that lives outside the village. This well has a headwall, three meters of inside concrete lining and a pulley. In total, 22 of the 64 wells have been improved from the basic addition of logs. The distribution of reinforcement type in the 64 wells is shown below in Figure 3.3. Pictures of the different types of reinforcement are also available in appendix C.

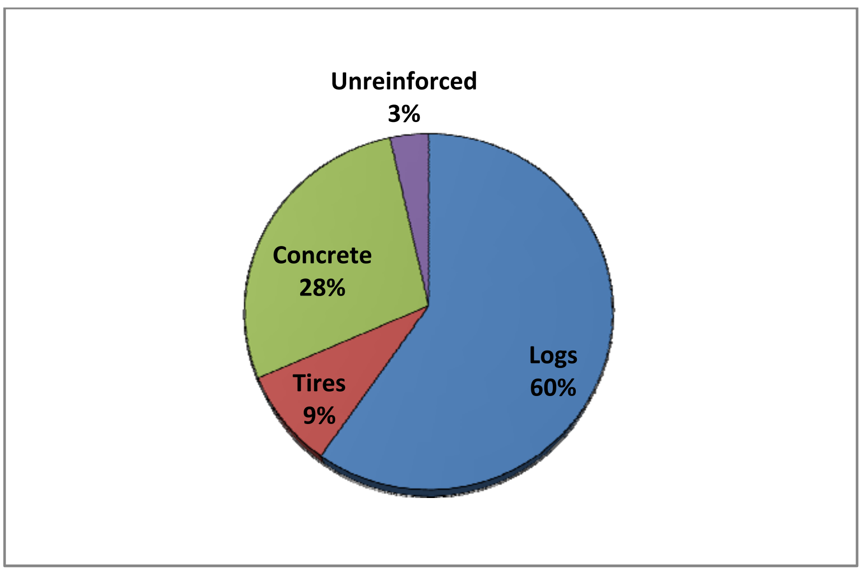

Figure 3.3 Distribution of well reinforcement in Horongo

[5] A compound is the collection of huts whose family members all have relation to the head male figure

Villagers take advantage of low water tables during the peak of the dry hot season to deepen existing wells or construct new ones. One man or a group of men participate in construction using basic tools, such as picks and shovels. Hand and foot holds are scraped into the side of the well during construction to provide an exit, but no shoring is used for protection from collapse. Concrete reinforcement and cutting rings are also not common practice, and therefore excavation is limited to 0.5-1 m below the lowest water table. As a result well depths then range from 4 – 12 m depending on their use and location. Obviously, the wells that are intended for use in the dry season must extend deeper than the lowest water table, but some wells, close to the wetland, are just used during the cold season to make bricks and water gardens.

Wetland

The wetland forms in low-lying areas along the western and southern boundaries of the village. It first appears in August at the peak of rainy season and remains until the end of February. Wetland levels are proportional to groundwater levels as determined from field measurements in three wells adjacent to the area. The same area where the wetlands appear is a pathway for surface runoff during heavy rain events. This runoff moves along the wetlands by overtopping their capacity and running into the next one slightly lower in elevation. Runoff is observed after almost all rain events starting in August.

The water in the wetland provides adequate drinking water for livestock, mud for brick making, occasional rice production, and serves as another water source for clothes and child washing. Women only wash their clothes and children in the stream when it is running after a rain event because the water is clearer. When washing occurs in the stream the women have collectively decided to spend time together away from the homes and provide supervision over small children who want to splash in the water.

4 METHODS

To estimate the amount of water that could be accessed from a drilled well(s) to supplement the village of Horongo during the dry seasons, the conditions of the subsurface hydrology in the watershed were simulated using a ground water flow model (Figure 4.1). The groundwater flow model was produced in the program GMS 6.5. GMS is an interface for triangulated irregular networks (TINs), solids (tools for modeling complex stratigraphy independent of a grid) , borehole data, 2D and 3D geostatistics, both finite element and finite difference models in 2D and 3D and models: MODFLOW-2000, MODPATH, MT3D, RT3D, FEMWATER, and SEEP2D (EMRL 2009). It was created by the Environmental Modeling Research Laboratory of Brigham Young University in partnership with the U.S. Army Engineer Waterways Experiment Station to perform groundwater simulations. The program is used by thousands of federal, state, private and international organizations as the most complete program available today to explore groundwater flow scenarios (EMS-I 2009).

Figure 4.1 Data input and expected outcomes for the groundwater flow model

To simulate subsurface water levels a conceptual model was first built using estimates of topography and aquifer thickness. The hydrologic parameters further used to characterize the modeled watershed were estimates of net precipitation (recharge to the aquifer) and hydraulic conductivity. The conceptual model was then placed in MODFLOW[6] 2000 to simulate subsurface water levels. The subsurface water levels where then compared to observed groundwater levels from the year 2008, calibrating the model for the further exploration of the impact of drilled wells on the subsurface hydrology. This method is very similar to a groundwater sustainability study performed by Lutz et al. (2008) along the Bani River in the region of Segou.

4.1 THE WATER BALANCE

A simple watershed-scale water balance adapted from Dingman (2002) was used to analyze the behavior of water in the up-slope watershed. The water balance equation, for a watershed, over a period of time is:

$$H_{in} + P + G_{in} - ET - RO - G_{out} - H_{out} = \Delta S \qquad \text{Eq. 4-1}$$

Where:

ET = Evapotranspiration (mm)

G_{in} = Groundwater Inflow (mm)

G_{out} = Groundwater Outflow (mm)

H_{in} = Human induced inputs from outside (mm)

H_{out} = Human induced withdrawals (not returned to the watershed) (mm)

P = Precipitation (mm)

RO = Recharge+Overland Flow Out (mm)

ΔS = Change in storage (mm)

[6] MODFLOW-2000 is a 3D, cell centered, finite difference, saturated flow model developed by the United States Geological Survey (McDonald and Harbaugh, 1998). It includes a wide assortment of boundary conditions and import options and can perform transient and steady state simulations. The version of MODFLOW-2000 in GMS 6.5 is very similar to the original version created by the USGS except it now facilitates multiple types of equations (Harbaugh et. al 2000).

Water moving into and out of the watershed as accounted for in Eq. 4-1 is the result of the hydrologic cycle depicted in Figure 4.2. Precipitation that falls on the watershed will flow overland, infiltrate and recharge groundwater and evapotranspire back to the atmosphere. However, humans now have the ability to move large quantities of water great distances. If human activiites move a significant amount of water in or out of the watershed, it also must be added or subtracted from the natural balance.

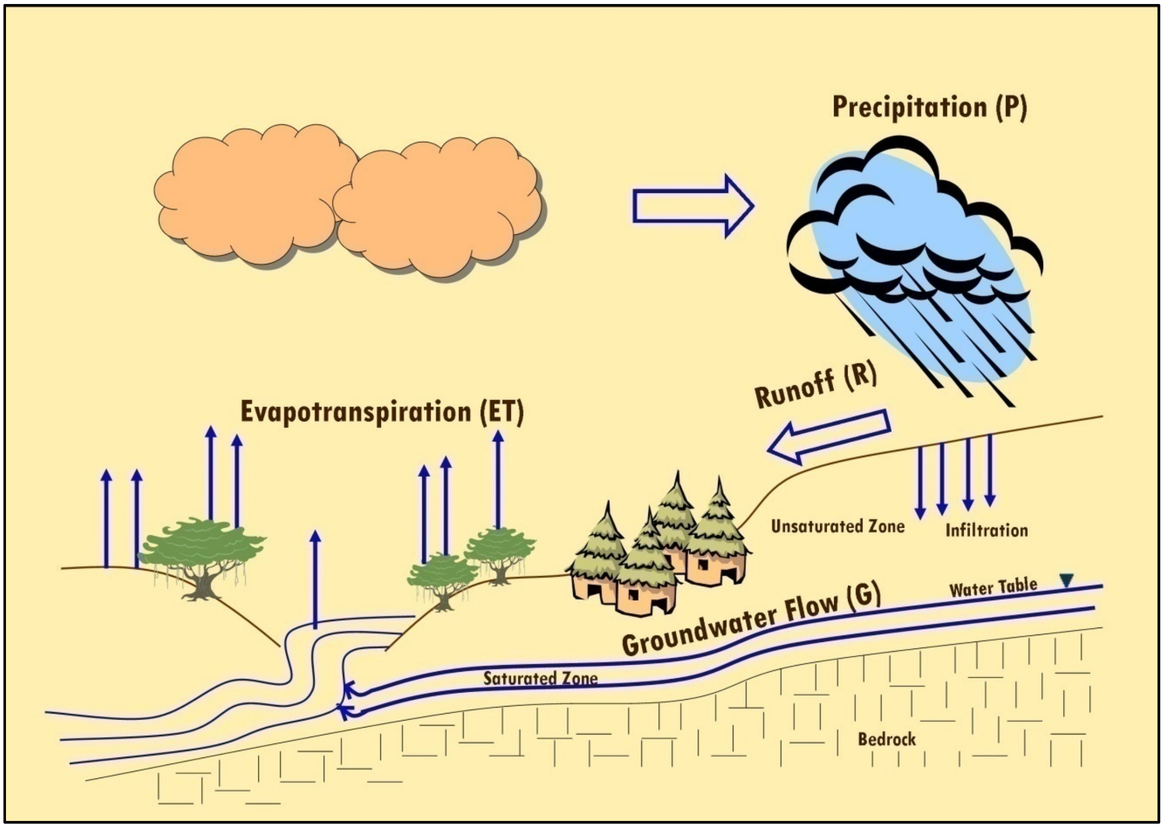

Figure 4.2 The hydrologic cycle

In this study groundwater recharge and surface water flow will be referred to jointly and defined as net precipitation. To solve for net precipitation, assumptions were made to simplify Eq. 4-1. First, groundwater inflow was assumed negligible according to Dingman (2002); subsurface geology should mimic topography. Second, the change in storage was assumed negligible (Dingman 2002). Measurements of this parameter are usually unavailable. The quantity is best minimized by analyzing data over long periods of time and selecting the beginning and ending of periods at times when the values are likely to be equal, such as the maximum storage potential of the watershed. Third, it was assumed that significant amounts of water were not being added or extracted from the watershed and taken elsewhere. This assumption was based on field observations. No large amount of water nor crops were moving in or out of the watershed. Most field crops grown in the watershed were stored for consumption, and vegetables sold at the market in Kita did not substantially extract water from the watershed (Appendix D). Net precipitation was then calculated as the difference between precipitation and evapotranspiration.

The water balance was deemed appropriate for this method because of its ability to simply estimate net precipitation (Zektser and Everett 2006) It was first developed by Thornthwaite in the 1940s to identify the importance of different hydrologic parameters in watersheds and has since been adopted and modified to answer hydrologic questions for a variety of basins (Xu and Singh 1998).

4.2 EVAPOTRANSPIRATION

Evapotranspiration and precipitation data were needed to estimate net precipitation, but in many watersheds evapotranspiration rates have yet to be determined. To efficiently overcome lack of data and complete the water balance, scientists have developed simulation models to specifically estimate these parameters. A suitable model should be chosen, depending on the problem, time/space scales, the availability of data and the quality of data processing facilities (Dyck 1985).

For this research, the Thornthwaite-Mather method was used because of its appropriate estimations of monthly evapotranspiration and for its simplicity (Alley 1984 and Calvo 1986). This method only requires the input of monthly precipitation, monthly temperature, root zone depth of vegetation and soil field capacity. The data inputs were appropriate for the Horongo watershed because monthly cumulative precipitation and median monthly temperature data were made available from a meteorologist in Kita. The climate data was actually measured in Kita, but were used because climate data did not exsist for the Horongo watershed. These data were appropriate for use in this research because of Kita's close proximity (14 km) to Horongo. The meteorologist possessed precipitation and temperature records as far back as the 1970's, but eight years of data from 2000 – 2007 were sufficient to estimate annual available water.

The supporting equations for the Thornthwaite-Mather water balance are:

$$\text{If } P_m \geq PET_m \text{ then } ET_m = PET_m \text{, but if } P_m < PET_m \text{ then } ET_m = P_m - \Delta SOIL_m \qquad \text{Eq. 4-2}$$

$$\Delta SOIL_m = SOIL_m - SOIL_{m-1} \qquad \text{Eq. 4-3}$$

$$SOIL_m = SOIL_{m-1}\left[exp\left(-\frac{PET_m - P_m}{SOIL_{max}}\right)\right] \qquad \text{Eq. 4-4}$$

$$Soil_{max} = \theta_{fc} Z_{fc} \qquad \text{Eq. 4-5}$$

Where:

P_m = Monthly precipitation (mm)

PET_m = Monthly potential evapotranspiration (mm)

ET_m= Monthly actual evapotranspiration (mm)

$\Delta SOIL$ = Monthly change in soil moisture (mm)

$SOIL_m$ = Present month's estimated soil moisture (mm)

$SOIL_{m-1}$ = *Previous month's estimated soil moisture (mm)

$SOIL_{max}$= Maximum achievable soil moisture (mm)

θ_{fc} = Field capacity of the soil

Z_{fc} = Vertical extent of the root zone (mm)

*To start calculations $SOIL_{m-1}$ is equal to$SOIL_{max}$.

The soil field capacity and root zone depth was estimated using literature for the types of soil and vegetation found in the contributing watershed. A detailed vegetation and soil study was not completed to define the specific distribution, therefore maximum and minimum values for the two parameters where used to establish a possible range of net precipitation. The maximum root zone depth was estimated using values for savannah tress from Knoop and Walker (1985). Minimum root zone depth was estimated using field crop and savannah grass values from SJRCD (2009) and Knoop and Walker (1985). The range for soil field capacity was estimated using the *Water Conditions in Natural Soils* table from Dingman (2002) for the two types of soil that were identified during the construction of a hand dug well(Appendix B). This soil was assumed consistent for the entire contributing watershed.

Table 4.1 Range of root zone depth and soil field capacity for the Thornthwaite-Mather and Hamon water balance model

Watershed Properties	**Maximum**	**Minimum**
Root Zone Depth (θ_{fc})	1 m	0.5 m
Soil Field Capacity (S_{fc})	0.37	0.18

The Thornwaite-Mather method required estimates of potential evapotranspiration (PET) to calculate evapotranspiration; therefore the Hamon method was used as recommended by Vörösmarty et al. (1998). In a study of nine methods' abilities to accurately estimate stream flow measured in the field, the Hamon method performed the best. This result was surprising because variations of the Penman–Monteith equation were included in the study. The Penman-Monteith method has become one of the most widely used approaches for estimating evaporation on land surfaces (Dingman 2002).

