ABSTRACT

WATER QUALITY AND PHYSICAL HYDROGEOLOGY OF THE AMARAPURA TOWNSHIP, MANDALAY, MYANMAR

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Mandalay is a major city in central Myanmar with a high urban population that lacks a wastewater management system, a solid waste disposal process, and access to treated drinking water. The purpose of this study is to investigate the groundwater quality of local dug and tube wells, determine quantitative data on characteristics of the Amarapura Aquifer, and compare seasonal variations in groundwater flow and quality. Major ion chemistry data was collected during the dry and wet seasons, and analyzed using ion chromatography to identify indicators of wastewater contamination to the shallow aquifer and compare seasonal variations in groundwater chemistry. An open-source analytical element model, GFLOW, was used to describe the physical hydrogeology and to determine groundwater flow characteristics in the aquifer. Hydrogeochemistry data and numerical groundwater flow models provide evidence that the Amarapura Aquifer is susceptible to contamination from anthropogenic sources. The dominant water types in most dug and tube wells is Na-Cl, but there is no known geologic source of NaCl near Mandalay. Many of these wells also contain water with high electrical conductivity, chlorides, nitrates, ammonium, and *E. coli*. Physical measurements and GFLOW characterize groundwater flow directions predominantly towards the Irrawaddy River and with quick average linear velocities (v_x) ranging from 1.76×10^{-2} m/day (2.04×10^{-7} m/s) to 9.25 m/day (1.07×10^{-4} m/s). This is the first hydrogeological characterization conducted in Myanmar.

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WATER QUALITY AND PHYSICAL HYDROGEOLOGY OF THE AMARAPURA TOWNSHIP, MANDALAY, MYANMAR

BY

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CHAPTER 1: INTRODUCTION

Myanmar, formerly known as Burma, was a military state closed to the Western world for over 50 years, until 2011 when a new government was established. Myanmar is considered to be the third most isolated country in the world (only behind North Korea and the Solomon Islands), which has caused a lack of access to basic information and a clear understanding of hydrogeology (Anatomy, 2013). To the best of our knowledge, there was not a known hydrogeologist in the entire country of Myanmar as of 2016. The lack of knowledge of hydrogeology has caused urban centers such as Mandalay to have poor water management policies that can result in contamination of their shallow aquifers. Many local inhabitants use these shallow aquifers as their source of water for cooking, cleaning, and drinking. Many organizations such as the United Nations Development Programme (UNDP), the Asian Development Bank (ADB), and the Myanmar Water Resource Utilization Department (MWRUD) have identified wastewater as the key water quality problem in urban cities in Myanmar (ADB, 2013; Moe, 2013, United Nations Development Programme, 2014).

Mandalay is a major city in central Myanmar with a population of 1,225,000 people that lack a wastewater management system, a solid waste disposal process, and access to treated drinking water. Myanmar only treats about 10% of its wastewater, and there is effectively no treatment in the city of Mandalay (United Nations World Water Assessment Programme, 2017). The United Nations Development Programme reported drinking water quality and access to drinking water as one of the serious problems in Mandalay State (UNDP, 2014). The Asian

Development Bank reports that there is a water point for every 80 households in Mandalay and that most of these are untreated, private supplies (ADB, 2013). Only 50% of the urban population has access to piped water in Mandalay, which consists of a mixture of untreated groundwater and surface waters (ADB, 2013). The Myanmar Water Resource Utilization Department reports that 68% of domestic water usage is from groundwater in Mandalay (Moe, 2013).

The Amarapura Township is an urban area on the south side of Mandalay surrounding Taung Tha Man Lake (TTML). No one in the Amarapura Township has access to piped water, so the people depend on tube wells, dug wells, or purchased purified bottled water (ADB, 2013). The majority of these wells are within 1-50 meters of untreated wastewater canals that are in direct contact with the ground surface. It is important to investigate the physical and chemical properties of this groundwater system to identify indicators of wastewater contamination that pose a potential risk to the groundwater supply in the Amarapura Township.

In developing areas, such as the Amarapura Township, costs of software and licenses are major limiting factors when conducting this type of research. Programs such as Quantum Geographic Information System (2016) and GFLOW (Haitjema, 2016) were used because they are open-source programs that are easy to obtain in developing countries such as Myanmar. QGIS provides the ability to project data spatially and GFLOW is used to assess groundwater flow throughout the study area. Digital elevation models (DEM) were chosen because of limitations on being able to conduct survey work with the proper equipment and in the time period allocated for the project. A workshop was conducted by Northern Illinois University at

Yadanabon University in December of 2016 for professors in Myanmar to teach the basics of hydrogeology and practice using this software.

The objectives of this first research study in Myanmar are to have a preliminary understanding of the physical and chemical hydrogeology of the Amarapura Township in Mandalay, Myanmar. This study 1) identifies drinking water contaminants and assesses water quality between dug wells, tube wells, and surface waters; 2) compares and identifies seasonal variations in groundwater flow and quality and yields quantitative data on the hydrogeologic properties of the Amarapura Aquifer using an analytical element model; and 3) uses open-source software programs that assist in educating the locals on issues in their region as they develop in the future.

CHAPTER 2: STUDY AREA AND GEOLOGY

Mandalay is in central Myanmar on the west side of Southeast Asia (Figure 1). Mandalay is the second largest city in Myanmar, containing about 1,225,000 people and a land area of approximately 160 square kilometers (UNDP, 2014). The city is about 70-80 meters above mean sea level (mamsl) in a flood plain for the Irrawaddy River between the Shan Plateau and the Sagaing Mountains (Figure 1). The Irrawaddy River starts in the Himalayas, running north to south and cuts west on the south side of Mandalay. The Irrawaddy River is approximately 2,100 kilometers long, and its drainage basin is about 414,400 square kilometers (Kravtsova et al., 2008). Between Mandalay and Sagaing the river depth ranges between 9 and 15 meters, its width between 1,800 and 3,400 meters, and its flow rate between 2,000-17,000 m^3/s (Kravtsova et al., 2008).

The Amarapura Township contains about 235,000 people and is located on the south side of Mandalay and is known locally for its textiles industry (UNDP, 2014). Taung Tha Man Lake (TTML) is an oxbow lake in the middle of the Amarapura Township on the south side of Mandalay (Kyi, 2005; Figure 1). Smaller streams from the Shan Plateau flow into TTML, and the Me-O Chaung is the outlet stream connecting TTML with the Irrawaddy River. The Myitnge River starts in the Shan Plateau, running east to west on the south side of the Amarapura Township. The Shwe-Ta-Chaung canal runs from Mandalay through the Amarapura region between TTML and the Irrawaddy River (Figure 1). The Shwe-Ta-Chaung canal is one of the larger discharges of wastewater from the city of Mandalay into the Irrawaddy River.

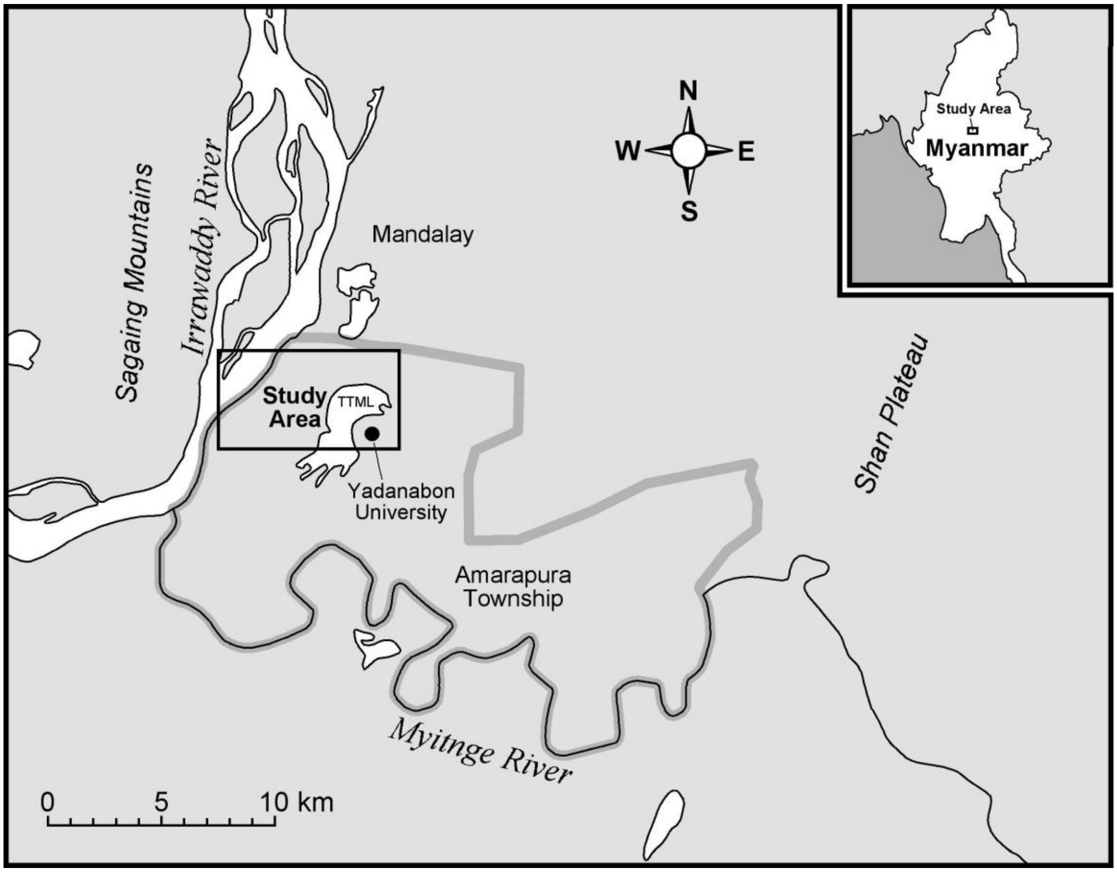


Figure 1. Map of Mandalay and the Amarapura Township (Myanmar pictured in the top right).

Climate

Mandalay experiences monsoon rains and is considered to be a tropical savannah, averaging 1,161 millimeters of rain annually, with the majority (91%) of this coming during the wet season (Harris et al., 2014). Mandalay observes three seasons: a wet season (May-October), a dry season (October-May), and a cold season (October-February). Temperatures throughout the year range from 13°-39°C with an average between 20°-30°C. The wet season averages temperatures between 27°-32°C, the dry season averages temperatures between 23°-31°C, and the cold season averages temperatures between 20°-25°C. A summary of average precipitation and temperature data from 1901-2014 is presented in Figure 2. Mandalay is subject to flooding during the wet season because of the intensity of the rain, its location in the Irrawaddy River flood plain, and higher rainfall rates in areas leading into Mandalay (Myitnge River/Irrawaddy River; Harris et al., 2014). Temperature and precipitation event data from the duration of the study is presented in Appendix A.