The Hamon method for potential evaporation is:

$$PET = 924 \cdot D \cdot \frac{e_a^*(T_a)}{T_a + 273.2} \qquad \text{Eq. 4-6}$$

Where:

PET = Potential Evapotranspiration (mm month^{-1})

D = Day Length (hr)

e_a^* = Saturation Vapor Pressure at the Mean Daily Temperature (kPa)

T_a = Mean Daily Temperature (°C)

Saturation vapor pressure can be estimated using the following empirical relationship (Dingman 2002):

$$e_a^*(T_a) = 0.611\, exp\left(\frac{17.3 T_a}{T_a + 237.3}\right) \qquad \text{Eq. 4-7}$$

Day length is estimated using the following set of equations, also from Dingman (2002):

$$\Gamma = \frac{2\pi(J-1)}{365} \qquad \text{Eq. 4-8}$$

$$\begin{aligned}\delta = {} & 0.006918 - .399912\cos(\Gamma) + 0.070257\ \sin(\Gamma) \\ & - 0.006758\cos(2\Gamma) + 0.000907\sin(2\Gamma) - 0.002697\cos(3\Gamma) \\ & + 0.00148\sin(3\Gamma)\end{aligned}$$

Eq. 4-9

$$D = 2\left(\frac{\cos^{-1}[-\tan(\delta)\tan(\Lambda)]}{\omega}\right) \qquad \text{Eq. 4-10}$$

Where:

Γ = day angle (radians)

J = day number (Julian days)

δ = sun declination (radians)

Λ = latitude (radians)

ω = earth's angular velocity (0.2618 radians/hr)

Simpler evapotranspiration models that only require precipitation data for input do exist, but a study by Xu and Singh (1998) concludes that these models are not reliable on a monthly time scale. Reliability is questioned because evapotranspiration is usually estimated as a fraction of precipitation, which does not account for evapotranspiration that is higher than precipitation. Evapotranspiration can be higher than precipitation especially during months that follow a rainy season. Other methods should be used if more data are available (Xu and Singh 1998).

4.3 HYDRAULIC CONDUCTIVITY

To better understand the rate at which water is moving through the Horongo watershed, the hydraulic conductivity (K_h) of the aquifer was determined by performing twelve manual pumping tests in four hand-dug wells. The recovery curves produced from the tests were fit to the solution outlined by Papadopoulos and Cooper (1967). The K_h estimated from this method was assumed constant for Horongo's entire contributing watershed.

Each of the four wells was tested three times, once in each of the main seasons that were described earlier in Section 3.1. The changing seasons affected the height of the water table; therefore each well was tested at three different saturated depths. The wells were chosen for their spatial distribution throughout the village and their ability to provide water during the driest period in the year.

Before the commencement of a pump test, the well was closed off for approximately nine hours in an attempt to achieve a static water level. This period was the maximum amount of time a water user felt that they could forgo pulling water from the well. The well was then pumped by 3-6 village women using rubber well bags for approximately 20 minutes. The water extracted from the well was poured into buckets and basins that were previously set next to the well. A post-pumping water depth was then recorded using a sounder, and the time was recorded. The sounder was then pulled up to a tenth of the overall drop in water level; when the water in the well recharged and reached the sounder the time was recorded. Recovery measurements were consistently taken using this process until the elapsed time was practical. The wells measured were the main source of water for many families limiting the time water extraction could be restricted. While waiting to document the time between the incremental recharge, the buckets and basins were counted to determine the volume of water extracted from the well. To verify this volume, the inside diameter of the well was also measured and multiplied by the drop in water level that occurred during pumping.

The recovery data of pumping tests were analyzed, due to the following recommendations from Gross (2008). In her paper she states that when there is no observation well, and data must be recorded in the pumping well, a recovery curve analysis is the best method to determine hydraulic conductivity. For this research the manual extraction method used did not significantly affect the surrounding well depths, therefore an observation well was not available. In the study by Gross (2008), the recovery curve analysis and three other methods were also evaluated based on their capabilities to estimate specific capacity. The results from the four manual pumping test methods were compared to data that were earlier determined from a conventional pumping test. The conventional pumping test was assumed to produce the best possible estimate of hydraulic conductivity for the area analyzed in the case study. In conclusion, Gross (2008) found that the recovery curve analysis provided appropriate results, underestimating the hydraulic conductivity from the conventional test by only 14%-33%.

The twelve sets of recovery data recorded in the field were fit to the Papadopoulos and Cooper (1967) solution in the program AQTESOLVE. AQTESOLVE is a software package that allows for the design and analysis of aquifer tests in confined, unconfined, leaky and fractured aquifers. In the program the solution was iteratively fit to the data by changing the following hydrologic parameters: transmissivity, storativity and the inside radius of the well.

The Papadopoulos-Cooper solution is applicable for pumping tests performed in large-diameter wells that fully penetrate a confined, homogenous, isotropic aquifer. Even though the aquifer has been assumed as unconfined, confined solutions can be fit as long as max drawdown is less than 20% of the saturated thickness (Driscoll 1986). Papadopoulos-Cooper solution is best used for dug well recovery curves because it accounts for well casing storage (Myre 2008). A large percentage of the water that is extracted from dug wells in pumping tests is from casing storage rather than recharge because of the shallow depths of the wells.

4.4 WATER USE INTERVIEWS

To accurately calibrate the groundwater flow model and explore the impact the village has on the subsurface water levels a daily village use rate and the locations of the extractions were estimated by conducting interviews. To efficiently obtain data for the project site, the interviews were focused on the daily water use of married women ages 15-50. In the Malian culture this group is responsible for acquiring most of the water used for domestic and agricultural tasks. Their reported water use was then normalized by their dependent family members to identify the average amount of water used daily per person.

The interviews were administered orally by one individual. The women were approached in their courtyards at varying times of the day and in two seasons where there would be minimum and maximum water use; cold dry and hot dry. Great effort was made to include representatives of all village ethnic groups and economic levels. However, discrimination against women who did not possess intermediate, West African Bambara language skills could not be eliminated. To understand the interview questions, women had to interpret the interviewer's limited mix of Bamabara and Malinke. All interview techniques followed the guidelines set forth by Michigan Technological University's Human Research Committee (Appendix J).

The interview questions were created using a year of village life observations and the help of Malian, female, Peace Corps staff. They were adjusted based on pre-testing. The questions shown below are the final questions used in the interviews. They allow women to organize their water responses by time of day and amount allocated to each task. This not only helped the women check their answers, but helped the researcher verify amounts stated during the interview. The comments added in italics are provided to explain the general qualitative responses or further explanation of why the question was asked.

Questions:

1. How many children do you have living with you, including working children from other villages? *If a family needs extra help with chores, often a girl will come from relatives in another village*

2. Do you store water at your house? *This is always "yes", but this question was used as an entry question about the types of vessels water is stored in*

3. What in? *Earthen wear pots called* <u>Dagas</u> *are usually the answer, but also large kettles and basins are used so they can pull water in the morning and then use it for the rest of the activities during the day*

4. How many buckets does it take to fill your Daga (s)? *Everyone's buckets and basins are different and are not always labeled by the manufacturer with a content volume. The women were pressed to show the interviewer the vessel and then a visual estimation of the volume was performed based on past visual identification of buckets with known volumes*

5. What do you use this water for? *They usually say drinking, cooking snacks and filling their tea kettles that they use for hygiene activities.*

6. When do you pull this water? *Usually in the morning*

7. Do you pull water to wash yourself? *Always "yes"*

8. When do you pull this water? *Usually morning and evening, but sometimes just morning*

9. How many buckets do you fill to wash yourself each time? *In the Bambara language this is a little confusing this question could be reworded*

10. Do you wash any of your children who live with you?

11. If so, how many buckets do you fill to wash them?

12. Do you cook every day? *This question usually worked to determine if a woman shared work with other women in their family (families can consist of 50 or more people); otherwise an example was given .*

13. If no, what are the names of the women who also cook and the names of their husbands and children? *This question helped the women establish how many people they cook for.*

14. Do you give food to other people who do not cook? *Ex. Older women, husband's brothers, other women in the compound who are incapable of cooking for their family*

15. If yes, how many people do you give food to? *Again listing names seems to help*

16. How many water vessels do you fill to cook? (When it is your turn)

17. When do you pull the cooking water? *Lunch and breakfast is usually pulled in the morning, but dinner water is usually pulled in the evening.*

18. Is this water also used to wash dishes? *It normally is*

19. Do you pound grain every day?

20. How much water do you use to wash the grain?

21. When do you pull the water for the grain? *This is normally in the morning, but not necessarily every day.*

22. How many times do you wash cloths in the week? *1-2*

23. Whose clothes do you wash?

24. How many water vessels do you fill to wash clothes each time? *Again visual identification of the vessel was needed to limit confusion*

25. How many times do you fill them when you wash clothes?

26. Do you give water to animals?

27. When do you give water to the animals? *Morning and evening*

28. How many water vessels do you fill to give them water?

29. Do you have a garden? *If yes the interviewer went out with the women to their gardens and counted the number of buckets they filled and measured the area of their plots.*

30. What well/s do you draw your water from?

31. Does your drinking water come from a different well than the rest of your water? *On many occasions people preferred specific wells for drinking water.*

To check the responses given by the women in the interviews, three interviewed women were also observed. Each woman's water use was observed for an entire day in each season. A range was established from these observations to estimate an amount used per person per day. This range was later expanded by time and village population demographics to estimate annual extraction from the aquifer and the specific amounts coming from each well.

4.5 THE GROUNDWATER FLOW MODEL

The conceptual model (Figure 4.3) of the watershed was simply defined as one homogenous, isotropic, unconfined layer because detailed watershed-wide, soils and bed-rock information did not exist. The bedrock aquifer is also not experiencing any of the recharge estimated from the water balance and is therefore not included in the conceptual model. The top elevations of the layer were created using the topography from the digital elevation model (DEM) from LPDAAC (2008) and the bottom elevations were set to a uniform depth of 25 m below the surface. The bottom of the layer was originally set to 20 m below the surface, but in some areas of steep topographic relief, grid cells would "go dry" (i.e. empty of water), causing numerical errors and poor mass balance. Setting the layer thickness at 25 m avoided the dry-cell problems and reasonable compared to reported bedrock depths around Horongo, which were determined as 5-30 m below the surface from the Kita-DNH bore-hole logs provided in Appendix F.

To represent the hydrological connection between the ephemeral stream/wetland and the shallow groundwater aquifer, a "drain" boundary condition was created at the location of the ephemeral stream/wetland and a portion of the southeast boundary was defined as constant head. The drain boundary condition allows water to flow out of the watershed only when the groundwater table in the drain cells is above the elevation of the drain. Otherwise the drain has no impact on the hydrology. The constant head condition was assumed solely because there was no hydrogeologic information to characterize the downstream watershed conditions. The drain and constant head conditions regulated the outflow from the watershed, balancing with the recharge during the rainy season.

The ephemeral stream/wetland's location was delineated using a handheld GPS mapped onto the DEM and its elevation was set two meters lower than the surface elevation of the basin. The southeast portion of boundary, determined using the surface topography, was assigned a constant, specified head that correlated with the bottom elevation of the wetland, as the wetland crossed the boundary of the watershed. Figure 4.3 illustrates the exported surface image of the conceptual model. Hand dug wells and ground elevation contour lines from the DEM described in Section 3.1 have been added to help identify the placement of the project site and the movement of water in the watershed.

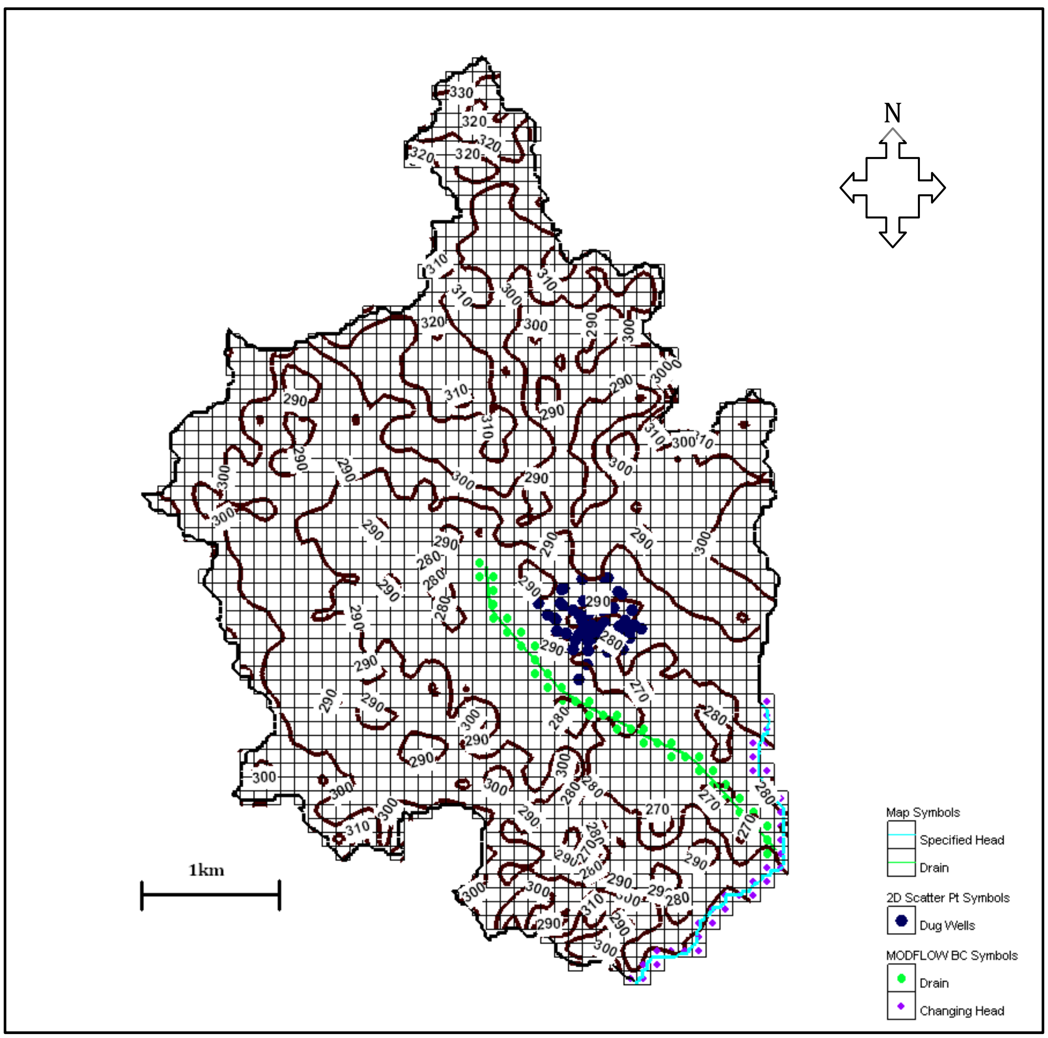

Figure 4.3 Conceptual model of the Horongo watershed (the image was exported from GMS 6.5)

For the Horongo watershed, MODFLOW-2000 was first used to calibrate the conceptual model and verify if net precipitation from the water balance and the hydraulic conductivity from the pumping tests were acceptable. This acceptance was based on the hydraulic parameter's abilities to match the end-of-rainy season observed depths in six wells using a steady state simulation for the rainy season. The steady state simulation incorporated net precipitation (initially)as recharge to the aquifer and hydraulic conductivity to best equilibrate the groundwater levels closest to the observations. The starting heads for the simulations were set just below the surface topography of the watershed to protect against possible errors that could occur.

The first steady-state simulation in MODFLOW incorporated the pumping test hydraulic conductivity and the estimated net precipitation. The next simulations then incorporated one or none of the estimated parameters (Table 4.2). This was done to estimate the range of values that were possible for the watershed. If the recharge and K_h was not initially defined automated parameter estimation was run along with the MODFLOW simulation to identify values that would best match the observed water levels.

Table 4.2 Parameter combinations run in the MODFLOW-2000, steady-state, rainy-season model

Simulation	1	2	3	4	5	6
Recharge (m/day)	0.0002[a]	0.0002[a]	0.0001[c]	0.0008[d]	0.0008[d]	0.00002[c]
Hydraulic Conductivity (m/day)	1[b]	2.27[c]	1[b]	1[b]	15.5[c]	.19[c]

[a] -estimated from the Thornthwaite water balance, distributed on a yearly basis

[b] -estimated from manual pumping test method

[c] -generated in MODFLOW using the automated parameter estimation (APE) option

[d] -estimated from the Thornthwaite water balance, distributed over the rainy season

To further verify the appropriateness of the estimated hydraulic conductivity and net precipitation, a transient simulation was then run in MODFLOW using the heads generated by the best fit steady state simulation as initial conditions. Instead of net precipitation recharging the model, evaporation from the water balance and village use was input as extractions. The simulated drop in the ground water table was then compared to the observed end of hot season groundwater levels that can be found in Appendix H.

5 RESULTS

5.1 NET PRECIPITATION

The average, annual net precipitation for the Horongo watershed was estimated at 73 mm or $8.2 \cdot 10^5$ m^3 for the contributing watershed. If this average was calculated using the yearly estimates of net precipitation for the years 2001-2007. The temperature and precipitation data from 2000 was not included in the average because it was used to initially estimate soil moisture. The yearly amounts of net precipitation and evapotranspiration for 2001-2007 are provided in Figure 5.1. The exact numerical estimations generated from the Thornthwaite-Mather/Hamon model are also available in Appendix E along with a more detailed description of the initial soil moisture calculation. The error, illustrated by bars on evapotranspiration and net precipitation, was a result of the range of root zone depth and soil field capacity estimated for the contributing watershed.

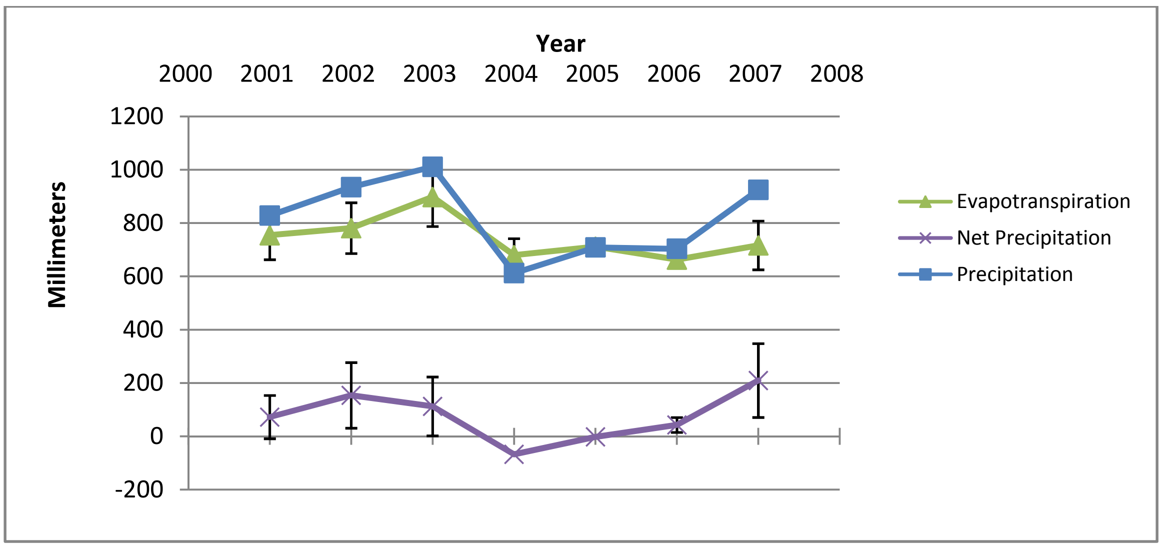

Figure 5.1 Annual evapotranspiration and net precipitation estimated from the water balance and the corresponding annual, cumulative precipitation records from Kita

Precipitation was depicted on Figure 5.1 to comparatively display the net precipitation, evapotranspiration and precipitation from each year. From the graph it can be seen that net precipitation was calculated as the difference between evapotranspiration and precipitation. For all years except 2004 cumulative evapotranspiration was less than precipitation. The percentage of precipitation that was estimated to be lost to evapotransipiration is very similar to a study performed in Mali by Lutz et al (2009).

The Thornthwaite-Mather and Hamon model estimated monthly amounts of evapotranspiration, but because of the level of uncertainty in the quality of the climate data specific conclusions could not be made about the specific amounts experienced during each month. However, Figure 5.2 has been provided to illustrate the possible distribution of precipitation, soil moisture, evapotranspiration and net precipitation throughout an average year. The graph was created using the average of the monthly values that were estimated using the water budget for the years 2001-2007. The data was generated using the average values of soil field capacity and root zone depth. Specific monthly values of net precipitation and evapotranspiration generated by the water budget for each year are provided in Appendix F.

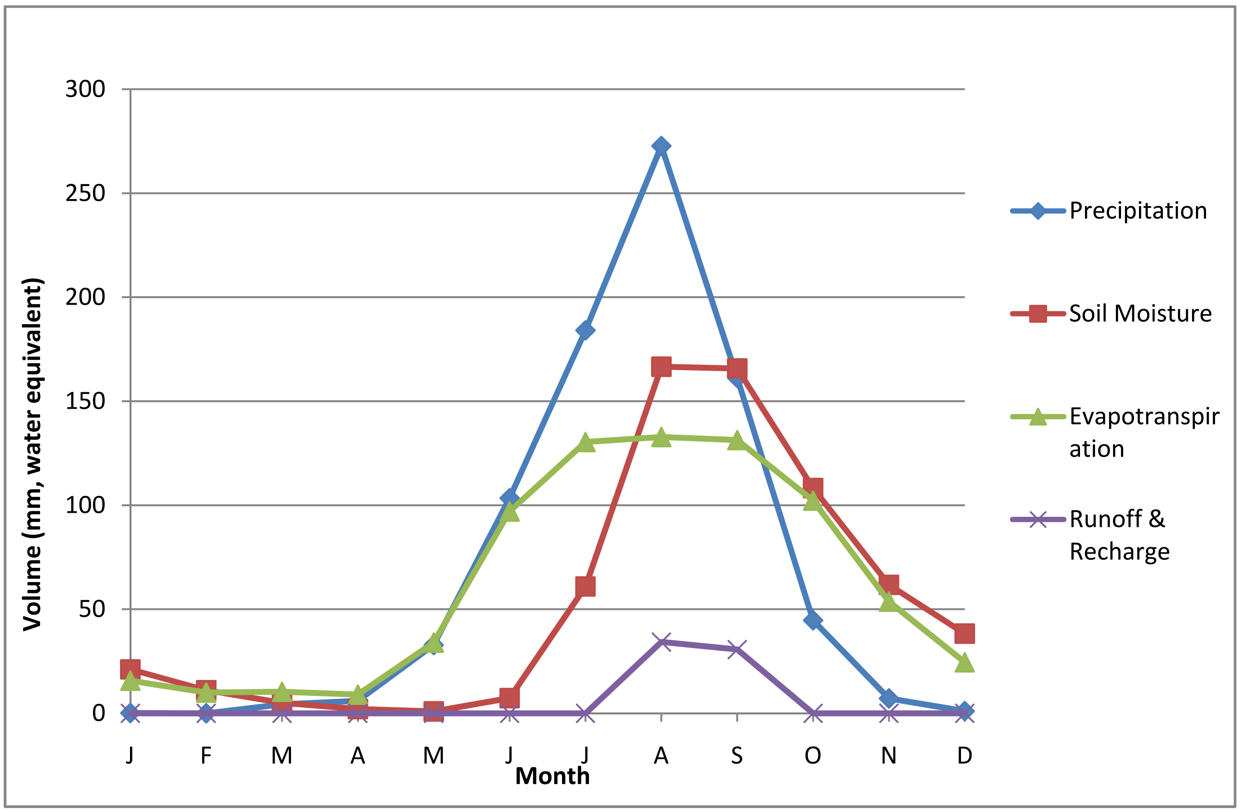

Figure 5.2 Monthly water balance estimated from the Thornthwaite-Mather and Hamon method

The distribution of recharge and runoff shown in Figure 5.2 was consistent with the appearance of the wetlands and surface water runoff observed in the Horongo watershed during the years 2007 and 2008. The majority of the precipitation falls between June and September, which corresponds with low evapotranspiration. When maximum soil moisture peaks around July the excess precipitation becomes recharge to the aquifer and surface runoff. When the precipitation starts to decrease rapidly in September and October, evapotranspiration, soil moisture and net precipitation also decrease. Evapotranspiration does not stop when the rain stops, but steadily drops with the water table until the next rainy season.

5.2 HYDRAULIC CONDUCTIVITY

The average hydraulic conductivity (K_h) for Horongo's contributing watershed was estimated at 1 m/day using data generated from ten manual pumping tests. Originally twelve tests were run, but because of large errors that occurred during two of the pumping tests only ten were included in the analysis. The estimated K_h for each test is displayed in Figure 5.3 and the curves fit to the Papadopoulos-Cooper solution using AQTESOLVE can be found in Appendix G . The maximum error for all ten tests was 20%, due to an estimated amount of water that was lost between the well and the collection buckets.

This method performed quite well due to its ability to estimate a K_h between the typical values reported for the soil types identified in Section 0. This was surprising because of the extremely crude measuring techniques used during the tests. However, even though pumping tests were performed at varying saturated depths, it could not be inferred if hydraulic conductivity changes with the seasonally changing water table. From Figure 5.3 it is apparent that there was no trend for the pumping tests. A change in K_h with depth is possible, but because of the method used a conclusion cannot be made. All pumping test data is available in Appendix F.

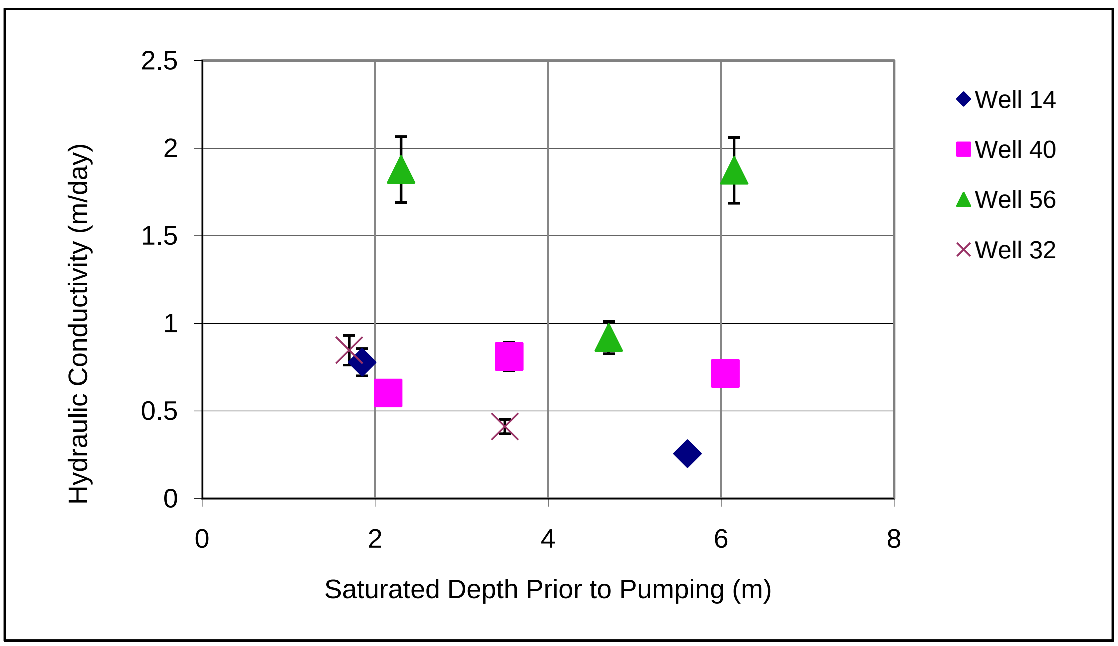

Figure 5.3 Hydraulic conductivity for the aquifer under the village of Horongo at varying saturated depths

5.3 VILLAGE WATER USE

Twenty women, representing 8% of the adult females living in the Horongo watershed, participated in water use interviews from February 5, 2008 to May 29, 2008; ten in the cold dry season and ten in the hot dry season. Their reported daily amounts were normalized by the number of family members that they provided water for and further extrapolated to estimate the daily amount of water used by the entire village and the specific amounts coming from each well. The amounts reported in the interview were checked by observing three women that had also sat for the interview. The observations showed that women were over reporting their water use by more than 40%, but the initial reported amounts were used in the groundwater flow model and further water development scenarios to overestimate the amount of water used by the village rather than underestimate. Table 5.1 is the summary of village daily water use for each season. All raw data from the interviews can be found in Appendix F.

Table 5.1 Daily water use for the village of Horongo

Season	**Village Water Use (m^3/day)**
Rainy	68
Cold Dry	172
Hot Dry	155

Seasonal change in water use was a result of the changing availability of groundwater in wells, surface water and the frequency of rain events. The water use is the highest during the cold dry season due to high availability and increased demand of water by agriculture. The hot dry season use would be the same as cold dry, but shallow water levels in wells limit the amount extracted. The rainy season requires the lowest use of water because agriculture is supported by surface water and rain.

For all seasons, the tasks that require women to extract water from the aquifer fall into two main categories; domestic and agricultural. For water use to be defined as domestic it must influence health and productivity (Howard and Bartram 2003). Domestic tasks for the village of Horongo include bathing, cooking and washing dishes, filling an earthen wear pot for drinking water and sanitation and washing clothes. Agricultural tasks include, providing drinking water for livestock and watering gardens. The amount of domestic tasks performed by the women outnumbers agricultural tasks, but water for agricultural needs is substantially greater. This conclusion was consistent with the water use case studies found in IRC (2004).

Domestic Daily Water Use

Domestic water use was consistent for each season. Every day, on average married women collected 560 L or 28 20-liter buckets to support their family's needs. When these numbers were normalized by the members of the supported family, total domestic water use was estimated at 56 Lpcd (Liters per capita day). The distribution of daily water among the various domestic tasks is shown in Figure 5.4.