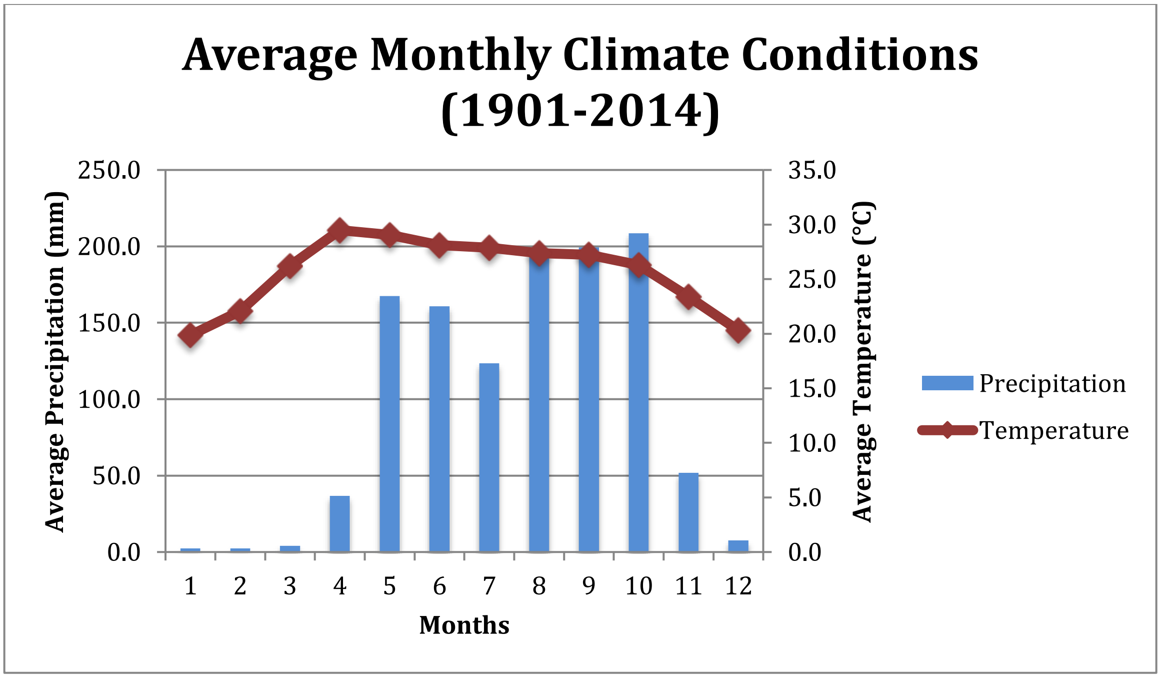


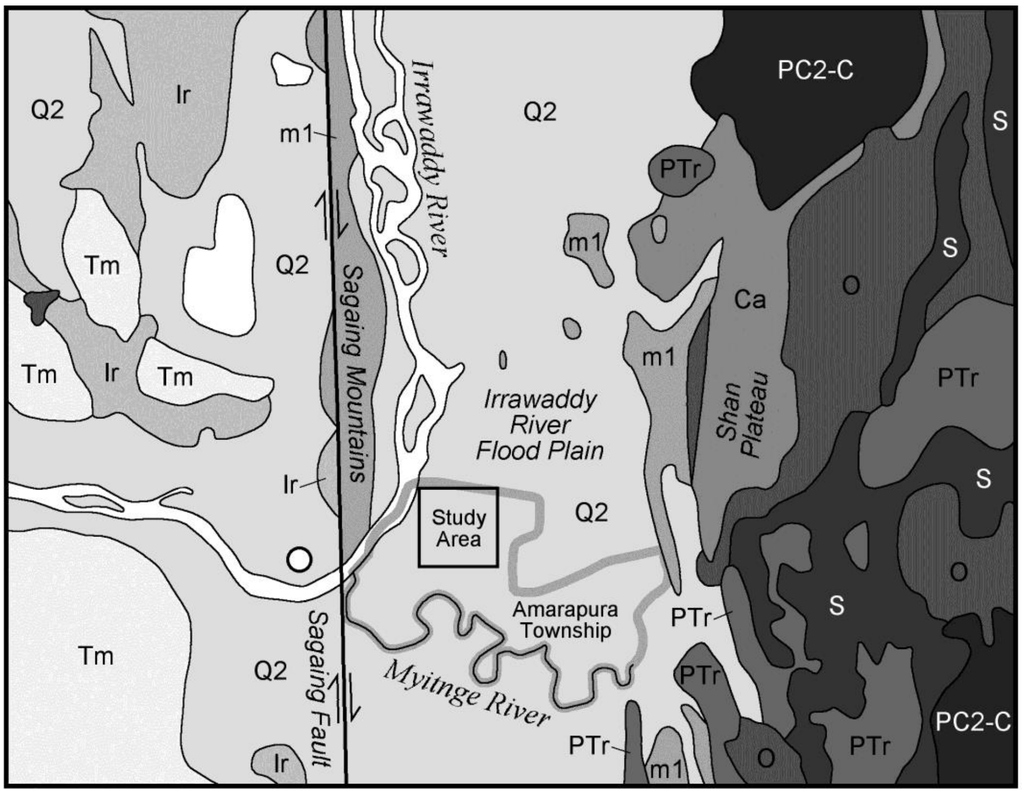
Figure 2. Average monthly climate conditions- Mandalay, Myanmar (Harris et al., 2014).

Geology and Hydrogeology

Mandalay is in an alluvial setting (Holocene Age) containing predominantly sands and gravels in a shallow aquifer, called the Amarapura Aquifer, from which most locals obtain their groundwater for cooking, cleaning, and drinking (Htay et al., 2014; Moe, 2013). The Irrawaddy River is the major hydrologic feature in the area and its watershed extends into the Himalayas. The Sagaing fault is an active strike-slip fault cutting north to south across the entire country and is located on the west side of the Irrawaddy River near Mandalay (Htay et al., 2014; Figure 3). The Shan Plateau is made of limestone formations containing predominantly calcite ($CaCO_3$), with other mineral deposits including magnesite ($MgCO_3$), barite ($BaSO_4$), and various gemstones (Myanmar Ministry of Mines, Ministry of Education, Ministry of Industry, 2017).

A local report written by Win Win Kyi, a geology professor at Yadanabon University (located in Mandalay), suggests that Taung Tha Man Lake (TTML) is an oxbow lake formed by either the braided Irrawaddy River or the meandering Myitnge River, which contains channel and bar deposits. Thin layers of flood plain deposits from the Irrawaddy River are also deposited in this region during periods when the Irrawaddy overcomes its current bank. During these flood periods TTML serves as a back swamp to the Irrawaddy River (Kyi, 2005).

No data on the hydrogeology of the city of Mandalay currently exists, and only one other peer-reviewed study has been conducted in Myanmar on the local hydrogeology. This was an inorganic chemistry study of groundwater quality in the Myingyan Township in Mandalay State (Bacquart et al., 2015). In this study, local groundwater samples were collected from tube wells, indicating unsafe levels of arsenic, manganese, fluoride, iron, and uranium. Other reports from the International Water Management Institute have collected basic hydrogeologic data in a region called the “Dry Zone” of Myanmar for improved water resource management practices related to local agriculture strategies (Pavelic et al., 2015). This region includes Mandalay State but has focused on rural areas outside of the city of Mandalay.



Q2	Holocene	Ca	Upper Cambrian	PTr	Middle Permian - Middle Triassic
Ir	Upper Miocene-Pliocene	O	Ordovician	PC2-C	Upper Precambrian - Lower Cambrian
m1	Paleozoic, Partly Jurassic	S	Silurian	Tm	Miocene

Figure 3. Geologic map of Mandalay (full geologic map of Myanmar in Appendix B).

CHAPTER 3: METHODOLOGY

Research was conducted during the wet and dry seasons in Mandalay, Myanmar. Wet-season sampling was conducted from July 20^{th}-August 12^{th}, 2016. Dry-season sampling was conducted from December 10^{th}-21^{st}, 2016. During the wet season the following activities were conducted: a field survey of groundwater wells in the Amarapura Township, drilling for grain size analysis, hydraulic conductivity measurements, water level measurements, groundwater modeling, geochemistry, *E. coli* testing, and stable isotope collection to determine δ^2H and $\delta^{18}O$ (Table 1). Geographical coordinates for tube wells, dug wells, surface-water sampling points, and other points of interest were taken using the built-in GPS of an iPhone 7. During the dry season, the following activities were conducted: water level measurements, slug tests (Tube wells YDB1, YDB2, and YDB3), water quality sampling, and *E. coli* testing (Table 1). Geographical coordinates for tube wells, dug wells, surface-water sampling sites, and points of interest were taken using a hand-held Garmin GPSmap 62st system (Olathe, Kansas; Figure 4). Pressure transducers were installed for long-term monitoring from July 25^{th} till December 13^{th} for YDB1 and YDB2.

Table 1. Activities Conducted in Each Sampling Season

Wet Season	**Dry Season**
• Field Survey • Water Level Measurements • Slug Tests (YDB1 & YDB2) • Water Quality Sampling • *E. coli* sampling • Stable Isotope collection • Geographical Coordinates (iPhone 7)	• Water Level Measurements • Slug Tests (YDB1, YDB2, & YDB3) • Water Quality Sampling • *E. coli* sampling • Geographical Coordinates (Garmin GPSmap 62st map)

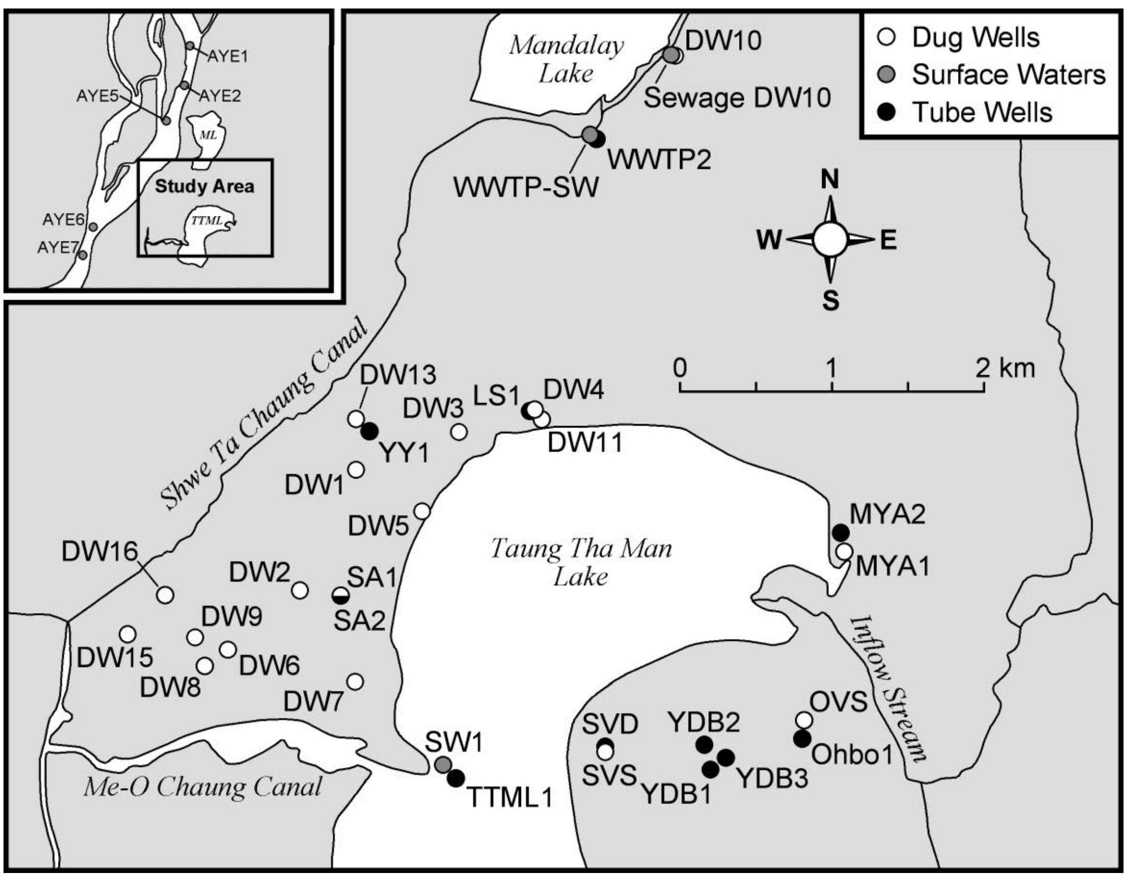


Figure 4. Mandalay- Study site sampling locations (Amarapura Township).