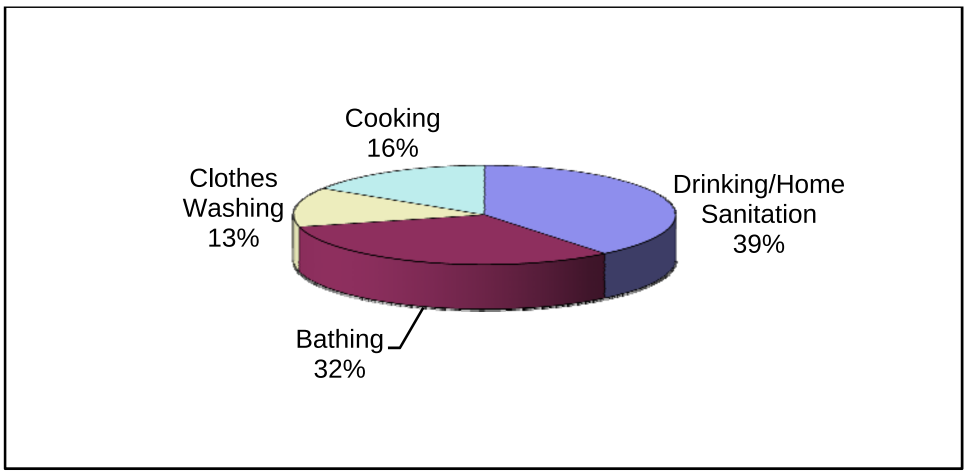

Figure 5.4 Daily domestic water use for the village of Horongo

The domestic water use estimated was comparable to the connection between water quantity, service and health levels made by Howard and Bartram (2003) (Table 5.2) because average village use was estimated at 56 Lpcd (reported amounts) or 22 Lpcd (observed amounts). In their summary they conclude that when basic to immediate access is available, people use 20-50 liters per day. The village of Horongo fell in between basic and intermediate access criteria, because consumption was always assured, hygiene and water for food was assured, but laundry water was usually sacrificed first during the hot dry season and could be difficult to access. The women also never walked more than 5 minutes for their water. However, women can spend 2-6 hours during a 24 hour period collecting water depending on the season. During the hot dry season most of this time is just spent waiting to take advantage of the time when the wells have recharged enough to extract water.

Table 5.2 Summary of needs met by varying water service levels (Howard and Bartram 2003)

Service Level	Access Measure	Needs met
No access (below 5L/p/d collected)	1000 m or 30 min. for collection	Consumption: not assured Hygiene: only if practiced at source
Basic access (does not exceed 20L/p/d)	100-1000m or 5-30 min. for collection	Consumption: should be assured Hygiene: handwashing and basic food possible; laundry/bathing difficult unless practiced at source
Intermediate access (50L/p/d)	100m or 5 min for collection or taps	Consumption: assured Hygiene: personal and food assured; laundry and bathing should be assured
Optimal access (100L/p/d and above)	Continuous supply through taps	Consumption: all needs met Hygiene: all needs should be met

Seasonal Agricultural Water Use

Women's responsibilities as water gatherers for the support of agriculture were dynamic throughout the seasons. During the rainy season agriculture was supported by precipitation and surface water, but once the rain had stopped, gardens needed watering and livestock required supplemental drinking water. Even though the family shared ownership of the livestock and shared consumption of garden produce and meat, agricultural water was not normalized throughout the family, and therefore only assigned to the women. This also helped estimate the amount of water extracted from each well. All remaining residents of the village, other than married women, are defined as using only domestic water throughout the year. Table 4.5 shows the increased water demand placed on women by agriculture during the dry seasons.

Table 5.3 The amount of water allocated daily to gardening, livestock and domestic tasks by the women of Horongo (Liters/woman/day)

Season	Garden	Livestock	Domestic	Total
Rainy	0	0	56	56
Cold dry	494	0	56	550
Hot dry	320	124	56	500

In the cold dry season, water use was at its peak because water was abundant from the previous rainy season. Even though livestock was supported by surface water, use was higher because women could tend large gardens due to the high availability of water. Approximately 80% of the women tended a 70 m^2 garden plot during the cold dry season. Only when the African savannah became too harsh in the hot dry season did women have to become more conscious of their water use, which in turn limited the intensity of their gardening. During the dry hot season women also gave water to a few head of livestock, but garden plots still received the most water. However, during the hot dry season only 50% of the women tended garden plots, and the plots diminished to approximately 20 m^2. The percent of women who tended gardens was actually higher for the hot dry season, but livestock often broke through garden fences and ate the produce. During the interviews if a woman mentioned she had lost a garden to livestock damage her previous garden water use was not recorded.

The amount of garden water used by the women of Horongo was comparable to water use in hand watered gardens in Zimbabwe. Two studies from the area of Harare, which has a very similar seasonal climate compared to Mali, state that Zimbabwean gardens require 3.5-4 L/m^2 on an average day (IRC 2004). The garden water use in Horongo is very similar to this when values from Table 5.3 are expressed in liters per square meter. In Horongo, women used about 8 L/m^2 each day to water their gardens during the cold dry season and about 15 L/m^2 each day to water their gardens during the hot dry season. Even though total water use dropped in Horongo from the cold dry season to the hot dry season, the average size of the gardens shrunk and it took more liters of water per square meter to keep them alive. The rate of water used per square meter is comparable to the results from the study in Zimbabwe, but water use for the gardens in Horongo is still quite high. This difference could be explained by the fact that the average monthly temperature is lower in Zimbabwe than in Mali (World Travel Guide 2009).

Locations of Daily Water Extraction

From the interview data the specific amounts extracted from each well were estimated on a seasonal basis (Figure 5.5). The inner wells of the village were assumed to provide domestic water needs and the outer-lying wells to provide agricultural water needs. However, during the interviews it was determined that some wells dried up or did not provide sufficient supply during the hot season and some wells had bad tasting water and were not used for drinking water. In these cases, the alternative wells were recorded and water extraction was allocated appropriately. The specific extraction amounts for each well are provided in Appendix F.

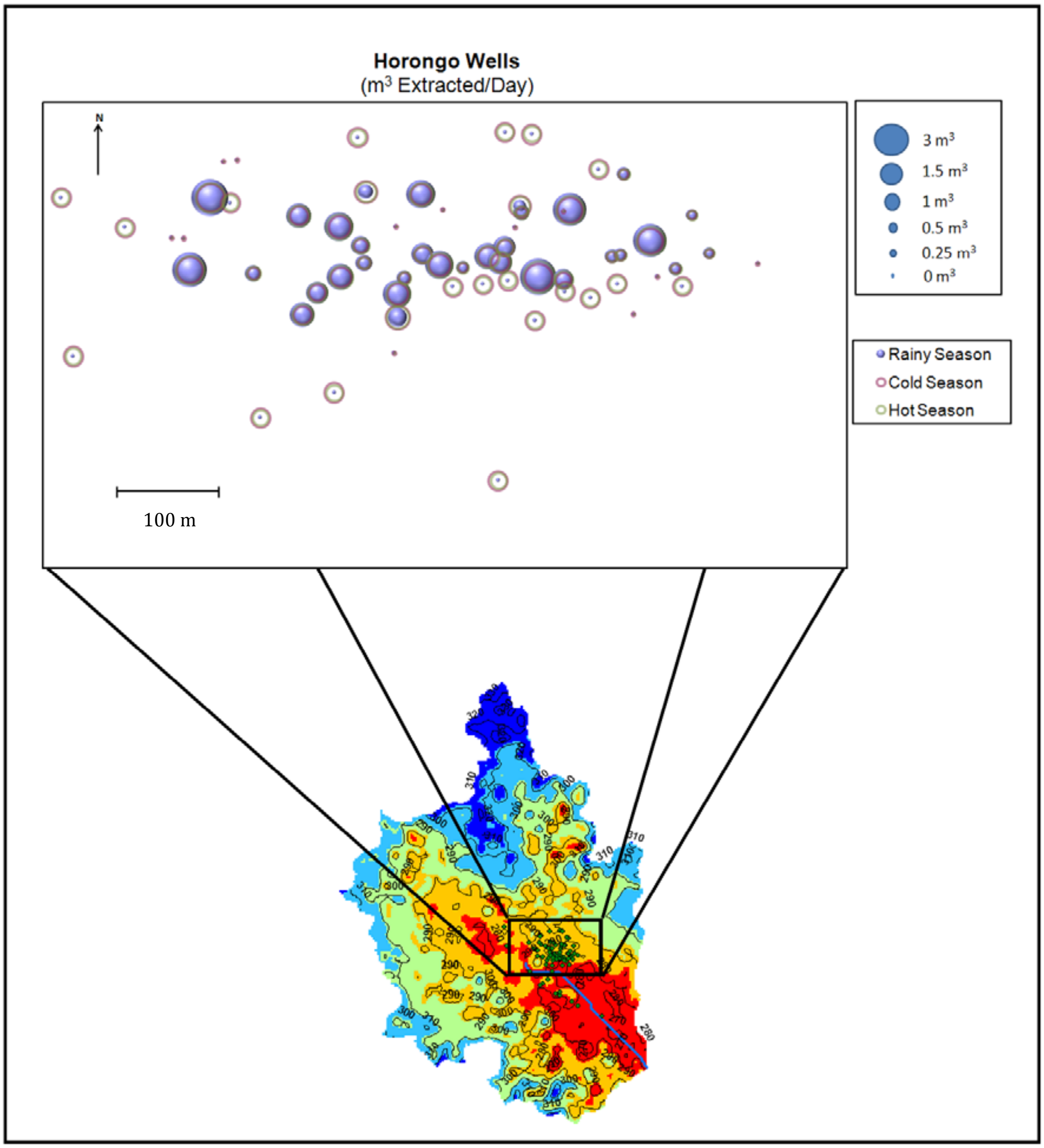

Figure 5.5 Seasonal water extraction from each well in Horongo

From Figure 5.5 it is apparent that the rise in water use created by garden watering during the cold dry season is mostly supplemented by the out-lying wells. In a few cases water use goes up or down for the interior wells that are used during all seasons due to lack of water availability or shared use with gardens. A greater estimate of extraction does not necessarily correlate with the depth of the well but rather with the taste of the water as determined by the village. Women will walk further in the village just to gather better tasting water for drinking purposes.

Accuracy of Estimated Water Use

Individual variations of water use were noticed during the water use interviews. However, for simplicity these changes in water use were omitted from the final results because they were observed as an inconsistent or insignificant addition to the total village water use. These variations include:

- Occasionally more or less water was used for bathing during the hot dry and cold dry seasons.
- Seasonal production of products such as shea butter and soap required a couple buckets of water at each production session.
- Donkey carts with 20 L bottles were occasionally sent to other villages, outside the watershed, when more water was needed for weddings.
- The women also collectively went to the ephemeral stream/wetland for a change of scenery to wash laundry and let their children splash in the water. Surface water was not collected for other uses
- Men were rarely seen pulling water from a well, but during the hot dry season after the crops are all harvested and sold the men started making bricks to reconstruct their mud dwellings and walls.

5.4 CALIBRATION OF THE GROUNDWATER FLOW MODEL

To calibrate the model and determine if the estimates of recharge and K_h were appropriate, subsurface groundwater levels generated by the steady-state simulations in MODFLOW-2000 were compared to observed water levels (Appendix H) for the months of July and August. Table 5.4 is the summary of the difference between the simulated and observed water levels (residual head) starting with the water balance and manual pumping test estimates in simulation 1. The average difference between the simulated and observed water levels or Root Mean Squared Error (RMSE) for the estimated values in simulation 1 is an appropriate error for this study, verifiying the use of the water balance and manual pumping test methods, but further simulations were run to the range of values possible for the watershed.

Table 5.4 Residual head (m) and root mean square error (m) of simulated water levels compared to observed water levels using MODFLOW-2000

Simulation	1	2	3	4	5	6
Recharge (m/day)	0.0002[a]	0.0002[a]	0.0001[c]	0.0008[d]	0.0008[d]	0.00002[c]
Hydraulic Conductivity (m/day)	1[b]	2.27[c]	1[b]	1[b]	15.5[c]	.19[c]
	Residual Head (m)	Residual Head (m)	Residual Head (m)	Residual Head (m)	Residual Head (m)	Residual Head (m)
Well 14	3.0	-1.2	-1.1	25.0	-2.0	-0.7
Well 31	5.6	2.8	2.7	20.5	2.7	2.6
Well 56	6.5	2.6	2.6	27.8	2.0	2.6
Well 40	2.1	-1.8	-1.8	23.4	-2.4	-1.7
Well W03	2.8	2.5	1.7	7.3	3.8	0.9
Well W01	-3.6	-4.6	-4.7	0.2	-4.6	-4.9
RMSE[e]	4.2	2.8	2.7	20.1	3.1	2.6

[a] -estimated from the Thornthwaite water balance, yearly cumulative amount distributed over the year

[b] -estimated from manual pumping test method

[c] -generated in MODFLOW using the automated parameter estimation (APE) option

[d] -estimated from the Thornthwaite water balance, yearly cumulative amount distributed over the rainy season

[e] -RMSE is the root mean square error difference from the observed value

In the first simulation, the recharge and K_h were the estimated values from the monthly water balance and pumping tests. The value of 0.0002 m/day was calculated by assuming 73 mm/year of net precipitation was distributed throughout the year. Precipitation did not actually fall and recharge the watershed all year long, but because annual evaporation rates are included in the calculation for total net precipitation this was the most appropriate value. This method was confirmed when the total net precipitation was distributed just over the rainy season ($8 \cdot 10^{-4}$ m/day) in simulation 4 and produced the highest root mean square error (RMSE) of 20.1. Only when K_h was set to 15.5 m/d, using APE in simulation 5, was the RMSE reduced to a level commensurate with the uncertainty in ground elevations, which translates directly with uncertainties in groundwater elevations.

The RMSE for simulation 1 is reasonable, therefore the recharge and K_h estimated from the water balance and pumping tests are appropriate for this conceptual model, but simulations 2, 3, and 6 were run to explore the range of values that are possible. K_h could be 0.19-2.27 m/d and net precipitation could be 0.0002-0.00002 m/d. The range of K_h was thought to be overestimated slightly because smaller creeks that feed into the stream are not included in the model. Even though the parameters in simulation 1 are appropriate, the combination of parameters generated from APE in simulation 7 were used for further modeling. The subsurface water levels generated from this simulation are shown in Figure 5.6. The flooded cells depicted in Figure 5.6 are places where the groundwater is simulated to be above the surface. Groundwater levels are actually not above the ground in as many places in the watershed as shown, but realistically water levels could be about 2-3 meters below the surface. Because of the shallow characteristics of the aquifer and the variability of estimates, these areas where groundwater is close to the surface show up as flooded cells.