Field Survey

In July and August 2016, a preliminary field survey was conducted in the Amarapura Township by documenting the types of wells that were accessible, observing potential pollution sources around each well. A downhole video camera was used to observe well construction in both dug and tube wells. Residents provided information on wells to determine their use and gather additional information on potential seasonal variations of accessibility to water and taste.

Geographical coordinates were taken using a hand-held Garmin GPSmap 62st (Olathe, Kansas) for tube wells, dug wells, and surface-water boundaries. These locations were plotted using QGIS. Digital aerial maps from Google maps ® determined the extent of incoming and outgoing streams and identified boundaries of other surface water bodies. Digital elevation models were obtained from the Shuttle Radar Topography Mission (SRTM) and were used to determine elevations (mamsl) at each sampling site.

Water Quality

During the dry and wet seasons, water from 13 dug wells, eight tube wells, and two surface-water sources were collected from TTML and the Irrawaddy River. Shwe-Ta-Chaung sewage canal was only sampled during the dry season (Figure 4). These were tested for physico-chemical parameters, major ion chemistry, selected metals, and *E. coli*. Isotope samples were collected from three rain events, three surface waters, and 20 groundwater wells during the wet season. These were transported back to NIU and shipped to the University of Wyoming Stable Isotope Laboratory in a cooler for $\delta^{2}H$ and $\delta^{18}O$ testing.

Geochemistry

All samples from tube wells, dug wells, and surface waters were collected in local plastic water bottles that were rinsed three times with water from the well sampled before filling. A HACH HQ 40d multi-probe (Loveland, Colorado) was used to take physico-chemical measurements including temperature, pH, reduction-oxidation potential (Eh), conductivity, and dissolved oxygen (DO) at each sampling site. Industrial Test Systems eXact Micro 20 photometers (Rock Hill, South Carolina) and test strips were used in initial screening of these water samples. All samples were tested for turbidity, calcium as calcium carbonate (Ca as $CaCO_3$), sulfate (SO_4^{2-}), chloride (Cl as NaCl), total chlorine (Cl^-), free chlorine (Cl^-), total alkalinity, total hardness, cyanide (CN^-), phosphate (PO_4^{3-}), nitrite (NO_2^-), nitrate (NO_3^-), sulphide (S^{2-}), fluoride (F^-), copper (Cu^{2+}), bromine (Br^-), aluminum (Al^{3+}), manganese (Mn^{2+}), ammonia (NH_3), and total iron (Fe). A HACH test kit (Loveland, Colorado) was used to determine arsenic (As) levels during initial screening. Alkalinity measurements were used to calculate carbonate and bicarbonate (Masters and Ela, 2008). Initial magnesium values were calculated by subtracting calcium as calcium carbonate from the total hardness. Laboratory analysis was conducted to obtain further results with the Dionex Aquion ion chromatograph (Waltham, Massachusetts) and from the University of Wyoming Stable Isotope Laboratory.

Major Ion Chemistry

Samples for analysis at Northern Illinois University were collected in sterile 50 mL centrifuge tubes. Each was filtered (0.2 μm) for major ion chemistry analysis. Major ion chemistry was performed by the Dionex Aquion ion chromatograph (IC; Waltham, Massachusetts) for all dug wells, tube wells, and surface-water samples. An injection volume of

25 μL and a five-point calibration curve were used in quantifying the results. Analysis was conducted to determine major cations including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), ammonium (NH_4^+), and lithium (Li^+). During major cation analysis a CS12A 4x250 mm column, a CERS 500 4 mm suppressor, and a 20 mM eluent of MSA were used. A 1 mL/minute flow rate and <60 mA current were established at room temperature during analysis. Analysis was conducted to determine major anions including fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}). During anion analysis a AS22 4x250 mm column, a AERS 500 4 mm suppressor, and a 4.5 mM sodium carbonate/1.4mM sodium bicarbonate eluent were used. A 3 mL/minute flow rate and <100 mA current were established at room temperature during analysis for anions.

Wastewater Indicators

Key indicators in major ion chemistry that may indicate contamination from wastewater in the subsurface are increased electrical conductivity (EC), total dissolved solids (TDS), chlorides (Cl), nitrates (NO_3^{2-}), ammonium (NH_4^+), and *E. coli* (Bajjali et al., 2015; Fetter, 1999; Hassane et al., 2016; Lawrence et al., 2000; Lee et al., 2010; Nagarajan et al., 2010; Nas and Berktay, 2010). Chlorides in natural waters are typically below 100 ppm and nitrates below 10 ppm (Fetter, 1999). The presence of ammonium and *E. coli* are also often contributed from domestic wastewaters (Fetter, 1999; World Health Organization, 2008). Concentrations higher than these may indicate contamination from industrial discharges and/or sewage. These indicators have been used to show wastewater contamination of groundwater in other cities in Asia with similar wastewater problems, such as Hat Yai, Thailand, and Shanghai, China, where increases in many of these parameters were observed in groundwater wells towards the city center in close proximity to wastewater canals (Lawrence et al., 2000; Weng et al., 2006). Chlorine-bromine ratios above 150 have also been shown to indicate wastewater contamination in areas without seawater intrusion (Vengosh and Pankratov, 1998).

Testing for *E. coli* was conducted using Aquagenx Compartment Bag Test (CBT) kits (Chapel Hill, North Carolina). This method was chosen because it did not require incubators or electricity. Water samples were collected from each sampling site in a sterile 100 mL Whirl-Pak bag ®. A chromogenic medium was added to the Whirl-Pak bag and allowed to dissolve for 15 minutes, before the water was transferred into a five-column Whirl-Pak bag. This bag separated the water into 5 mL, 10 mL, 15 mL, 20 mL, and 25 mL columns. This was allowed to sit for 24-48 hours depending on temperature. Each column would either change to a green color if positive or remain yellow if negative. A reference chart from Aquagenx was used to compare combinations to determine the most probable number (MPN) of *E. coli* per 100 mL (Stauber et al., 2014).

Stable Isotopes

Stable isotope samples were collected using 2.0 mL National Scientific Amber Glass I-D Target DP vials with septa caps. Vials were filled with no headspace. Rainfall samples were collected from three events during the wet season. Groundwater-well, surface-water, and rain-event samples were analyzed for $\delta^{2}H$ and $\delta^{18}O$ ratios using the Picarro L2130-I Cavity Ring Down Spectrometer (CRDS) by the University of Wyoming Stable Isotope Laboratory. Results were plotted on and compared to the Global Meteoric Water Line (GMWL) line. These were then used to compare sampling sites and to determine whether water was rain derived or from other sources.

Physical Hydrogeology

During the dry and wet seasons, 18 wells were examined (Figure 4). These included 15 dug wells and three tube wells in the Amarapura Township (Table 2). Drilling was conducted at Yadanabon University to install YDB3 and to determine grain sizes. Hydraulic conductivities were determined in the three tube wells that were accessible (YDB1, YDB2, YDB3). Water level measurements were taken with a Heron Instruments 150-foot water level meter tape (Dundas, Ontario, Canada), two or three times in all dug wells and three tube wells during both field seasons. A numerical horizontal groundwater flow model, GFLOW, was used as a screening model to test the conceptual model and to determine groundwater flow velocities (Haitjema, 2016).

Drilling

Drilling for YDB3 (tube well) was done on the campus of Yadanabon University as part of a workshop. Drilling observations provided information on local tube well construction. These observations were key in analyzing and comparing chemical and physical data between seasons. Grain size analysis was important information in understanding and confirming assumptions made about the Amarapura Aquifer.

Table 2. Physical Hydrogeology Sampling Wells

Name	Sample Type	Latitude	Longitude	Elev. (m)	Total Depth (m)	Diameter (cm)
YDB1	Tube Well	21.8919	96.0699	70	22.37	5.08
YDB2	Tube Well	21.8932	96.0696	71	24.84	5.08
YDB3	Tube Well	21.8925	96.0708	70	7.93	4.90
SVS	Dug Well	21.8929	96.0639	79	6.45	109.22
OVS	Dug Well	21.8945	96.0752	79	7.64	100.89
SA1	Dug Well	21.9009	96.0490	80	13.32	121.92
DW1	Dug Well	21.9075	96.0499	79	11.99	150.57
DW2	Dug Well	21.9012	96.0466	80	14.84	11.35
DW3	Dug Well	21.9096	96.0556	78	8.53	114.91
DW4	Dug Well	21.9107	96.0599	77	7.26	143.87
DW5	Dug Well	21.9054	96.0536	73	8.93	143.26
DW6	Dug Well	21.8981	96.0426	80	14.59	125.88
DW7	Dug Well	21.8964	96.0499	80	10.26	219.46
DW8	Dug Well	21.8972	96.0413	81	14.67	122.83
DW9	Dug Well	21.8987	96.0407	76	11.72	128.63
DW10	Dug Well	21.9294	96.0678	74	7.74	198.12
DW11	Dug Well	21.9102	96.0603	73	9.02	127.10
DW13	Dug Well	21.9102	96.0499	76	10.55	150.88

Grain Size Analysis

Grain size analysis was conducted for sediments collected from the drilling of YDB3. An attempt was made to identify a sediment core every foot, but the cores were sporadic and it was not always feasible to collect every foot. The samples were placed in Whirl-Pak bags and shipped to the United States for analysis. Dry-sieve grain size analysis was performed at Northern Illinois University to determine the percentage of sand, silt, and clay in each section. Five USA ASTM-standard testing sieves were used: gravel (≥1.41 mm), course sand (0.35-1.41 mm), medium sand (0.125-0.35 mm), fine sand (0.062-0.125 mm), and silts/clays (<0.062 mm) were caught in a pan at the bottom. Porosities were estimated from Fetter (2001) using the percentages of grain size determined in the sieve grain size analysis. Hydraulic conductivities were estimated using Hazen's approximation (West, 1995). Appendix C contains the YDB3 core log.

Hydraulic Conductivity Measurements (K)

Hydraulic conductivities were determined by conducting falling and rising head slug tests in two tube wells (YDB1 & YDB2) in the Amarapura Aquifer during the wet season and three tube wells (YDB1, YDB2 & YDB3) during the dry season. Heads were measured every second during the slug test with an In-Situ, Inc. Rugged Troll 100 pressure transducer (Fort Collins, Colorado). Hydraulic conductivities in YDB1 and YDB2 were evaluated using a high hydraulic conductivity method developed by the Kansas Geological Survey because of the oscillatory behavior observed of the water level in the well during the slug test caused by the formation being highly permeable, which violated common assumptions used in the Hvorslev method (Butler et al., 2003). The Hvorslov method was used to determine hydraulic conductivity in YDB3 because it did not exhibit oscillatory behavior in the water levels during the slug test nor violate other assumptions in the Hvorslov method (Fetter, 2001).

Groundwater Level Measurements

Depth to groundwater from the top of casing was measured using a Heron Instruments 150-foot water level meter tape accurate to 0.01 decimal feet in all dug wells, as well as tube wells YDB1, YDB2, and YDB3. Depth to water, stickup, and total depth were measured in all wells (Appendix D). All other tube wells were in use and total depths provided by their owners. An In-Situ, Inc. Rugged Troll 100 (Fort Collins, Colorado) and Solinst Levelogger 3001 (Georgetown, Ontario, Canada) pressure transducers were installed in YDB1 and YDB2 to conduct long-term monitoring of water levels from July through December 2016.

Groundwater Modeling

GFLOW is a 2D numerical code based on the analytical element method using line elements and the Poisson equation as the governing equation (Haitjema, 2016). Line elements represent hydrologic features, such as stream and lake boundaries. GFLOW was used to simulate steady-state groundwater flow based on head measurements taken during the dry and wet seasons in order to examine groundwater flow during these two time periods. These regional groundwater flow models were then used to test the validity of the conceptual model, simulate seasonal groundwater flow, map the location of groundwater divides, and determine average linear groundwater flow velocities (v_x) across the site.

A conceptual model was created based on local hydrologic features, preliminary water level measurements, electrical conductivity measurements, and initial hydraulic conductivities. The initial parameters for the model were 67 m/day for hydraulic conductivity (K) and 0.301 m/day for recharge (R). Hydraulic conductivity was measured on site and recharge was estimated using precipitation data from the CRU (Harris et al., 2014). Data from the International Water Resource Institute's hydrogeologic study in the dry zone of Myanmar estimated infiltration rates at 10% of annual rainfall (Pavelic et al., 2015). In the unconfined Amarapura Aquifer, connected with the Irrawaddy River, infiltration is assumed to equal recharge. Therefore, recharge was estimated as a percentage of precipitation (10%). Average linear groundwater flow velocities were calculated in each hydraulic conductivity zone from modeled data using the average linear velocity equation (equation 4.24 from Fetter, 2001).

Groundwater and surface-water heads were calculated from field data and elevations provided by the digital elevation model. Latitude and longitude at each sampling site were taken using a Garmin GPSmap 62st hand-held instrument. These were then plotted on the Quantum Geographical Information Systems (QGIS) program using an open-source plug in map from Google (www.qgis.org, 2016). Digital elevation models were downloaded for the country of Myanmar from the 2000 Shuttle Radar Topography Mission (SRTM) at a resolution of three arc seconds (2016). These shaded relief maps were then interpolated into one-meter contour maps on QGIS (www.qgis.org, 2016). Elevations from these contours were used to determine elevations of the top of casings. Water levels were measured from the top of casings and used to obtain the heads for all dug and tube wells. Elevations from these maps were used to identify elevations at surface water boundaries, which were used as head measurements for line sinks in GFLOW.

The groundwater flow model was calibrated using the head measurements from both the tube and dug wells during the dry season because the dry-season head measurements represented groundwater flow at a more steady state than in the wet season. Initial calibration was done manually by sensitivity analysis, and once approximate values were obtained, the PEST (Haitjema, 2016) module was used. Sensitivity analysis was used to determine the hydraulic conductivity zones and estimate effective porosity (n_e) for the site by determining the values that provided a better calibration. PEST is an automated parameter estimation algorithm that determines ideal values for parameters such as hydraulic conductivity (K) and recharge (R). Once calibrated, average linear velocities (v_x) were calculated in each hydraulic conductivity zone.

Both the initial parameters as well as those determined through sensitivity analysis and PEST are presented in the results section. Recharge, hydraulic conductivity, and average linear velocities values from the model were then compared with measured values from the field to further validate the model. These idealized parameters from the dry season model were then used in the wet season model to compare differences in groundwater flow between seasons. Only heads and surface-water boundaries were changed in the wet season model. Groundwater flow models are presented in a 2D aerial view showing potentiometric surface of groundwater levels across the study site.

CHAPTER 4: RESULTS

Field Survey

The city of Mandalay has access to piped water, but many people in the outlying areas rely on old dug and tube wells for access to water resources, thus the population in the Amarapura Township obtain their water supply from groundwater by access to dug and tube wells. Dug wells are about a meter in width and range from 7-15 meters deep in mixed medium-coarse sand and gravel layers (Figure 5). The dug wells are lined with brick and contain concrete pads at the top, but these pads do not always direct water away from the well. The dug wells are community wells that are shared between sections of each community. The number of people that use these on a daily basis is unknown but is estimated to be from 50-100 people per well (ADB, 2013). Most often, the locals use a small bucket to extract water from the well, but a few contain pumps to bring water to the top. Dug wells are primarily used for cooking, cleaning, and bathing. These activities occur directly next to the well and the buckets are not sanitary. Buckets were usually made of excess rubber from tires or steel. From conversations with well owners, most people report their water tastes salty. They also claimed that many of these dug wells go dry during March and April (at the end of the dry season).

Many people have access to tube wells, which are shared among individual families or for private business purposes, such as the textile industry. The tube wells range from 15-60 meters deep and are usually installed by local drillers using a primitive drilling method. Often these wells were installed next to an old dug well (Table 3). Most tube wells had hand pumps, but a few had compressors. Many of the owners who used hand pumps reported they could not access water during the months of March and April due to low groundwater levels.

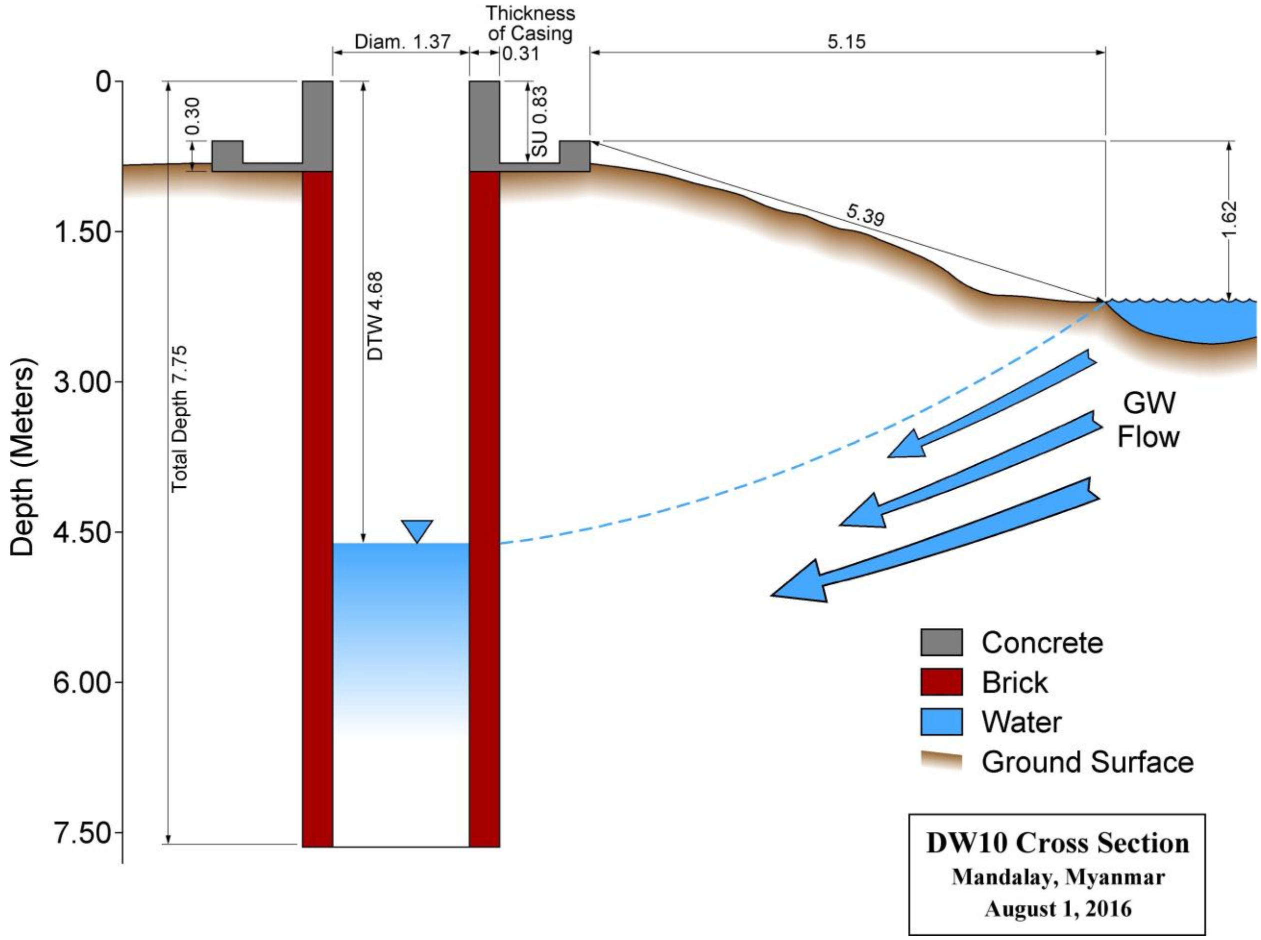


Figure 5. Dug well construction diagram (DW10 adjacent to Shwe-Ta-Chaung canal).

Table 3. Dug and Tube Wells Adjacent to Each Other

Dug Wells	**Tube Wells**
DW4	LS1
SA1	SA2
SVS	SVD
OVS	Ohbo1
MYA1	MYA2
DW13	YY1

Potential sources of groundwater contamination include unlined wastewater streams that run beside many of these wells and solid waste in the Amarapura Township. Large volumes of domestic and industrial wastewater from the city of Mandalay flows through the unlined Shwe-Ta-Chaung canal, which stretches north to south through the Amarapura Township between TTML and the Irrawaddy River (Figure 4). Subsidiary canals connect with it at various intersects. A wastewater treatment plant is in the Shwe-Ta-Chaung canal between Mandalay and Amarapura but has not been operational the majority of the time. However, in December 2016 a basic sprinkler oxidation system appeared to be operational. Metal grates cross the stream to collect solid waste, but this is often overflown by rising water levels during the wet season. The disposal process is unknown but is suspected to be collected and piled in local landfills. Local landfills are open pits, which are unlined and uncovered.

Water Quality

Geochemistry

Results indicate that chlorides, nitrates, ammonium, total dissolved solids, electrical conductivities, and *E. coli* are key indicators of wastewater contamination to the Amarapura Aquifer (Tables 4, 5 and 6). Chlorine-bromine ratios were compared for similar signals from other studies indicating anthropogenic contamination from wastewater sources (Table 5; Vengosh and Pankratov, 1998). Full water quality data is presented in Appendices E, F, G, and H.

Table 4. Comparison of Wells Exceeding Background Levels of Potential Wastewater Indicators

Parameter	Units	Background Levels		Wells exceeding background levels (%)			
		Dry	Wet	Dry		Wet	
				Dug	Tube	Dug	Tube
Electrical Conductivity	µS/cm	713.5	502.3	81	44	82	63
Total Dissolved Solids	ppm	209.4	174.68	81	44	82	63

Table 5. Comparison of Wells Exceeding Wastewater Indicator Levels

Parameter	Units	Wastewater Indicator Level	Wells exceeding wastewater indicator levels (%)	
			Dry	Wet
Chloride	ppm	100	39	39
Nitrate as N	ppm	10	61	56
Ammonium	ppm	>0	17	44
Cl/Br Ratio	Unitless	150	67	56

Table 6. Percentage of Wells Exceeding WHO Drinking Water Standard for *E. coli*

Parameter	Units	WHO Drinking Water Standard	Dug Wells		Tube Wells	
			Dry	Wet	Dry	Wet
E. coli	MPN/100 mL	<1	86	100	11	33

Major Ion Chemistry

Piper diagrams are used to classify water types (Figures 6 and 7). Major ion chemistry revealed the water types in this system to be predominantly Na-Cl. The predominant water type in dug wells, tube wells, and TTML in both seasons were Na-Cl type. Secondary water types such as Ca-Cl, Ca-HCO_3, Na-SO_4, and Na-HCO_3 were also present in the Amarapura Township. Only a few wells had different water types between seasons and were all on the east or north side of TTML (YDB1, SVD, and DW4). The Irrawaddy River water type is Ca-SO_4 on the north side of Mandalay, but changes to Ca-HCO_3 south of the city.