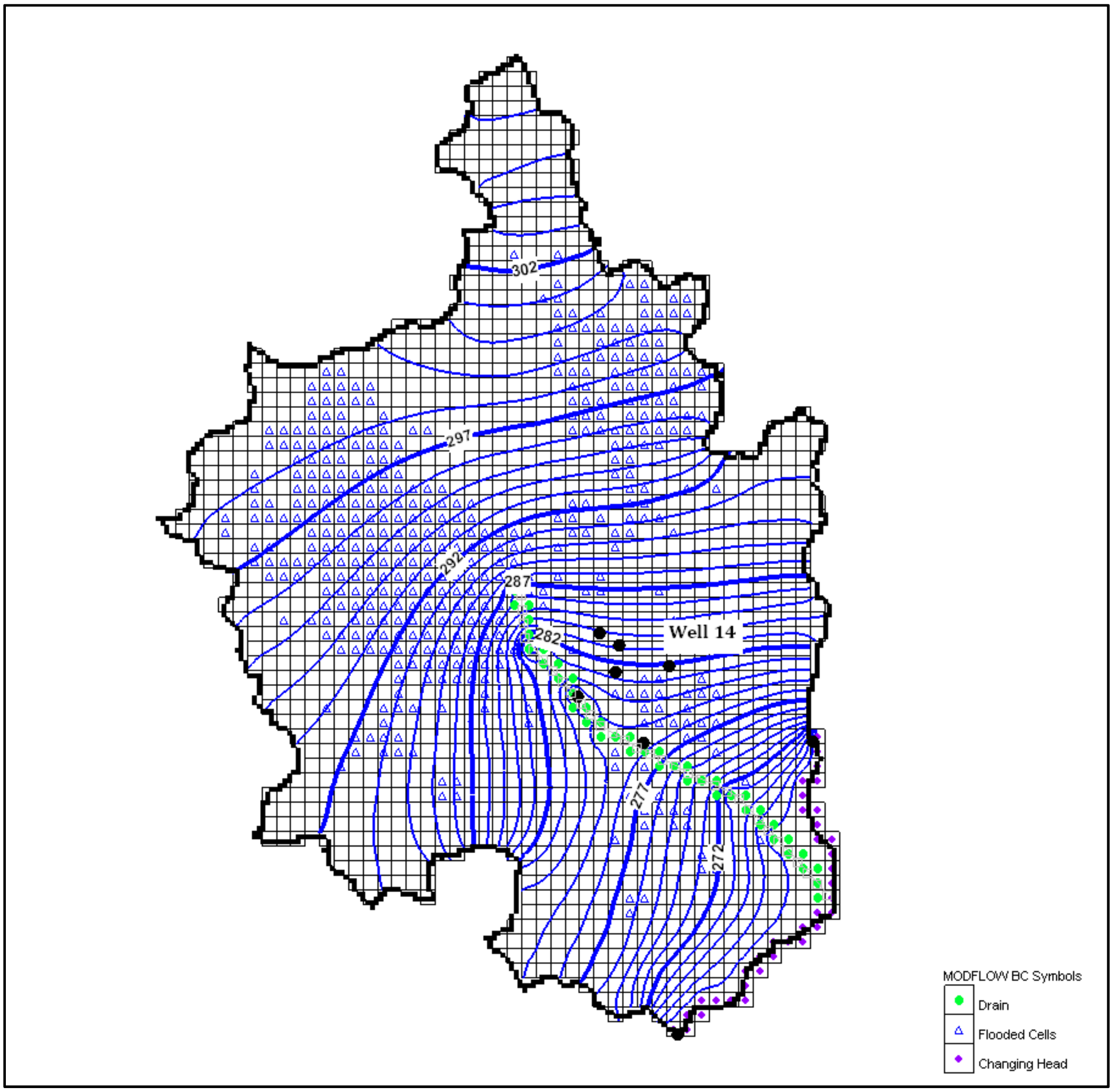

Figure 5.6 Simulated subsurface water levels for the calibrated model at the end of rainy season (the image was exported from GMS 6.5)

To further check the accuracy of the calibrated model, a MODFLOW transient simulation was run for the dry seasons using a varying geometric time step progressions with a time step multiplier of 1.1 for 50 time steps. The calibration accuracy was determined by the ability to accurately simulate water table drops at the end of the cold dry and hot dry seasons shown in Table 5.5. Using the heads shown in Figure 5.6 as initial conditions, the simulation was run for 230 days using an evapotranspiration rate of 0.0013 m/d and the estimated extraction from each well in Section 5.3. The daily evapotranspiration rate was determined by distributing the average annual evapotranspiration estimated from the water balance (Appendix E) over the dry seasons. Dry season does not begin until the end of September, therefore 230 days is the time from October to the time the observations were taken in May.

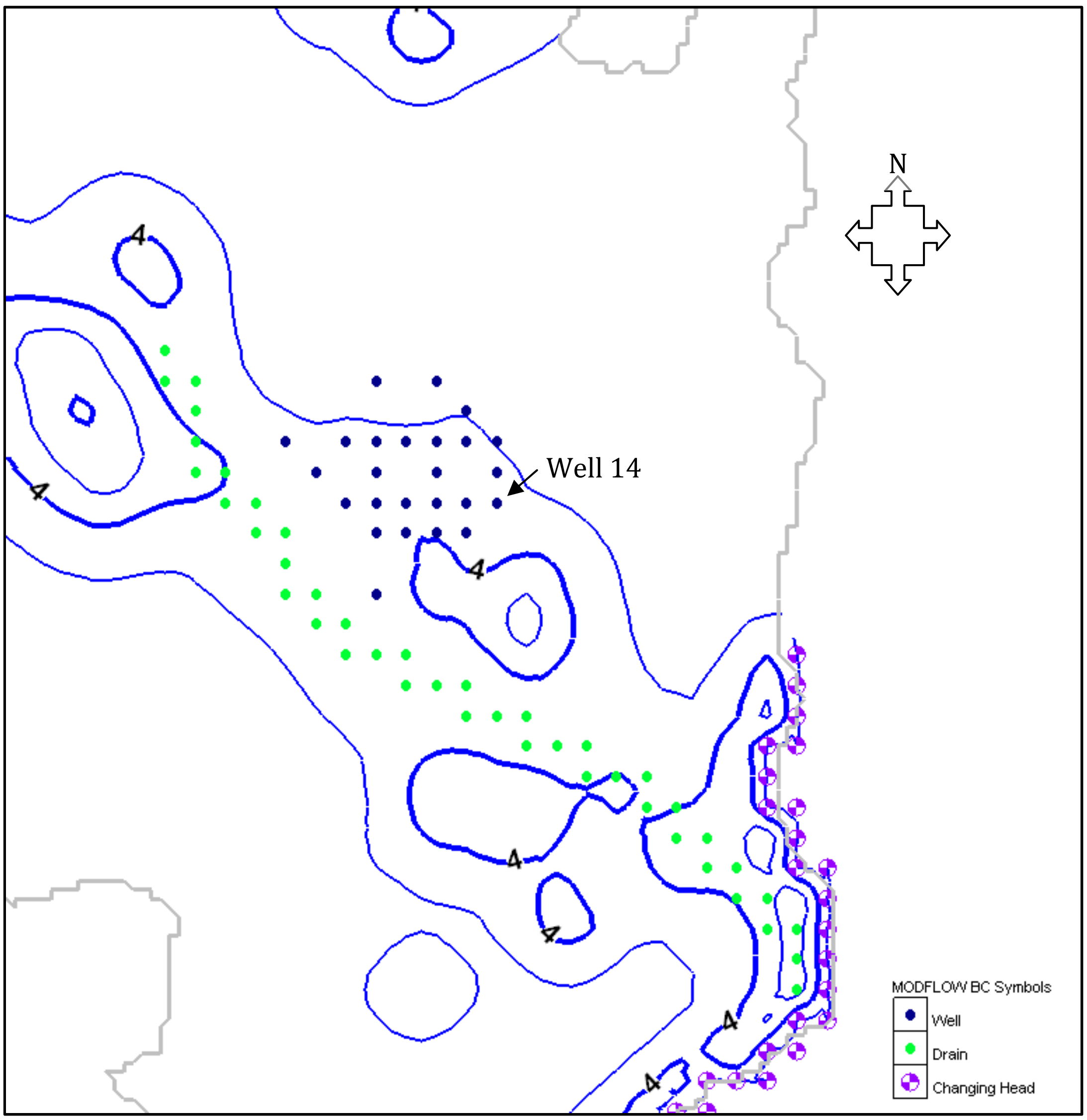

Figure 5.7 Contours of water table drop (m) around the time of the February observations or after 120 days of no recharge (the image was exported from GMS 6.5)

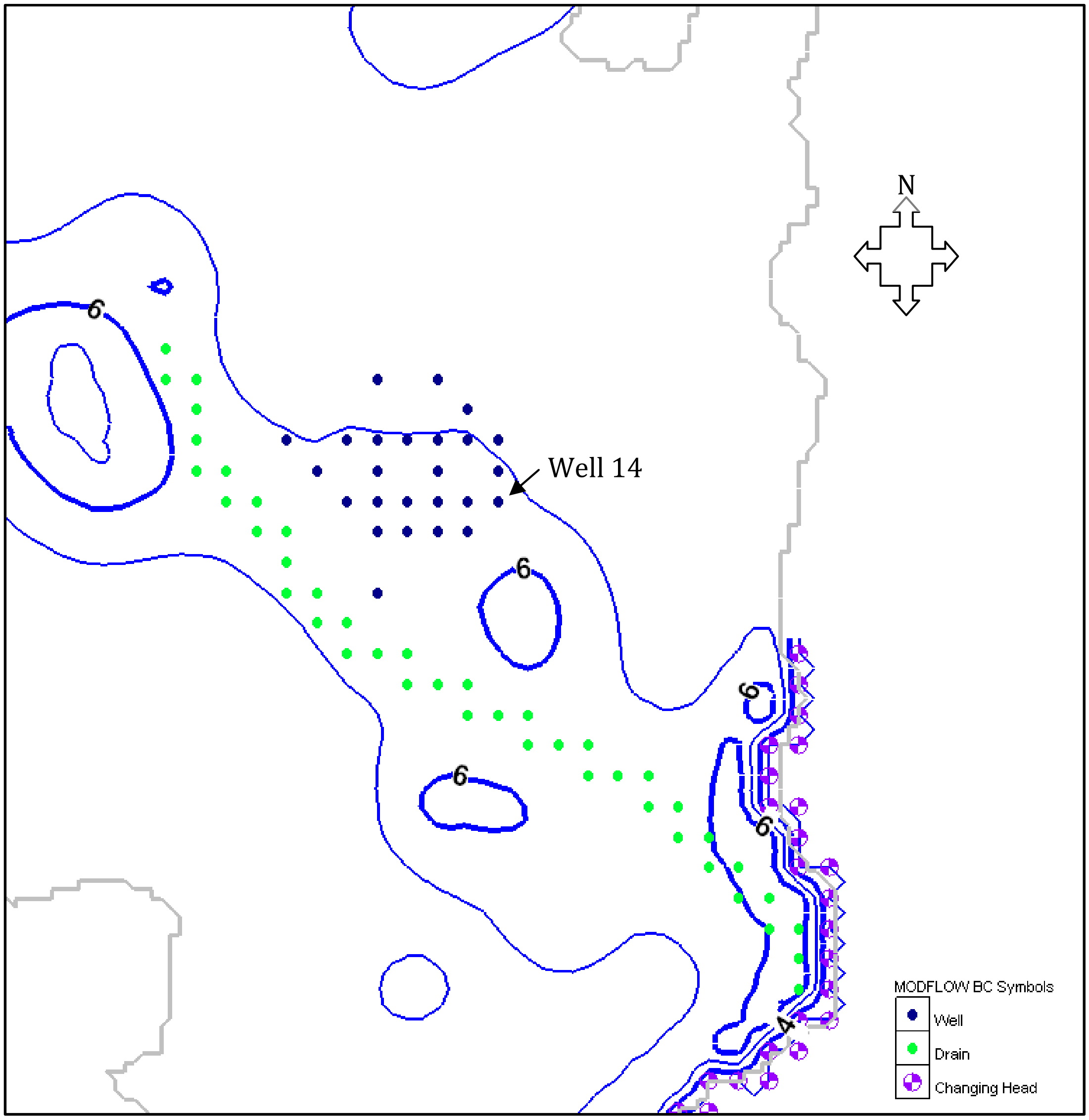

Figure 5.8 Contours of water table drop (m) around the time of the May observations or after 230 days of no recharge (the image was exported from GMS 6.5)

The simulated water level drops depicted in Figure 5.7 and Figure 5.8 were quite close to the observed values in Table 5.5. MODFLOW simulations predicted a drop of 2-4 m after the first 120 days of the dry season and a drop of 4-6 m after 230 days in the area of the village. The water level drops observed in the field were 1.5-3.8 m after 120 days and 3.6-5.3 m after 230 days of the dry season. The simulations also predicted a greater water level drop the further southeast the well was located. Again, the model exhibits reasonable agreement with the observations; well 14 was located the farthest southeast (Figure 5.6) and experienced the greatest drop in water level after 120 and 230 days of the dry seasons.

Table 5.5 Observed seasonal groundwater table (GWT) drop from the rainy season equilibrium state for the year 2008

Well	Date	GWT Drop (m)	Date	GWT Drop (m)
14	2/24/2008	3.8	5/19/2008	5.3
31	2/21/2008	1.8	5/17/2008	3.6
56	2/20/2008	1.5	5/13/2008	3.9
40	2/23/2008	2.5	5/12/2008	3.9
W03	-	-	-	-
W01	-	-	-	-

6 AVAILABLE WATER

After the groundwater model was calibrated it could be used to explore water supply development options for the village. Extractions from the model are assumed to come from drilled wells with motorized pumps and maximum GWT draw downs at the end of the dry season are restricted to two thirds of the aquifer's total saturated thickness as recommended by Krešić (2006). All simulations were conducted using the same transient simulation conditions described in Section 5.4, except daily water use was not distributed throughout the hand dug wells.

From the model it was estimated that if the water in the aquifer under the entire area of the village (0.38 km^2) was evenly extracted over the dry seasons the village could potentially access a total of 420 m^3/day (Figure 6.1) or almost three times as much water than their maximum use rate from Table 5.1. However this scenario would assume that pumping wells would be spaced throughout the village running at similar rates. The estimate of 420 m^3/day should be treated as the maximum theoretical availability of water from the aquifer under the village. Realistically, if the village were to develop improved water supplies similar to the neighboring villages one to two pumping wells would be constructed to provide water for the entire village.

When a simulation was run that assumed entire village use (170 m^3/day) came from one pumping well during the dry seasons the GWT draw downs in that area were lower than two thirds of the saturated aquifer thickness, therefore the construction of one pumping well is not appropriate if all water needs of the village are expected to be produced from that one source. However, when the village daily water needs were equally divided between two pumping wells the simulation produced appropriate draw downs. Figure 6.2 depicts the placement of the two pumps that would produce the maximum amount of water (80-100 m^3/day) if desired maximum draw down is set at two thirds of the aquifer saturated thickness.

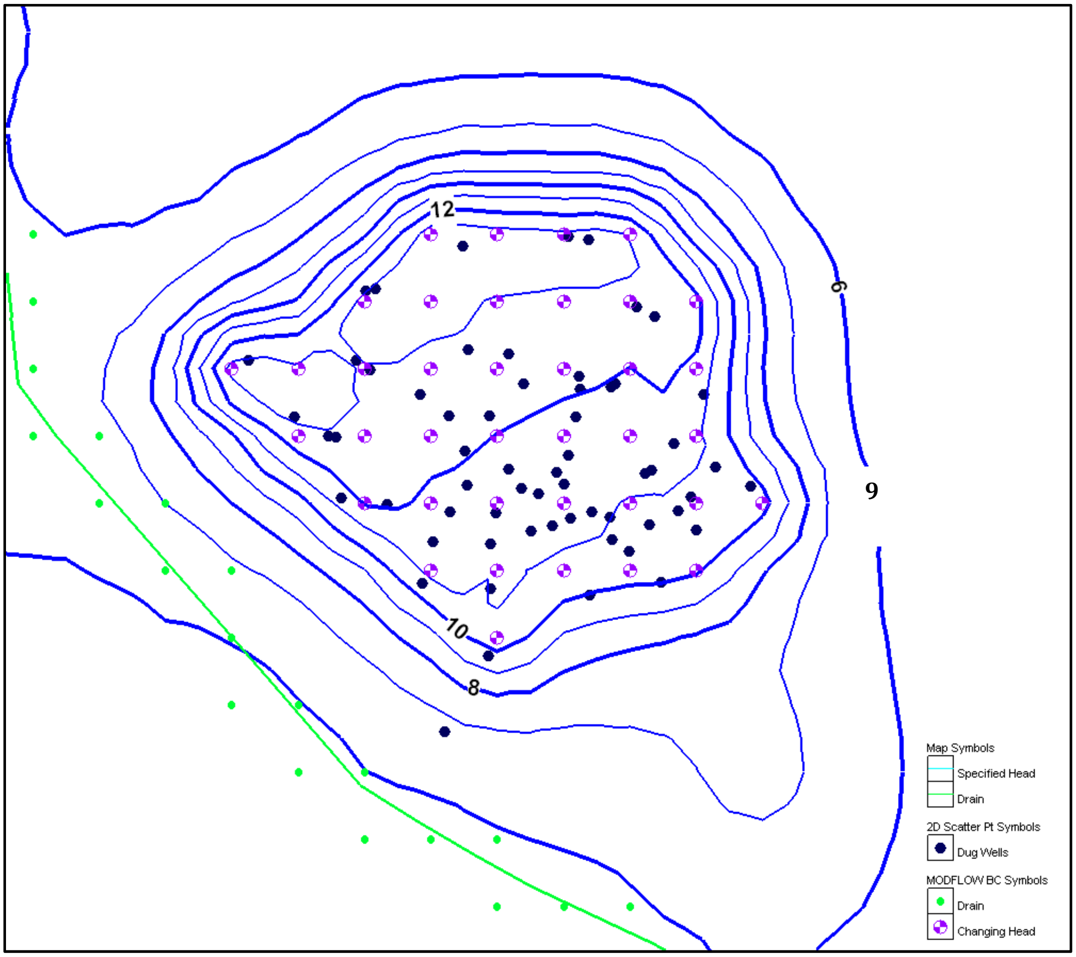

Figure 6.1 Simulated GWT draw downs at the end (230 days) of the dry seasons if the entire area under the village was evenly pumped (the image was exported from GMS 6.5)

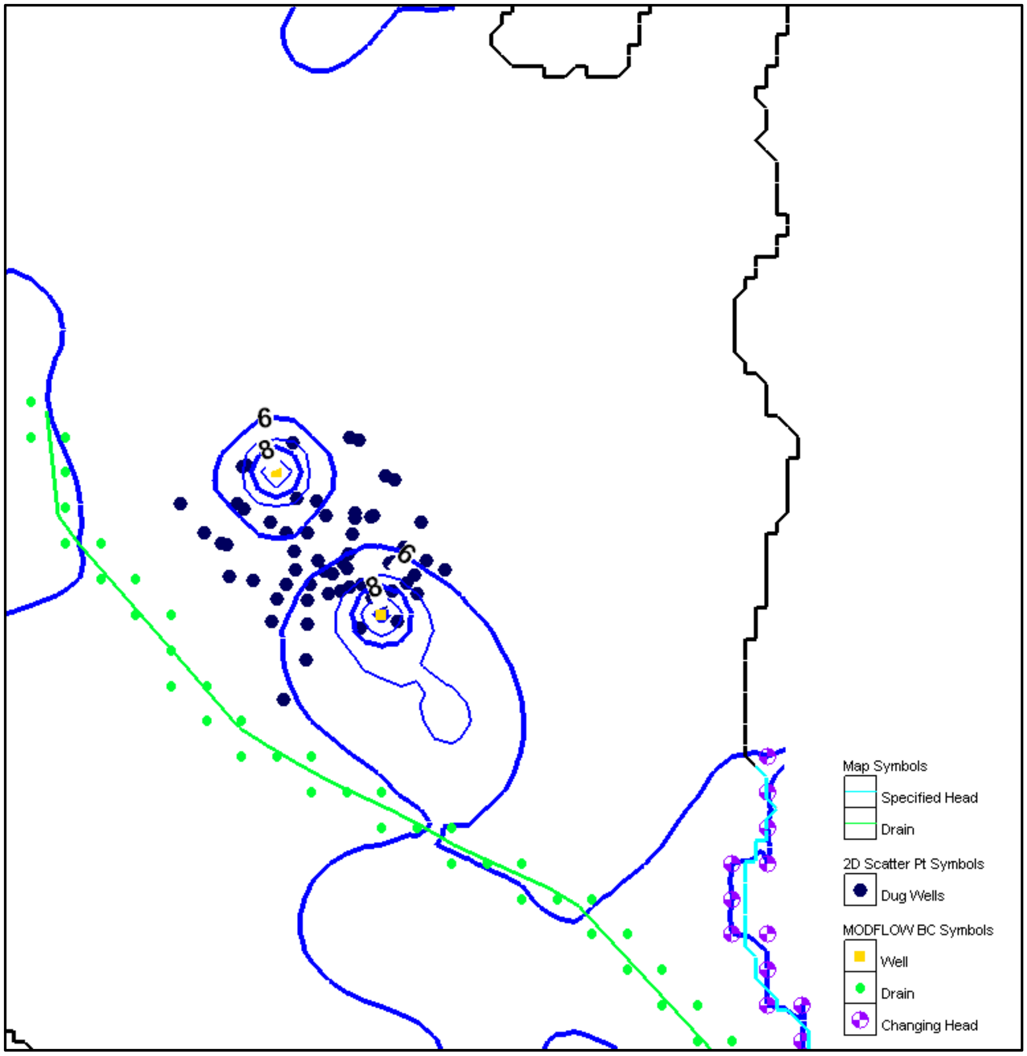

Figure 6.2 Estimated GWT drawdowns at the end of hot season from two pumps, assuming equal extraction. (the image was exported from GMS 6.5)

To take the duel-pumping scenario one step further, pumping wells were added one at a time to determine the maximum amount of water that could be extracted with the least amount of pumping wells. After a few simulations is was estimated that the addition of every one pump up to four will produce a maximized amount of 80-100 m^3/day. Figure 6.3 depicts the best placement of these pumps that was estimated to achieve this extraction rate. With four pumping wells the cumulative available water would be 320-400 m^3/day , which is very close to the first simulation with evenly distributed drawdown.

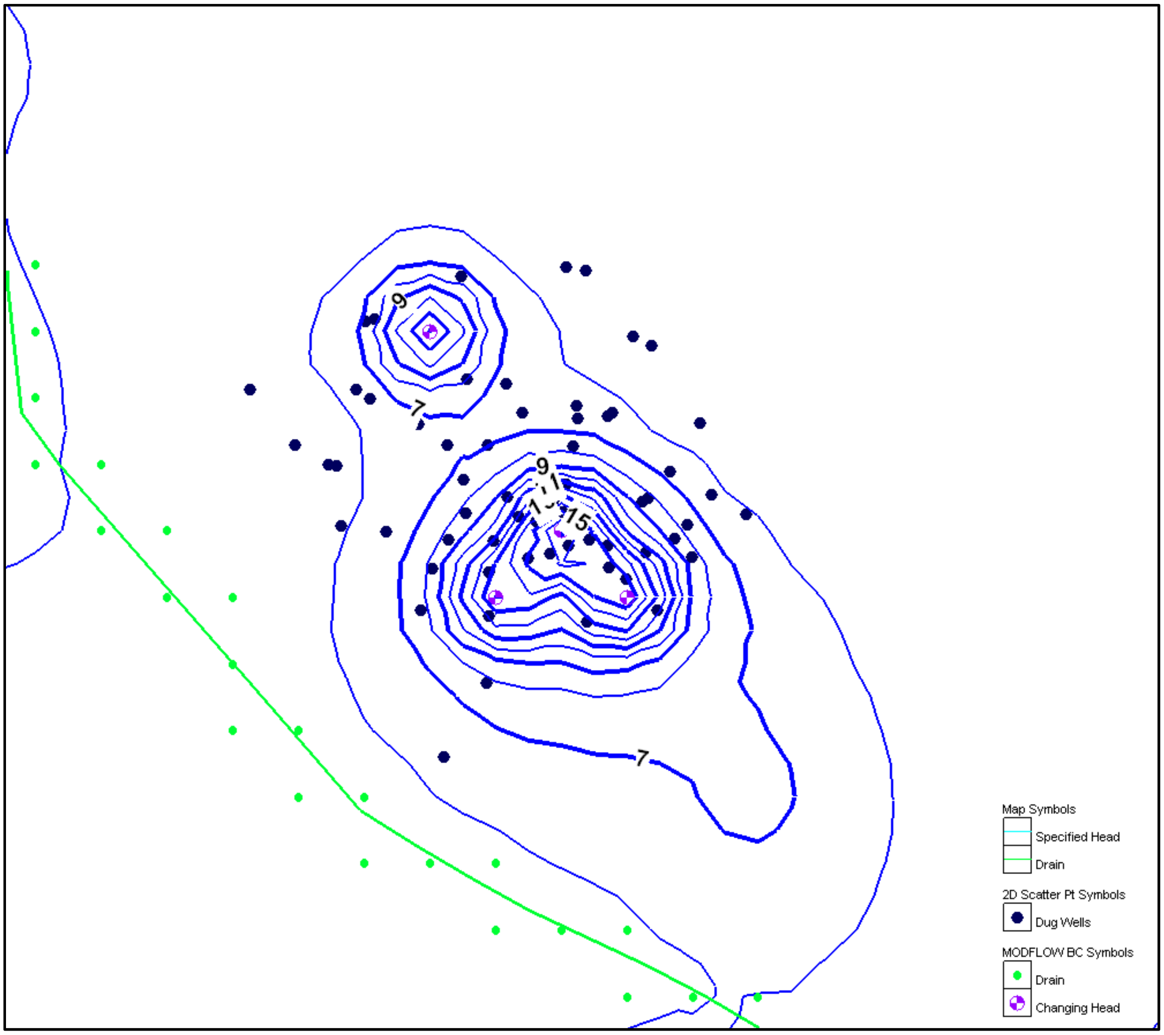

Figure 6.3 Simulated GWT draw downs for the maximum production of four pumps (80-100 m3/day) at the end of the dry seasons (230 days) (the image was exported from GMS 6.5)

In summary, the contributing watershed was estimated to have 800,000 m3/year of water in the form groundwater recharge and surface water flow. However, realistically if pumping wells could be constructed within the village maximum water availability during the dry seasons is estimated at 320-400 m^3/day.

7 FUTURE WORK

Future work should be performed to determine if the water balance method outlined in this research, or a close variation of this method, could be used to accurately estimate monthly available water conditions. If funding is not readily available to communities for the construction of pumping wells, water conservation strategies or water containment projects might be the only option and would rely on such data.

8 CONCLUSIONS

The world's countries are working toward providing water access for all residents, but there are still large numbers of people who struggle every day to provide adequate water for their families. This situation is not projected to improve, especially for large areas of South America, Asia and Africa where available water is threatened by increased temperatures and decreased precipitation rates. The use of methods, such as the Thornthwaite-type water balance, manual pumping tests and groundwater flow modeling described in this research, are necessary to characterize available water resources for the continued and improved support of developing populations. All hydrologic data acquisition methods incorporated for this research could be similarly reproduced for other developing communities.

Net precipitation was estimated on a monthly basis for the years 2001-2007 for the Horongo watershed in Mali, West Africa. The accumulated net precipitation estimated by the Thornthwaite-Mather and Hamon method for each year was then averaged to acceptably estimate the amount of available water that could be accessed by the village on a yearly basis. The average annual net precipitation for the Horongo watershed is approximately 73 mm or 800,000 m^3/year for the contributing watershed.

Daily water use data was collected from 8% of the adult women in the village to determine the relationship between annual village water use and the subsurface hydrology of the watershed. Their water use was then normalized by the family members that they supplied water for and was then extrapolated for the entire village. Yearly village water use was estimated as $5 \cdot 10^4$ m^3 per year or 56-172 m^3/day.

Hydraulic conductivity for the watershed was also determined to better understand the rate at which water is moving through the aquifer. Ten manual pumping tests were performed at varying saturated depths, in four different hand dug wells. The recovery curves from these tests were then fit to the Papadopoulos-Cooper solution for large diameter dug wells. The average hydraulic conductivity estimated for the entirety of the Horongo watershed was 1 m/d.

Locally procured data, the water balance and the manual pumping tests were estimated to appropriately characterize water resources by comparing modeled subsurface water levels to seasonally observed water levels. By estimating the appropriateness of these methods and data model was calibrated and then used to explore water development options. From the model it was estimated that two pumping wells that fully penetrated the aquifer would satisfy the estimated village water need by producing 80-100 m^3/day during the dry seasons. However, if the village was to develop a need for more water during the dry seasons and the estimated annual net precipitation stayed fairly consistent, the village could effectively add two more pumping wells, producing at the same rate, resulting in a total production rate of 320-400 m^3/day. The groundwater flow model can also be used to evaluate the effect of village use on the subsurface hydrology for a variety of scenarios that could develop in the future.

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APPENDICES

A. CULTURAL ATTRIBUTES OF HORONGO

Almost all the families in the village of Horongo would describe themselves as part of the Malinke ethnic group. This is normal for the Kita area, which is also predominantly Malinke. Malinkes are known culturally by other ethnic groups as the "peanut growers." This is accurate from field observations of village life in Horongo. Each family dedicates parts of their land for peanut production to sell or use as a dietary staple. The other major ethnic groups present in Horongo are the Soninkes and the Peuls. The Peuls are culturally associated with owning cows and producing milk and meat products. The Soninkes are culturally associated with small families that strive to retain similar lineage in marriages. The Soninkes in Horongo used to be farmers along the Mali-Mauritania boarder.

The primary language spoken in the village is also referred to as Malinke. Bambara[7] is occasionally mixed in speech because it is taught in the early grades of school and because villagers frequently travel to Kita, where Bambara is the primary language. French is also mixed in speech, but less frequently, because it is not widely spoken in the area. Grades 6-8 have the opportunity to take classes in French, but all school material is not taught in the language until Mali's equivalent of high school located in Kita. Most of Horongo's current population only participated in school until grade six.

The predominant religion in the village is Muslim. The religious holidays of Ramadan and Tabaski are observed in the village, but at other times of the year a prayer of five times a day is not practiced. Men may marry up to four wives, but in small villages the level of wealth normally limits men to two. The only other religion present is protestant which is practiced by only one small family.

Almost all communities in Mali have a <u>dugu tigi</u> (chief) that is the leader of the village and a <u>muso kun tigi</u> (woman chief) that is the leader of the women's community. The <u>dugu tigi</u> settles all major disputes and oversees all major business transactions that are made on behalf of the village. The <u>muso kun tigi's</u> role is very similar, but only presides over women's issues. In many villages she is also the primary midwife.

[7] The official language of Mali is French, but Bambara is used as the common language to communicate in commerce throughout Mali. It is widely spoken by the inhabitants of Mopti and Segu.

Livelihood

All families in the village practice subsistence farming. All field crops are planted around the beginning of July and are harvested from November to January. Crops are not irrigated; therefore planting and harvesting coincide with the rainy season. Men and women farm different crops, but everyone (even children) is involved in harvesting. Men's field crops are: two types of sorghum, corn and cotton; women's field crops are peanuts and rice. Until 2008 the main cash crop in the village was cotton. Cotton has now been replaced by corn because of poor yields from soil degradation. Women also tend small gardens (average area of 50 m^2) for production of onions, lettuce, manioc, eggplant, mint and beans. Most villagers also produce processed goods, such as shea butter. If goods are sold they are usually taken to the market in Kita.