Piper diagrams (Figures 6 and 7) are used to compare proportions of key geochemical parameters in the major ion chemistry used to determine water types. The dominant anions in most groundwater samples contain a high proportion of sulfate and chloride anions (40-95%) and lower proportions of carbonate and bicarbonate ions (5-60%). The dominant cations in most groundwater samples contained higher proportions of sodium (20-90%), calcium (0-60%), and

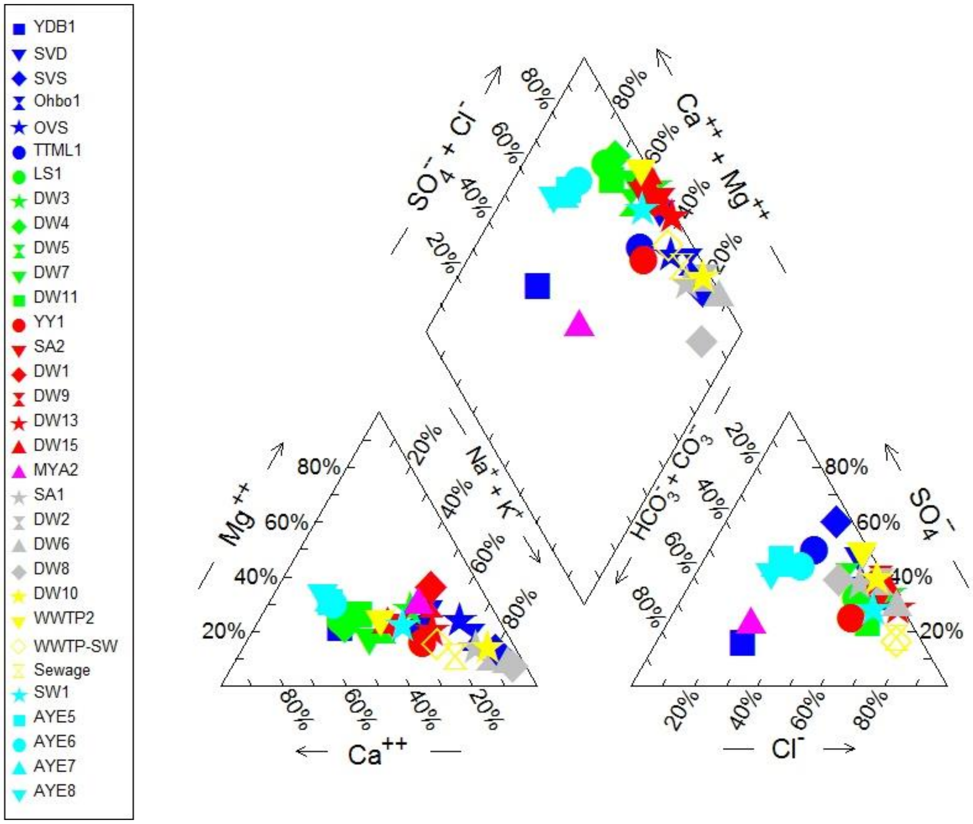


Figure 6. Piper diagram- Dry season. Colors represent different regions of the study site: Blue represents wells on the east side of TTML. Pink represents the wells on the northeast side. Green represents the wells in the lower hydraulic conductivity zone around the north and west edges of the lake. Red represents the wells around the groundwater divide. Gray wells represents wells between TTML and the Irrawaddy River on the south side. Filled in yellow represent wells further north of the Amarapura Township near one of the major wastewater canals. Yellow with no filling represent wastewater from the Shwe-Ta-Chaung canal. Light blue represents surface waters.

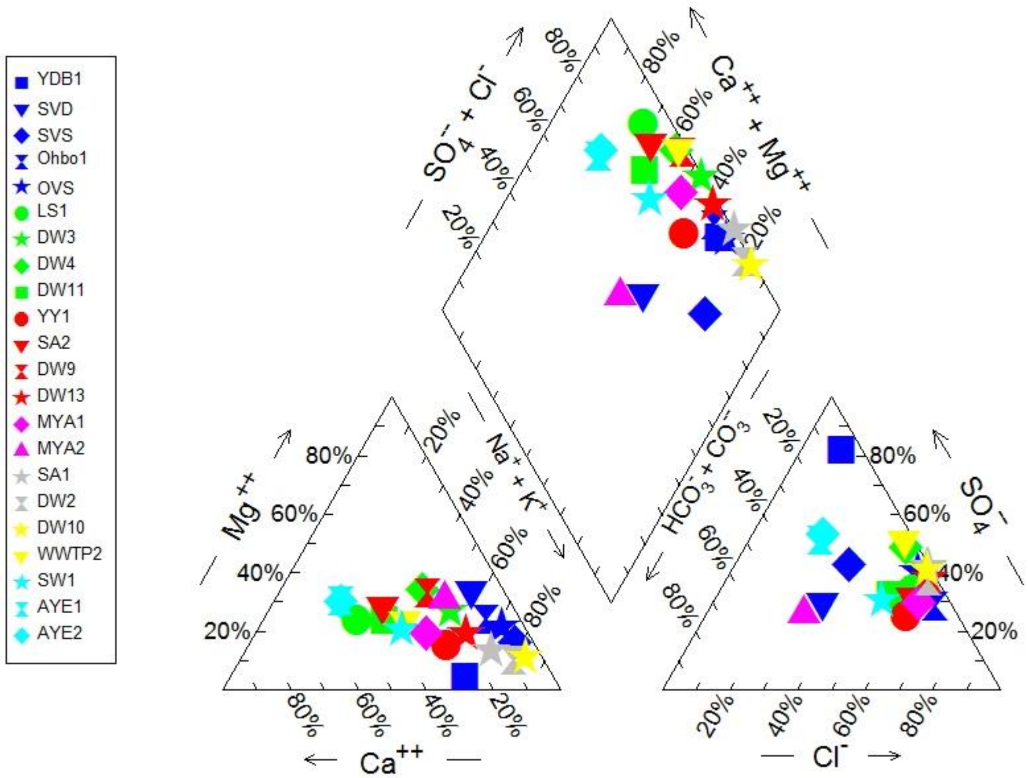


Figure 7. Piper diagram- Wet season. Colors represent different regions of the study site.

magnesium (0-40%). Wastewater samples also contained high proportions of sulfate and chloride (90-95%), but contained a higher proportion of sodium (50-60%) than calcium (20-30%). TTML's water type is also Na-Cl and is very similar to groundwater samples, but contains a slightly lower proportion of carbonate and bicarbonate anions (10%) than the Irrawaddy River (20-40%). In the Irrawaddy River, a Ca-SO_4 water type is observed towards the north side of the river during both the wet and dry seasons. During the dry season, sampling was extended further south, revealing a shift from sulfate to bicarbonate as the dominant anion, but was a minor shift.

Wastewater Indicators

Electrical Conductivities

Electrical conductivity (EC) is a common measurement used to evaluate water quality. During the dry season EC values in groundwater samples ranged from 305-2,590 μS/cm and averaged 1,385 μS/cm. During the wet season EC values in groundwater samples ranged from 183-2,950 μS/cm and averaged 1,168 μS/cm. Background electrical conductivity values were estimated from six deep tube wells sampled during both seasons (YDB1, LS1, SVD, YY1, SA2, and MYA2). Background values for the dry and wet seasons were 713.5 μS/cm and 502.33 μS/cm, respectively. Background levels were exceeded during the dry season by 44% of tube wells and 81% of dug wells. During the wet season, 63% of tube wells and 82% of dug wells exceeded background levels. During both seasons most dug wells exceeded background levels. The few that did not were the dug wells located closer to TTML (DW4, DW5, and DW11). In the region between TTML and the Irrawaddy River, a divide was noticed between higher and lower values of EC. Higher values (>1200 μS/cm) were located on the west side (closer to the Shwe-Ta-Chaung canal) and lower values (<1200 μS/cm) were observed on the east side (closer to TTML). This was identified as a potential groundwater flow divide. Data is presented in Appendix E and summarized in Table 4.

Total Dissolved Solids

Total dissolved solids (TDS) is a commonly used water quality parameter to describe the presence of inorganic salts in the water. The World Health Organization (2008) sets a limit on TDS of 1000 ppm as reasonable quality but specifies 300 ppm as the preferred limit for drinking water. TDS values during the dry season ranged from 59-1,039 ppm and averaged 497 ppm. TDS values during the wet season ranged from 79-1,326 ppm and averaged 467 ppm. Only DW10 exceeded the WHO limit of 1000 ppm during both seasons. WWTP2 and Ohbo1 are the only tube wells to exceed the 300 ppm limit during both seasons, but SVD also exceeded this level during the dry season. The majority (>70%) of dug wells exceeded this limit during both seasons. WWTP2 and DW10 are both located on the north side of the study area within 15 meters of the Shwe-Ta-Chaung canal. Background TDS was estimated using the six tube wells from above. Background values for the dry and wet seasons were 209.4 ppm and 174.68 ppm, respectively. TDS values that exceeded background levels from both seasons followed the same pattern as EC values. Data is presented in Appendix G and summarized in Table 4.

Chlorides

Excess chloride concentrations in groundwater have been shown to be indicators of wastewater contamination in other studies (Lawrence et al., 2000). Fetter (1999) established chlorides in excess of 100 ppm are usually associated with wastewater contamination. During the wet and dry seasons, 39% of wells exceeded 100 ppm. Background chloride concentrations for the Amarapura Aquifer were estimated from the six deep tube wells sampled during both seasons (YDB1, LS1, SVD, YY1, SA2, and MYA2). During the wet season, background chloride concentrations averaged 11.93 ppm and ranged from 2.66-26.00 ppm. In the wet season, 72% of groundwater samples exceeded the average, and 61% exceeded the range maximum. During the dry season, background chloride concentrations averaged 23.86 ppm and ranged from 1.43-57.46 ppm. In the dry season, 72% of groundwater samples exceed the average, and 56% exceed the range maximum. Data is presented in Appendix G and summarized in Table 5.

Nitrates and Ammonium

Nitrate and ammonium contamination has been documented in a number of areas from anthropogenic sources (Fetter, 1999). Nitrates (NO_3 as N) above 10 ppm and the presence of ammonium in urban areas often indicate influences from domestic wastewater (Fetter, 1999). Ammonium concentrations ranged from 0.05-3.14 ppm and averaged 0.15 ppm. Ammonium was present in 44% of wells during the wet season and 17% during the dry season. Nitrates ranged from 0.10-331.07 ppm and averaged 55.68 ppm; 56% of nitrates exceeded 10 ppm during the wet season, and 61% during the dry season. Data is presented in Appendix G and summarized in Table 5.

Cl/Br Ratios

Chlorine-bromine ratios (Cl/Br) have been used to determine the influence of wastewater contamination in regions without seawater influences (Vengosh and Pankratov, 1998). In this study, Cl/Br ratios from domestic wastewater are greater than 400 and 150 for groundwater contaminated with domestic wastewater (Vengosh and Pankratov, 1998). During the wet and dry seasons, 70% of dug wells exceeded the Cl/Br ratio for groundwater. In tube wells, 38% and 63% exceeded this ratio during the wet and dry seasons, respectively. Cl/Br ratios are summarized in Table 5.

E. coli

E. coli is measured in "most probable number" (MPN) per 100 mL, and detection of *E. coli* at any level is considered unsafe for drinking water. During the wet season, 100% of dug wells and 33% of tube wells sampled contained unsafe levels of *E. coli* for drinking water. During the dry season, 86% of dug wells and 11% of tube wells sampled contained unsafe levels of *E. coli* for drinking water. *E. coli* counts in most dug wells (>55%) exceeded 100 MPN/ 100 mL during both seasons, which is the United States Environmental Protection Agency (2012) recreational limit. Only two wells (DW7 and DW15) during the dry season did not contain any. *E. coli* was only detected in one tube well (YDB1) during the dry season and two tube wells (WWTP2 and LS1) during the wet season. *E. coli* counts are high in most dug wells compared to tube wells, but it is difficult to draw a direct correlation between *E. coli* and sewage infiltration to the wells because of hygiene practices that occur around these wells every day. Either way this is most likely from anthropogenic causes. *E. coli* results are presented in Appendix H and summarized in Table 6.

Stable Isotopes

All isotopic values of δ^2H and $\delta^{18}O$ are presented in Appendix I. Figure 8 shows the local meteoric water line (LMWL) to be similar to the global meteoric water line (GMWL). All of the samples tested for δ^2H and $\delta^{18}O$ fall on the LMWL/GMWL. This shows groundwater being recharged by recent rain events, meaning this system is unconfined, supporting the conceptual model. From this we can assume the Amarapura Aquifer does not contain significant evaporite deposits that would account for the Na-Cl water type or high concentrations of these ions. It can be assumed that all waters in the Amarapura Aquifer are directly recharged by recent precipitation events, indicating all the wells are in the unconfined Amarapura Aquifer. YDB1 is the tube well plotted between most wells and precipitation events, further proving that its chemical type change between seasons is influenced by overland flow.

Physical Hydrogeology

Drilling

Drilling was conducted to install tube well YDB3 in December 2016 using a local drilling technique similar to the cable tool method. One driller used bamboo sticks to lift and drop a steel pipe repeatedly to loosen unconsolidated material. A second driller covers and uncovers the top of the steel pipe to create suction, which helps to bring the surficial material to the top. If extra water is needed to break up aggregates stuck in the pipe, additional water is poured down the pipe (https://www.youtube.com/watch?v=bdZ2RHFOqEs&t=1s). Water poured down the pipe was not cleaned prior to use but was taken from a nearby retention pond. Typically, the annulus is backfilled with material taken out of the borehole or allowed to collapse around the casing. Development of the well was not done.

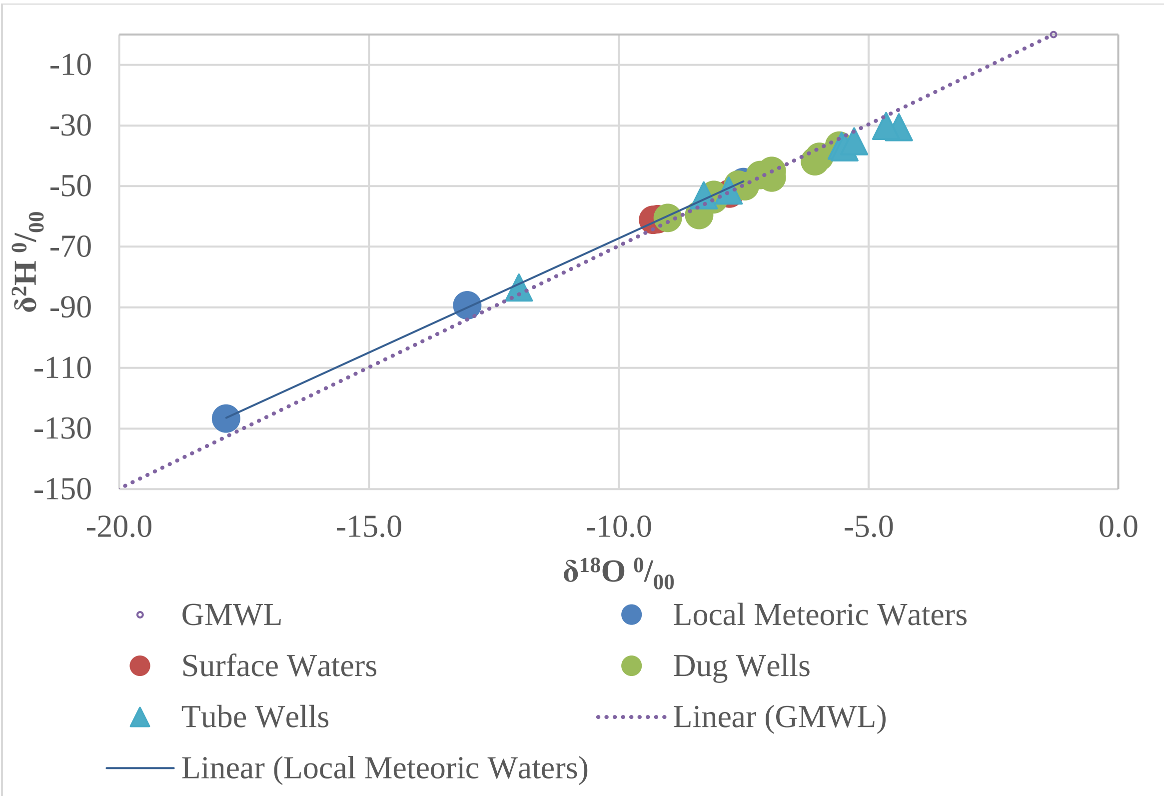


Figure 8. Stable isotope data of δ^2H and δ^{18}O plotted against the GMWL and the LMWL.

Grain Size Analysis

Sediments collected from the drilling of YDB3 are used to determine grain sizes in the upper eight meters of surficial material. Sieve analysis was conducted using five USA standard testing sieves to determine the type of environment the sediments were deposited in. The sieve analysis (Table 7) of sediment from YDB3 confirmed a predominantly medium-coarse sand and gravel material, which is in agreement with the suspected channel and bar deposits in this area. Small percentages of clay, around 10%, were present in the upper 6 meters, indicating thin flood plain deposits. This provides a wide range of porosities estimates from 20-35%. Hazen approximations provided hydraulic conductivities estimates between 4.98 and 726.62 m/day.

Table 7. YDB3 Grain Size Analysis

	Gravels	**Course Sand**	**Medium Sands**	**Fine Sand**	**Silts & Clays**	**Error**	**Hazen Method**
Depth bgs (m)	(%)	(%)	(%)	(%)	(%)	(%)	K (m/day)
0.31	5.68	49.50	22.52	10.08	11.23	0.98	21.60
2.13	27.25	38.65	17.26	7.65	8.72	0.47	55.30
3.05	26.16	27.47	15.47	13.98	15.21	1.72	4.98
3.66	47.95	25.22	9.00	7.33	9.83	0.66	33.21
4.27	41.67	25.06	10.53	8.98	12.79	0.96	8.85
4.88	42.28	27.76	9.18	8.26	11.71	0.81	15.24
5.18	29.78	23.42	13.39	18.44	12.81	2.15	12.48
5.49	34.91	36.11	14.50	7.08	6.42	0.97	86.40
6.10	25.24	27.46	20.08	14.84	11.82	0.58	17.50
6.71	46.26	24.07	12.36	7.74	8.40	1.16	55.30
7.01	26.82	35.91	24.27	6.18	5.69	1.13	124.42
7.62	0.95	74.49	21.30	1.96	0.49	0.81	381.02
8.23	3.57	80.47	13.89	1.15	0.23	0.70	726.62

Hydraulic Conductivity Measurements (K)

Slug tests of tube wells at Yadanabon University were conducted to determine the hydraulic conductivities of YDB1, YDB2, and YDB3. High hydraulic conductivities were observed at wells with screening intervals at approximately 25 meters below ground surface. YDB1 and YDB2 recovered within seconds of the start of the slug tests and produced oscillating slug test curves. YDB1 has a hydraulic conductivity of 54.86 m/day and YDB2 has a hydraulic conductivity of 67.06 m/day. Lower hydraulic conductivities of 1.31 m/day were observed in YDB3 at a shallower screening interval of 7-8 meters below ground surface.

The high hydraulic conductivities measured at YDB1 and YDB2 are assumed to be a layer of mixed sand and gravel from either the Irrawaddy River or Myitnge River sediments. This high hydraulic conductivity resembles values expected from the mixed sand and gravel layers that were observed during drilling of YDB3. Lower hydraulic conductivities observed in YDB3 are assumed to be from medium-coarse sand layers, such as those observed in the screening interval of YDB3. These slug tests provide a range of values that exist across the site. Overall, these hydraulic conductivities are in agreement with the types of sediments observed from the grain size analysis of YDB3.

Water Level Measurements

Long-term monitoring of water levels in YDB1 and YDB2 was conducted to observe changing conditions over the duration of the study. Long-term monitoring showed transient conditions of water levels between seasons (Figure 9). Water levels generally declined between the wet and dry seasons and often spiked 1-2 meters during rain events. Heads varied from approximately 66-71 mamsl.

During both seasons, heads in the Amarapura Aquifer were relatively shallow. Heads range from 64-71 meters across the Amarapura Aquifer and were approximately 2-6 meters higher during the wet season than the dry season. These heads are tremendously affected by heavier thunderstorms/prolonged rain events and additional inflow of water from the Irrawaddy River and other surface-water features in the region. The Amarapura Aquifer’s high hydraulic conductivity (50-70 m/day) allows water to flow in and out of the aquifer with higher average linear velocities (9.25 m/day) causing quick water level fluctuations during rain events. This means water levels in this alluvial aquifer are susceptible to changing weather conditions. During the wet season water levels were transient and reflected changing weather conditions.

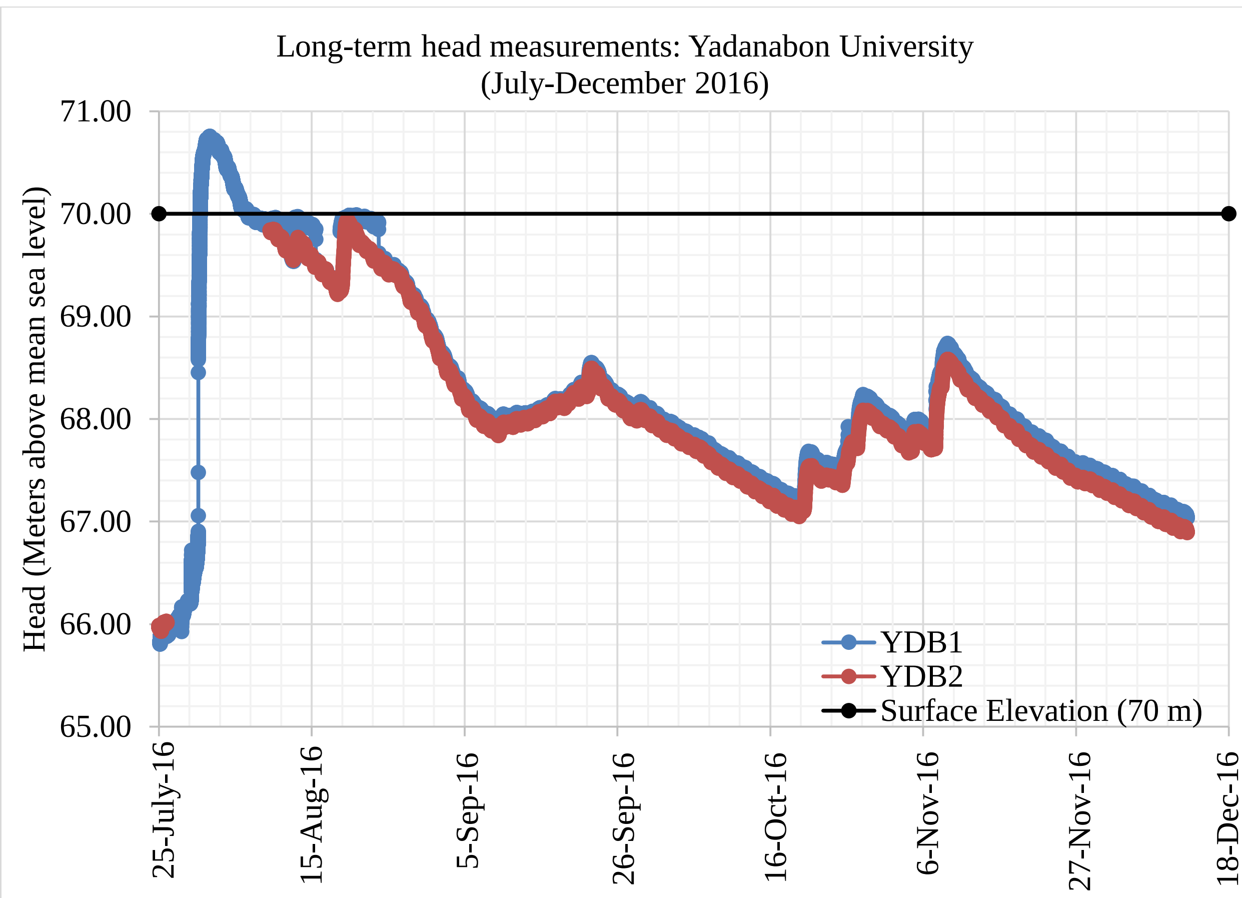


Figure 9. Long-term head monitoring (YDB1 and YDB2).