The villagers also own livestock. This livestock includes: goats, sheep, cows, donkeys, chickens, guinea fowl and ducks. Most livestock is eaten in the village and is rarely sold. Goats, sheep and cows will change hands from village to village in dowries or if a life is lost in an accident that was caused by a non-resident.

Supporting Entities

Plan International is the only NGO presence in Horongo. One representative is specifically assigned to Horongo and its surrounding villages, but specialists in a wide range of development activities are available for consultation in their office in Kita or state office in Bamako. Their first large construction project in Horongo was a community building in the late 1990s, and they have since built a three room school house at the east end of the village, finished in 2006. In 2000 they also improved 11 drinking water wells with covers and concrete reinforcement. Annually, they take pictures of the students in the school to send to possible aid donors and give seeds to the women for gardening.

The only example of government service in the village is a road with accompanying drainage structures that was built in early 2008. Water and all waste is individually managed by each family in simple hand dug wells, hand dug latrines and trash piles. Government support offered outside the village include: the commune mayor's office in Kofeba (3 km east); the cercle capital staff offices in Kita, including an office of the Department of Hydraulic Infrastructure (DNH); a small rural hospital in Kofeba; and a larger, better equipped hospital in Kita.

The preferred transportation by the villagers is bike, motorcycle or donkey cart, but buses also come by twice a day that are traveling to a from Kita.

B. OBSERVED WELL CONSTRUCTION

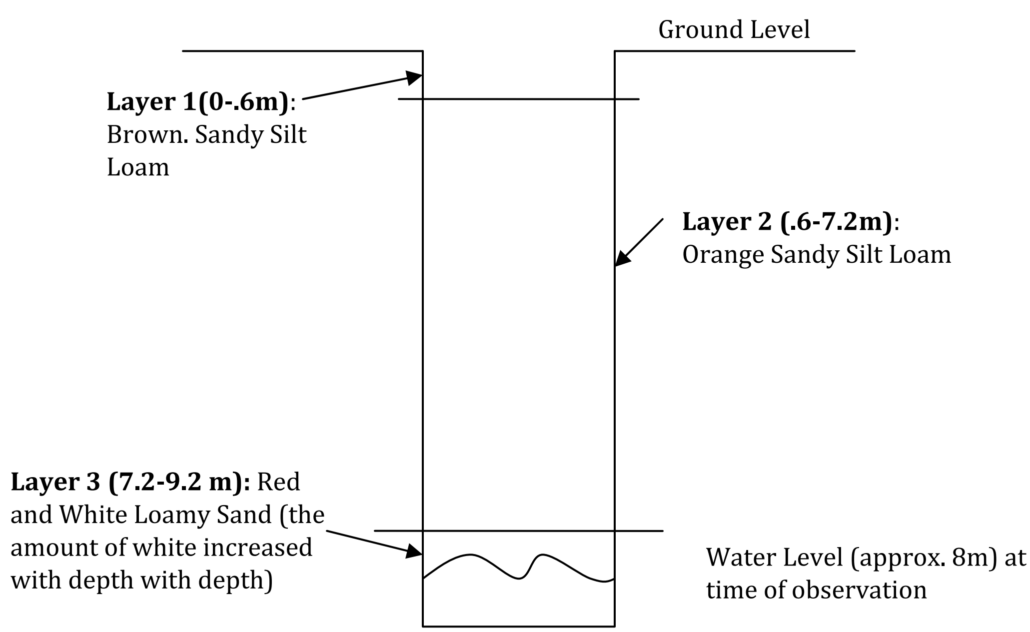
Well # 9

(N13o01.984', W009o36.615')

Date of Observation: May 18th, '08

Date of Well Created: April '08

Laborer/Owner: Bakari Keita



*Soil identification made using classification chart from Davis and Lambert (2002)

C. EXAMPLES OF WELL REINFORCEMENT

Figure C.1 Concrete well reinforcement (photograph by author)

Figure C.2 Example of concrete and tire reinforcement (photograph by author)

Figure C.3 Example of traditional log reinforcement (photograph by author)

D. WATER LEAVING THE WATERSHED AS VEGETABLES

Vegetables produced by the women of Horongo were the only significant good that contained water and frequently left the watershed. However, it has been estimated that only 30 L of water could be leaving the village with vegetables during each growing season. Even if the women could harvest their gardens three times a year, the amount of water would still not be substantial enough to include as a withdraw from the water balance. This estimation is based on:

1.) Water content for most fruits and vegetables is between 80-90% (Table D.1) of its mass weight (Pennington and Douglass's 2005). *The poor quality and less hardy varieties found in Mali will possibly contain less water than what has been estimated .*
2.) The average amount of vegetables produced by an acre of land in the U.S. is found in (Table D.1).

Table D.1 Average vegetable production per acre in the U.S. (Smith 2000)

Crop	lb/acre	lb/m^2	Grams of Water/m^2	Liters of Water/m^2
Bush Beans	2700	0.67	0.57	0.00057
Lettuce	16000	3.95	3.36	0.00336
Eggplant	9900	2.45	2.08	0.00208
Potato	15000	3.71	3.15	0.00315
Onion	18000	4.45	3.78	0.00378
Tomato	8400	2.08	1.76	0.00176
Cucumbers	7440	1.84	1.56	0.00156

3.) Women only sold vegetables when there was an excess. Excess of vegetables occurs during the rainy season when precipitation was abundant to support plots.
4.) On average during the rainy season 200 women in the village produce vegetables from plots approximately 70 m^2.
5.) On average 0.002 L of water from every m^2 of garden could be leaving the watershed.

E. ANNUAL NUMERICAL ESTIMATES OF NET PRECIPITATION AND EVAPOTRANSPIRATION FROM THE WATER BALANCE

Table E.1 Annual estimates of Net Precipitation and Evapotranspiration from the water balance and cumulative precipitation records from Kita (mm)

Year	Evapotranspiration	Precipitation	Net Precipitation
2000	829.3	894.1	64.1
2001	754.4	828.0	72.3
2002	781.1	934.7	153.9
2003	897.9	1010.9	112.5
2004	679.5	612.1	-67.4
2005	711.2	708.7	-1.9
2006	662.9	703.6	42.9
2007	716.3	924.6	209.5
Average*	743.3	827.1	73.2

*The average is estimated from the data for the years 2001-2007

To best estimate consecutive years of evapotranspiration, the data from the year 2000 was started in September when the initial soil moisture had the best chance of being equal to max soil moisture. The December soil moisture for the year 2000 was then used as initial soil moisture for January 2001. December soil moisture from the previous year was used as the January initial soil moisture for the rest of the years of data (2002-2007).

By using the maximum soil moisture possible for the initial soil moisture in September of 2000 a negative value of net precipitation was calculated for that month (Appendix F, skewing the cumulative net precipitation for that year. The estimated net precipitation for the year 2000 was therefore not included in the calculated average of annual evapotranspiration.

F. DIGITAL FILES ON ATTACHED CD

Physical Characteristics of the Horongo Wells.xlsx

Precipitation and Temperature Data from Kita, Mali.xlsx

Water Balance Calculations.xlsx

Manual Pumping Tests.xlsx

Water Use Interview Data.xlsx

G. RECOVERY CURVES FROM AQTESOLVE

Well 14

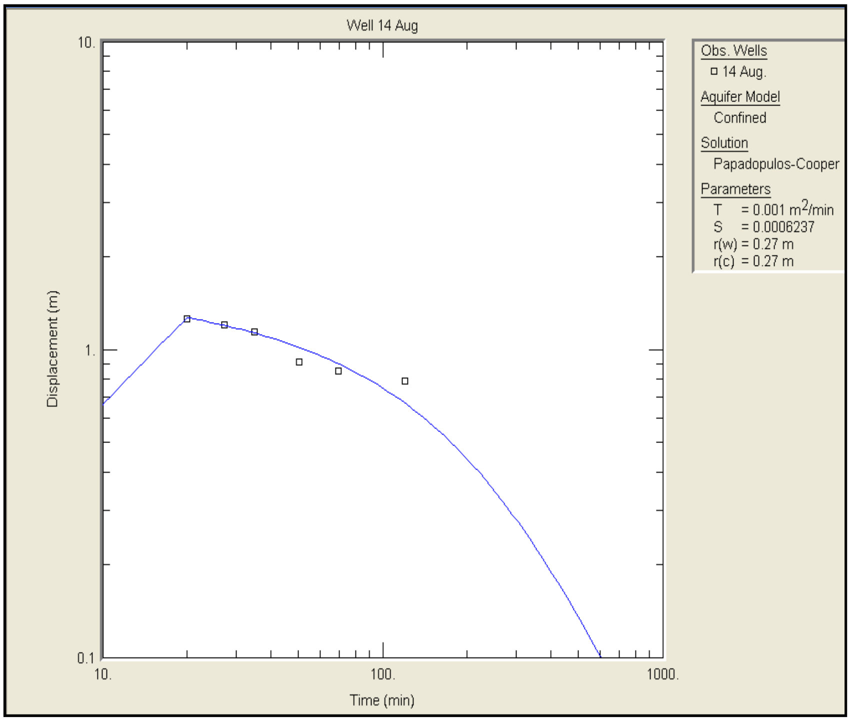


Figure G.1Well 14, 8/2/2008 (image exported from AQTESOLVE)

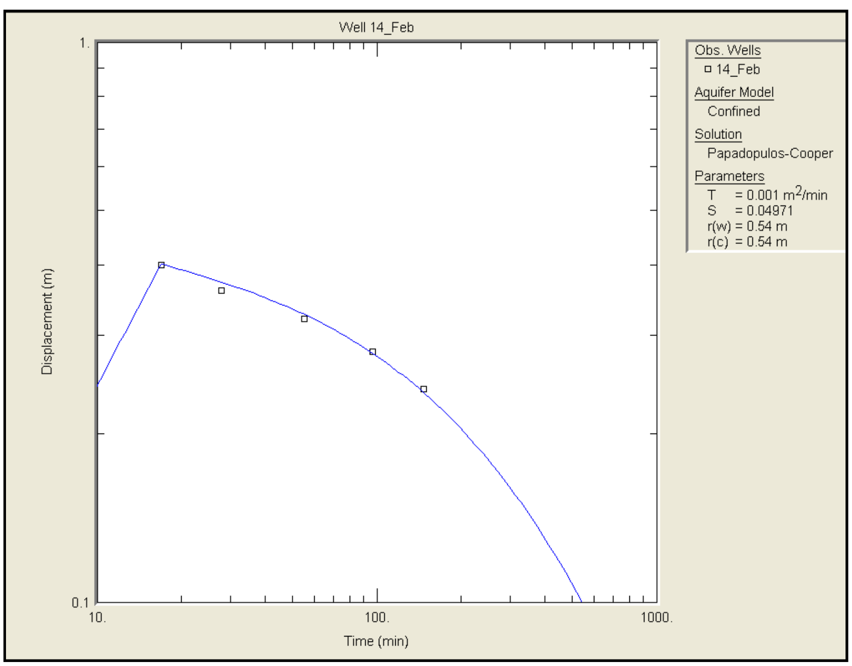


Figure G.2 Well 14, 2/24/2008 (image exported from AQTESOLVE)

Well 31

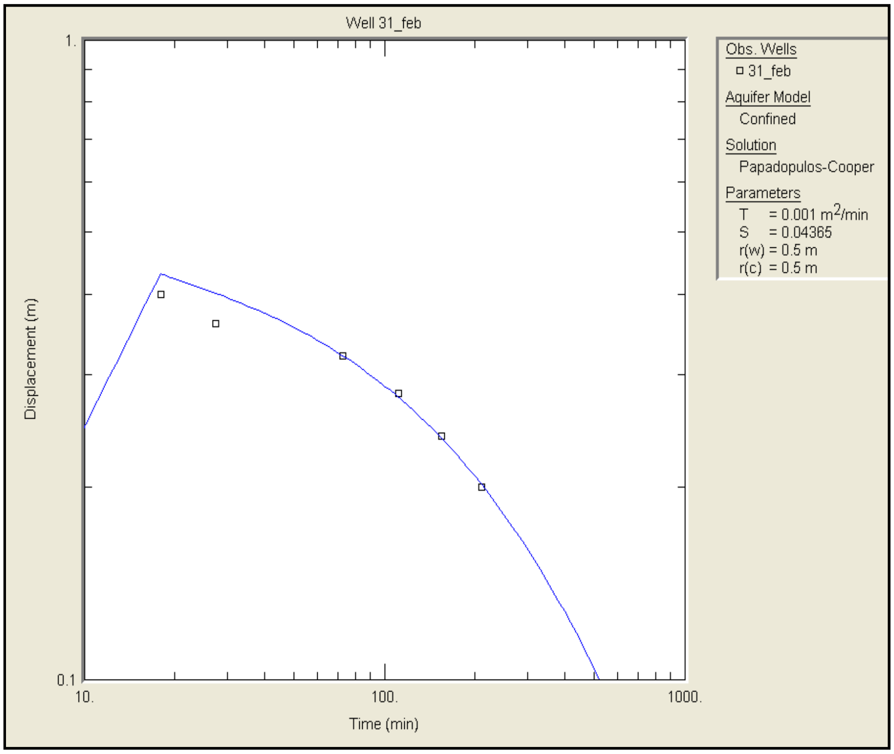


Figure G.3 Well 31, 2/21/2008 (image exported from AQTESOLVE)

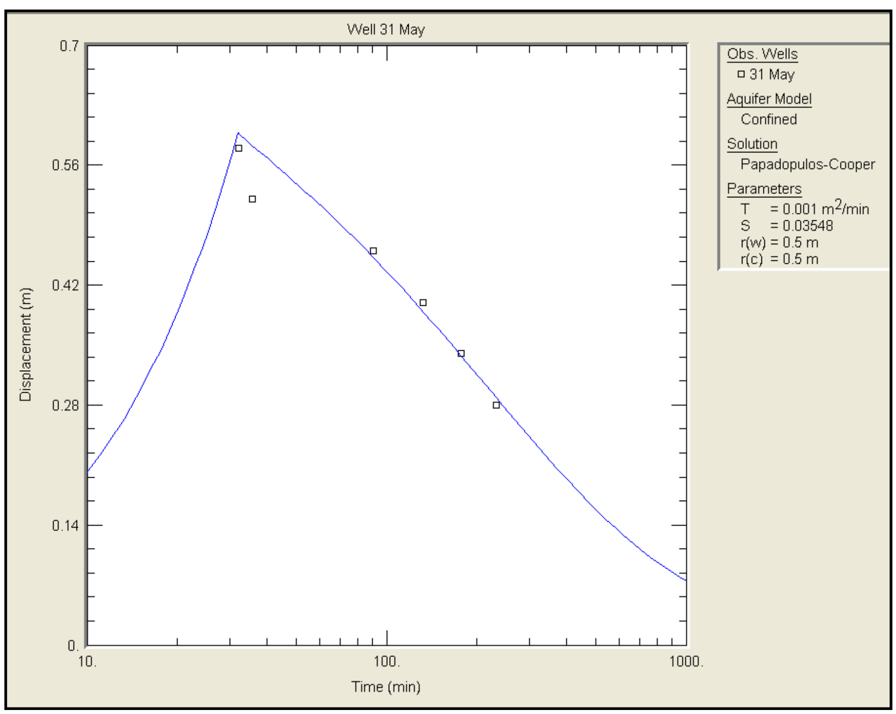


Figure G.4 Well 31, 5/17/2008 (image exported from AQTESOLVE)