Groundwater Modeling

Conceptual Model

The initial groundwater flow conceptual model of our groundwater flow system was from east to west towards the Irrawaddy River. Head measurements on the east side of TTML appeared to be rising during the wet season periodically, which suggested the system was controlled by the water level in the Irrawaddy River. A potential groundwater divide was noticed when taking electrical conductivity measurements between TTML and the Irrawaddy River. The electrical conductivities appeared to be high (>1200 μS/cm) towards the west side and low (<1200 μS/cm) towards the east side (Figure 10). When oscillating slug test data were seen and hydraulic conductivity on the order of 67 m/day was calculated, it could be assumed there were areas of lower gradients across the site.

Initial Parameters

The infiltration percentage of 10% from the IWMI report was applied to the CRU average annual rainfall data for Mandalay of approximately 1100 mm/year (Harris et al., 2014; Pavelic et al., 2015). Therefore, recharge is 110 mm/year (3.01×10^{-4} m/day). An effective porosity of 25% is assumed in calculating average linear velocities (v_x) for comparison with modeling results. To express the actual velocity at which groundwater flows through the porous material of the Amarapura Aquifer, average linear groundwater flow velocities were calculated from measured heads. Average linear groundwater flow velocities ranged from 3.38×10^{-2} m/day to 9.25 m/day and averaged 7.54×10^{-1} m/day.

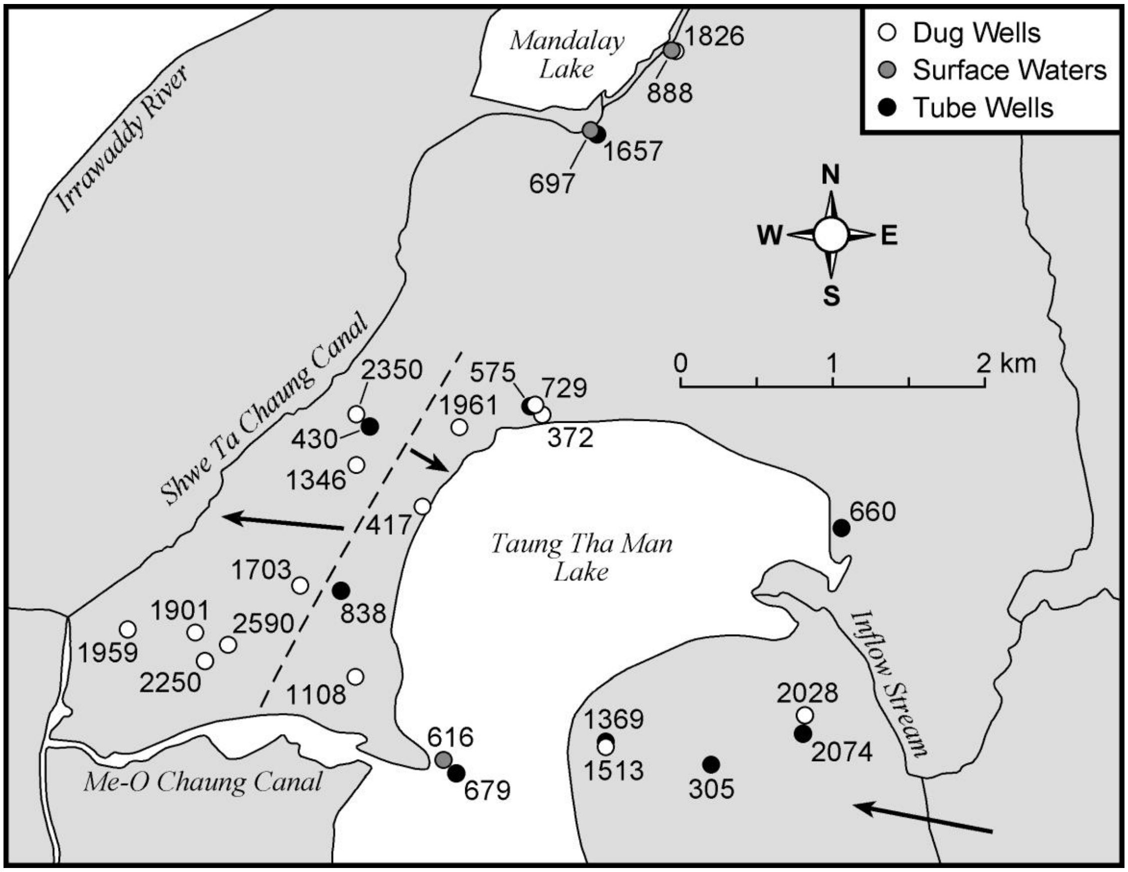


Figure 10. Conceptual groundwater flow model. Values displayed are electrical conductivities in (μS/cm) and the dashed line represents the potential groundwater divide. Arrows represent suspected groundwater flow direction.

Model Calibration

Model calibration was conducted using sensitivity analysis and a PEST module to determine ideal values of the Amarapura Aquifer properties: porosity (n), hydraulic conductivity (K), recharge (R), and average linear velocities (v_x). Sensitivity analysis increased the recharge value to 6.1×10^{-4} m/day. This value provided a better calibration in the model and was within reason of what was measured. From sensitivity analysis, the ideal porosity for the model calibration is 25%, which falls within the estimated range for earth materials analyzed during the sieve analysis. Further, the sensitivity analysis/manual calibration of the dry season model assisted in dividing up the sampling locations into four zones. A more optimal calibration is observed when the zone on the east side of TTML contains a higher hydraulic conductivity, and the zone on the north and west side contains a lower hydraulic conductivity. The PEST module was then run to approximate ideal hydraulic conductivity values for the rest of the study area, which gave an average hydraulic conductivity of 15 m/day for the site (K1).The zone on the north and west side was assigned a lower hydraulic conductivity of 0.5 m/day (K2) and the zones on the east side a higher hydraulic conductivity of 70 m/day (K3 and K4) (Figure 11). Model calibration results can be seen in Figure 12. Average linear groundwater flow velocities calculated from the modeled heads ranged from 1.76×10^{-2} m/day to 2.10 m/day and averaged 3.20 m/day in the dry season model (Figures 13). These optimized parameters were used in creating the wet season model (Figure 14). A comparison of field data and modeling data is summarized in Table 8.

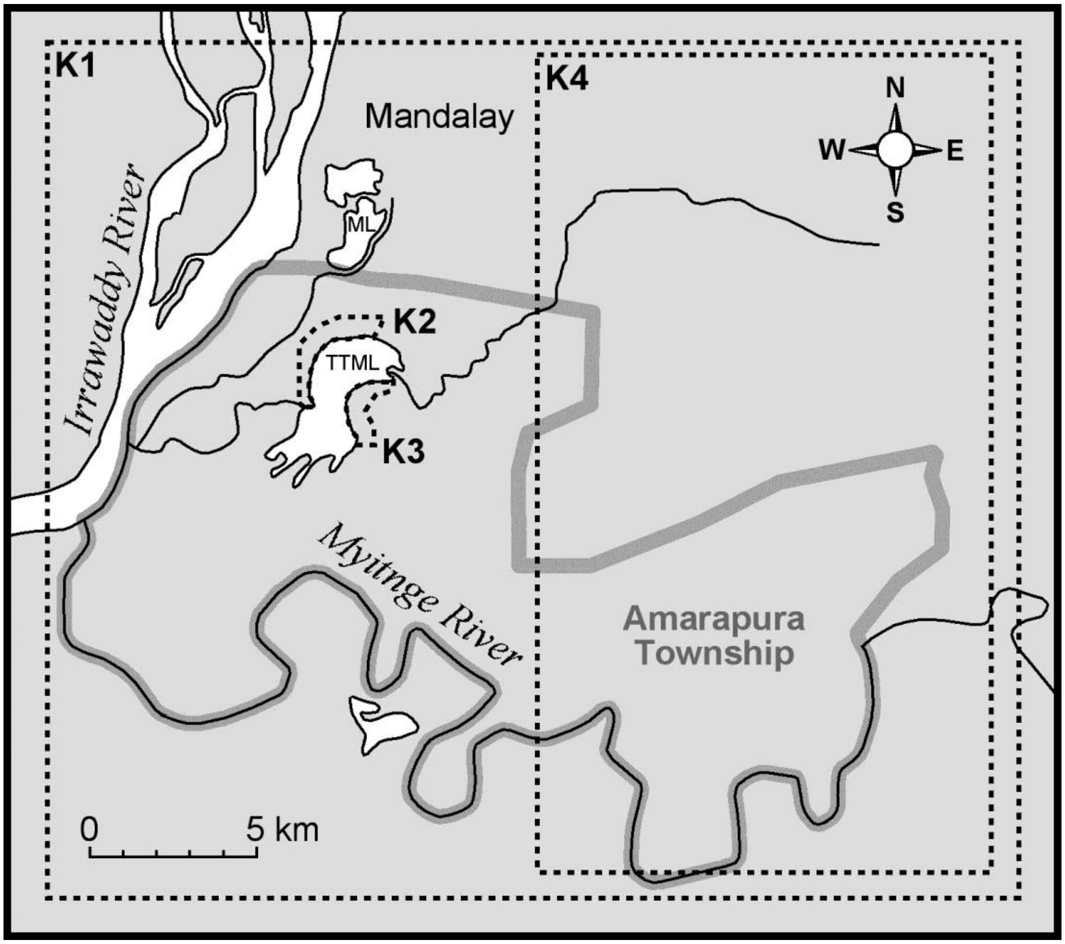


Figure 11. Model features. K1, K2, K3, and K4 are hydraulic conductivity zones; all solid-black lines represent surface water features/line elements with specified heads.