Well 56

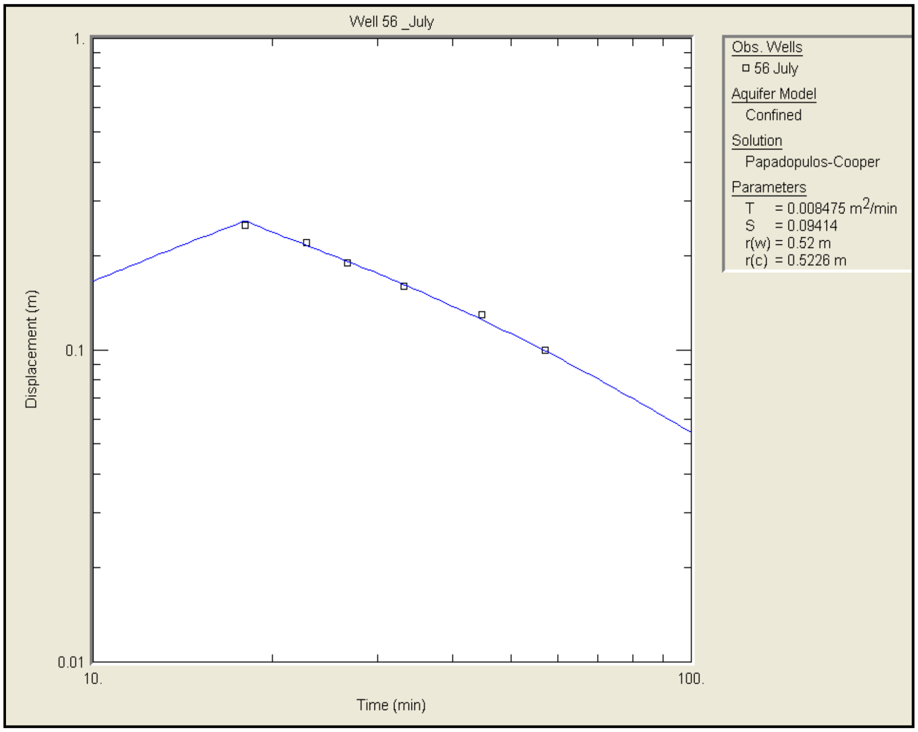


Figure G.5 Well 56, 7/31/2008 (image exported from AQTESOLVE)

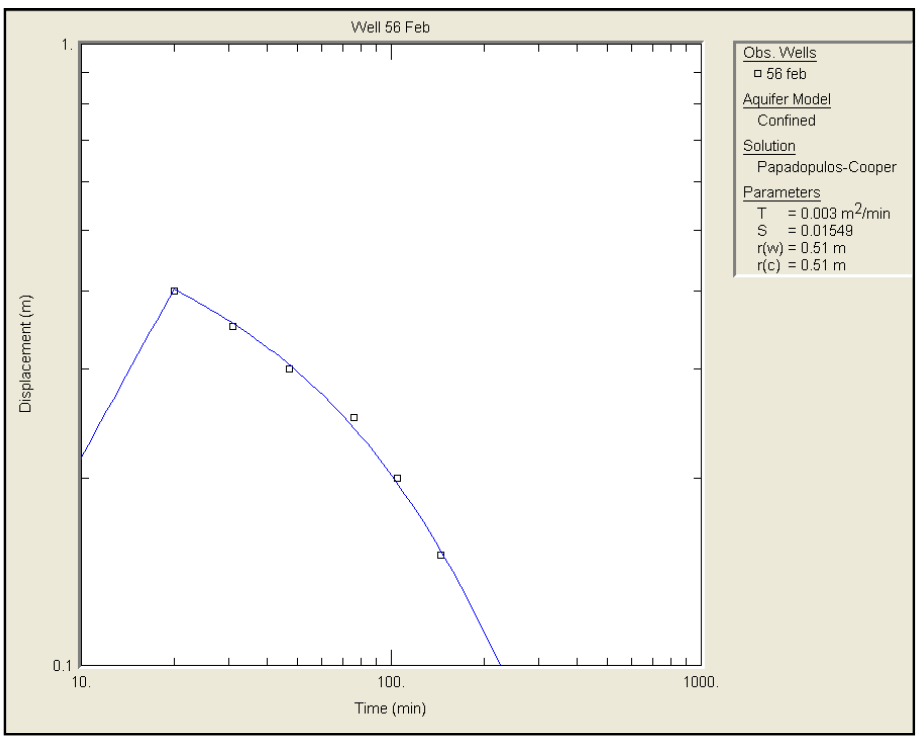


Figure G.6 Well 56, 2/20/2008 (image exported from AQTESOLVE)

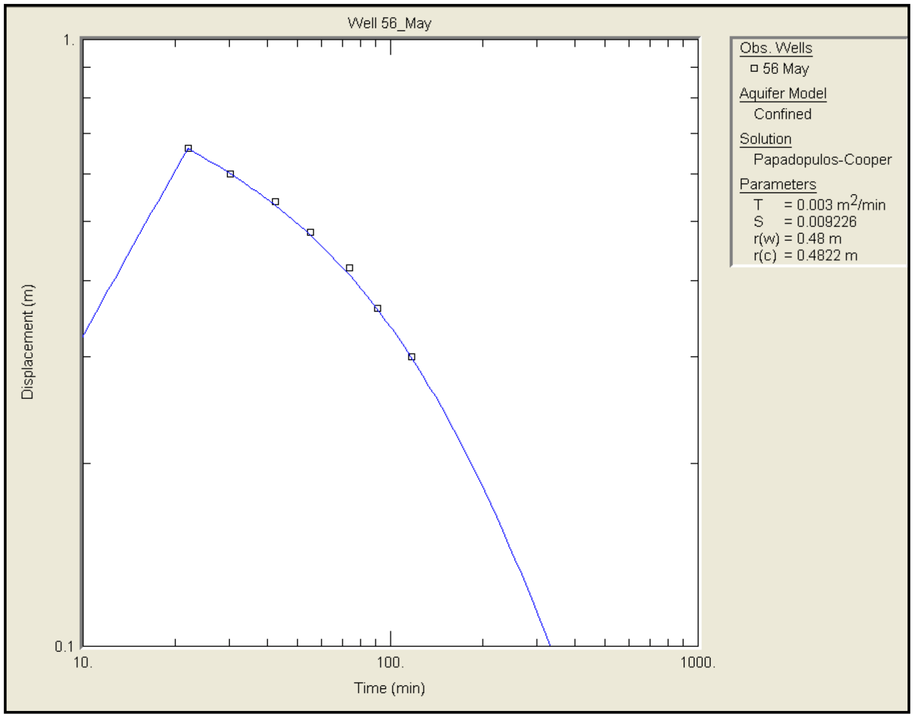


Figure G.7 Well 56, 5/13/2008 (image exported from AQTESOLVE)

Well 40

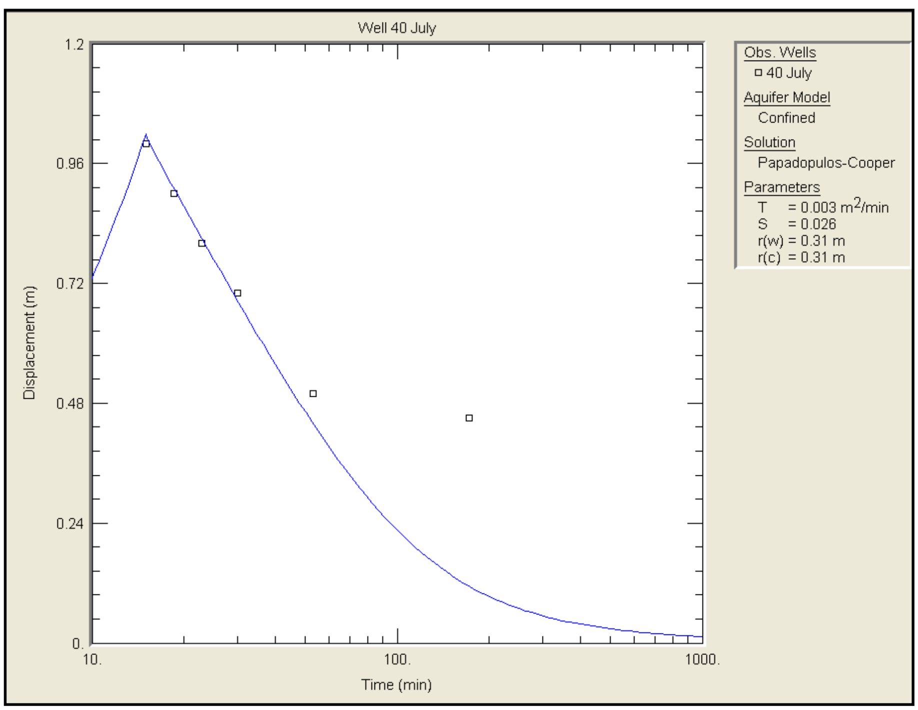


Figure G.8 Well 40, 7/29/2008 (image exported from AQTESOLVE)

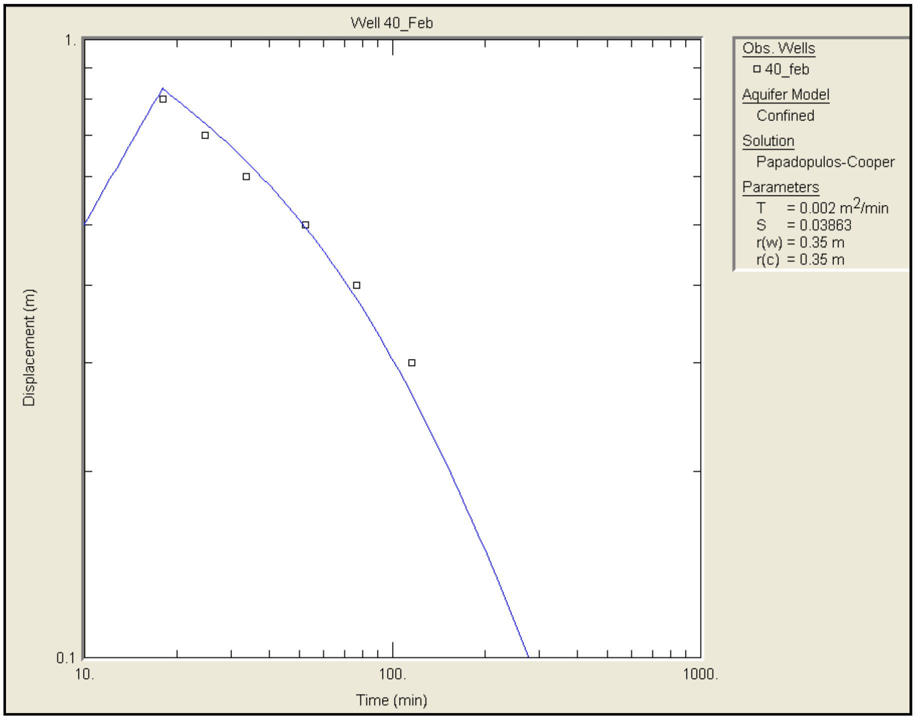


Figure G.9 Well 40, 2/23/2008 (image exported from AQTESOLVE)

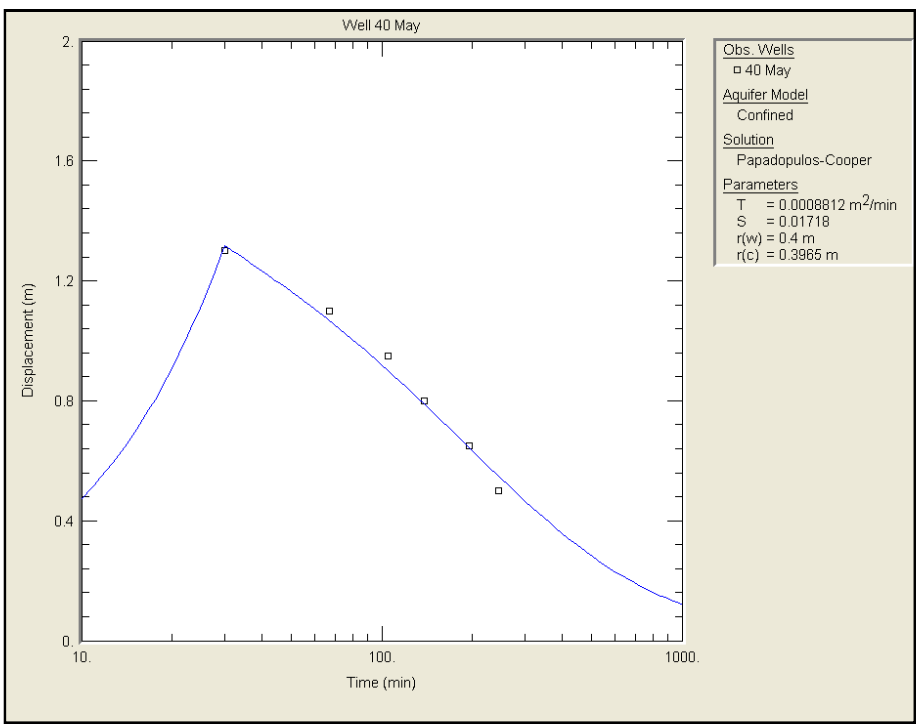


Figure G.10 Well 40, 5/12/2008 (image exported from AQTESOLVE)

H. OBSERVED, SEASONAL GROUNDWATER LEVELS IN HAND-DUG WELLS

Table H.1 Seasonally measured GWT depths from surface

Well	Date	Rainy Season depth to GWT (m)	Date	Cold Dry Season depth to GWT (m)	Date	Hot Dry Season depth to GWT (m)
14	8/2/2008	4.39	2/24/2008	8.15	5/19/2008	9.7
31	8/1/2008	6.17	2/21/2008	8	5/17/2008	9.8
56	7/31/2008	5.75	2/20/2008	7.2	5/13/2008	9.6
40	7/29/2008	6.1	2/23/2008	8.6	5/12/2008	10
W03	7/29/2008	1.23	-	-	-	-
W01	7/29/2008	1.31	-	-	-	-

I. IMAGE PUBLICATION PERMISSION

Figure 2.1 "Increased global water stress"

Source: UNEP/GRID-Arendal (2009)

Original image name: **Increased global water stress**

Email communication: Wednesday, May 06, 2009 2:42:04 AM

RE: Maps feedback: About a specific page

From: Janet.F.Skaalvik@grida.no (Head of Communication UNEP/GRID-Arendal)

To: cwshonse@mtu.edu (author)

Dear Cara

Thank you for your interest in the graphic. Permission to use it in your thesis project is granted provided credit is given to UNEP/GRID-Arendal as the source of the graphic. We also want you give full credit to the cartographer/designer and data sources for the graphics, as well as include the link to our website.

Figure 3.1 "Map of Mali, West Africa"

Source : Map Library (2009)

Original File Name: Mal_outline_SHP.zip

Excerpt from website maplibrary.org - "The Map Library is a source of public domain basic map data concerning administrative boundaries in developing countries. The data is broken down into manageable chunks to make it easier to download for those with poor internet connections."

J. HUMAN SUBJECT RESEARCH APPROVAL: MICHIAGAN TECHNOLOGICAL UNIVERSITY