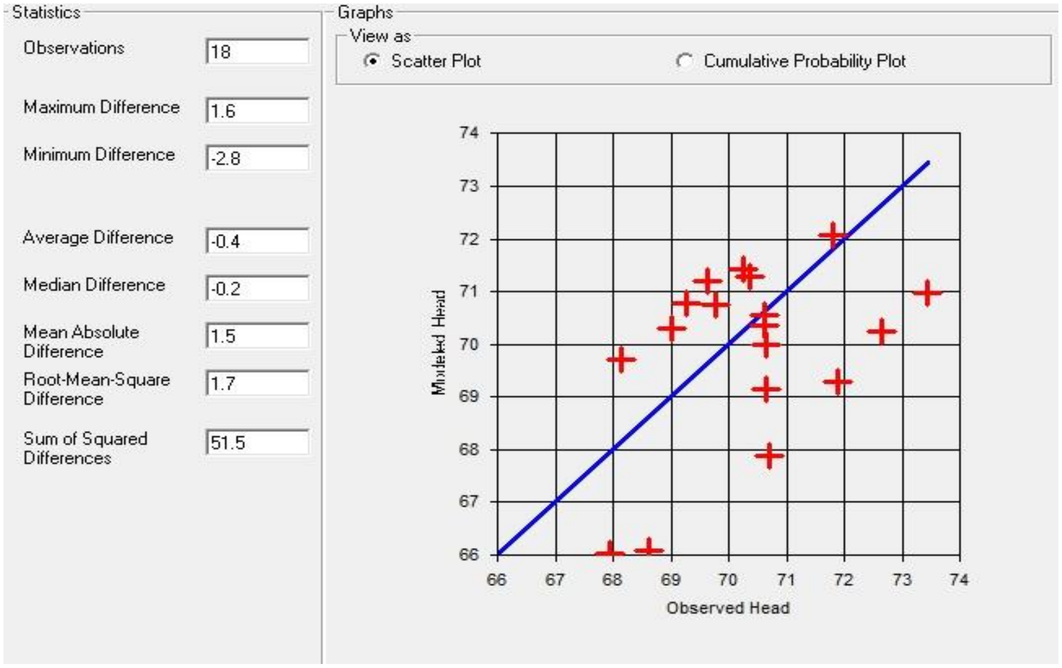


Figure 12. Dry season model calibration. Output from GFLOW; R^2=0.1987. An attempt was made to have the same number of points above and below the line, and decrease the differences.

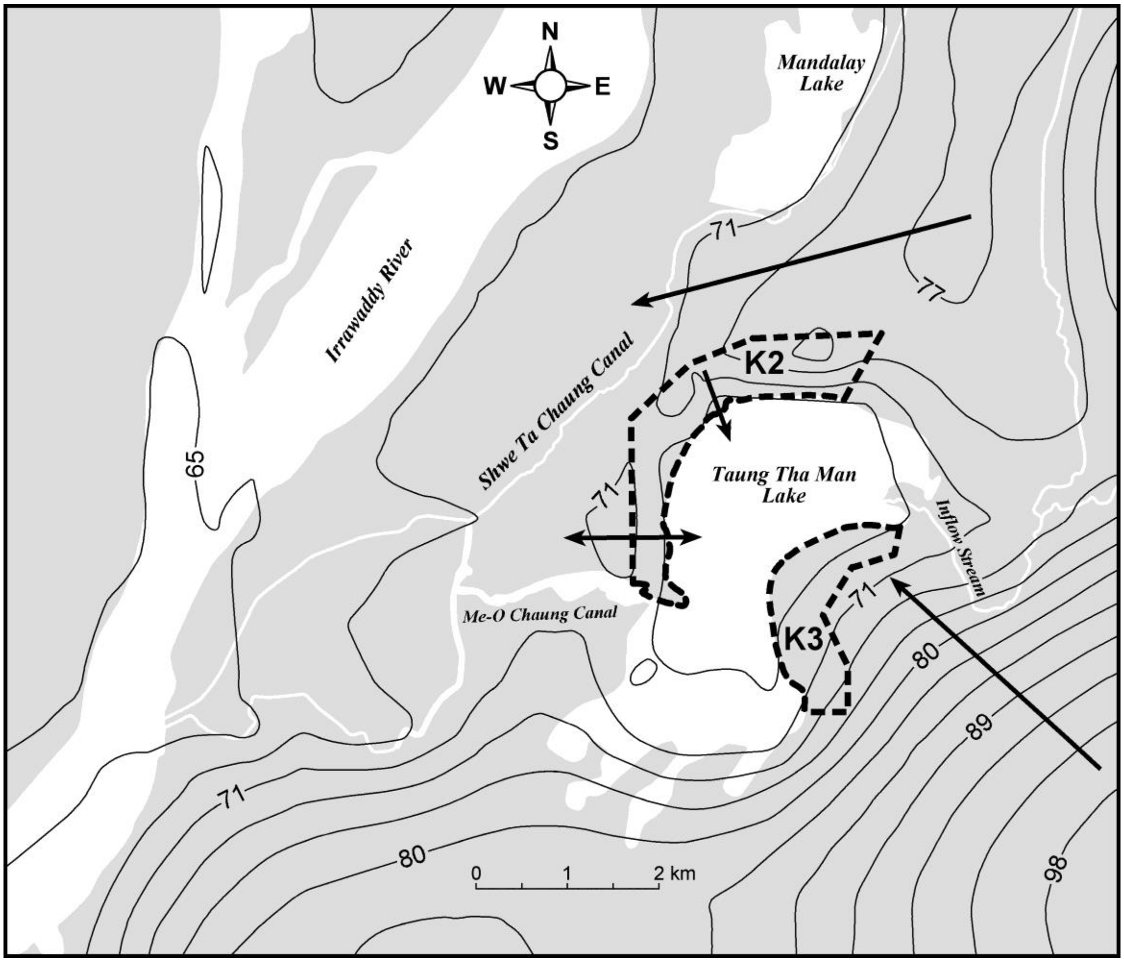


Figure 13. Dry season model- Study site.

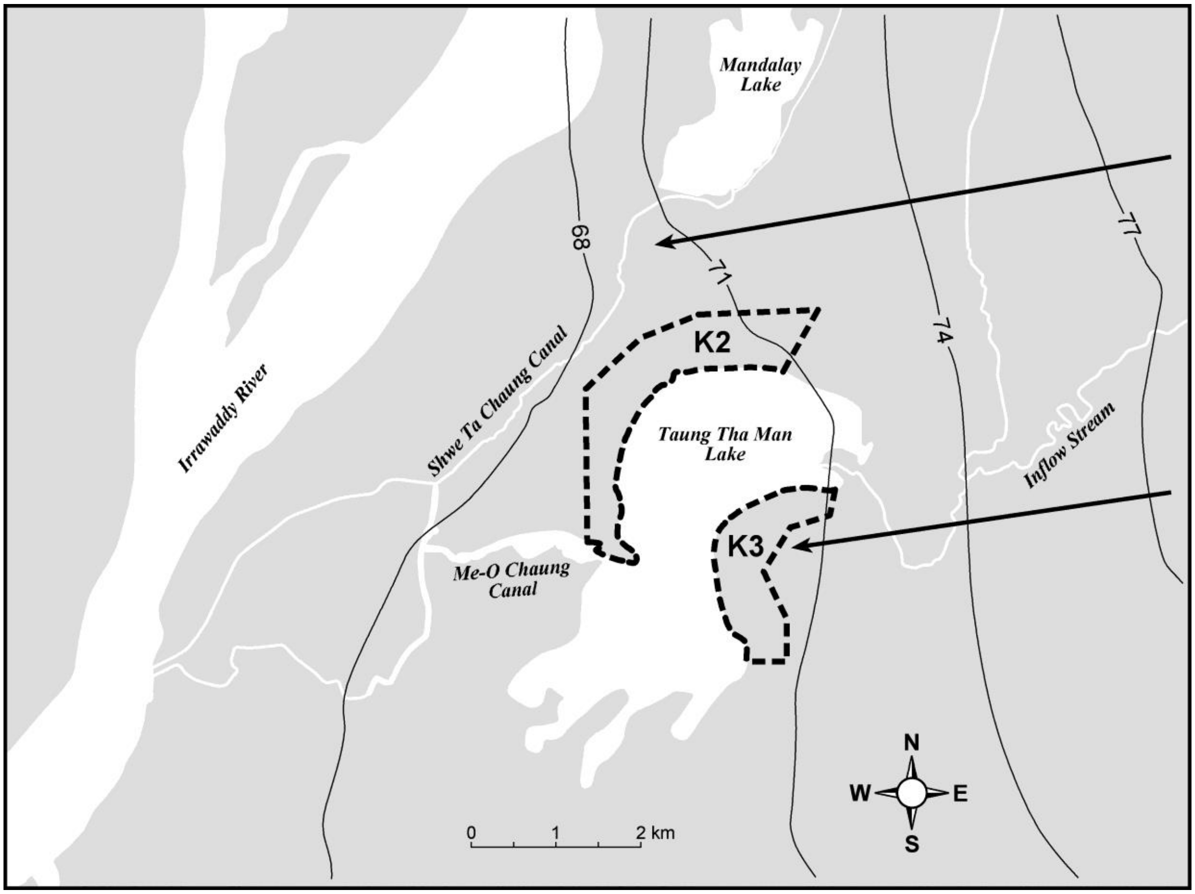


Figure 14. Wet season model- Study site.

Table 8. Model Calibration with Field Data (All values displayed in meters/day)

Parameter	**Field Data (m/day)**	**Modeling Data (m/day)**
Recharge (R)	3.01×10^{-4}	6.1×10^{-4}
Hydraulic Conductivity (K)	1.31-67	0.5-67
Average Linear Velocity (v_x) (K1-Zone)	3.04×10^{-1}	1.46×10^{-1}
Average Linear Velocity (v_x) (K2-Zone)	3.38×10^{-2}	1.76×10^{-2}
Average Linear Velocity (v_x) (K3-Zone)	9.25	2.10

Groundwater Flow Models

Dry Season Model

The dry season model shows a potentiometric surface map of heads across the study site. Modeled heads in meters above mean sea level (mamsl) are represented in Figures 13 and 14 by solid-black lines. Dashed-black polygons represent the different hydraulic conductivity zones (K1, K2, K3, and K4). The outer black polygon (K1) also represents the area that recharge is applied to. Boundaries between white and gray fills represent surface waters/line elements with specified heads. Black arrows are pointing in the direction of predominant groundwater flow. The Irrawaddy River is defined as an inflow and outflow stream on the west side of the model. The Myitnge River is a natural boundary on the south side of the model. The Shan Plateau is considered a boundary on the east side, since the geology changes from surficial material to limestone formations. The north side of the model is set as a constant flow boundary. This model showed predominant groundwater flow towards the Irrawaddy River and contained a groundwater divide in the region between TTML and the Irrawaddy River (see Figure 13).

Wet Season Model

Groundwater flow was predominantly towards the Irrawaddy River during the wet season. Gradients were decreased across the site, and the groundwater divide between TTML and the Irrawaddy River was not present when heads were increased during the wet season (see Figure 14).

CHAPTER 5: DISCUSSION/CONCLUSIONS

Wastewater has been identified as the largest water quality problem in urban cities in most of Southeast Asia, but very little information exists on its effects in Myanmar (ADB, 2013; Moe, 2013; UNDP, 2014). Existing information on the hydrogeology of Myanmar is very limited, and this study provides the first characterization of a local hydrogeologic system in Myanmar. The Asian Development Bank (2013) identifies the occurrence of diarrhea in children under the age of 5 to be highest in Myanmar of any other Southeast Asian country because of inadequate water, drainage, and sanitation services.

Water Quality and Wastewater

In Southeast Asia, management of wastewater, or lack thereof, has posed a major problem and contamination issue to groundwater and surface waters (ADB, 2013). In Myanmar, wastewater is considered to be the most important water quality issue in urban areas, such as Mandalay and the Amarapura Township (ADB, 2013; Moe, 2013; UNDP, 2014). In this study, the water quality of the Amarapura Aquifer was examined to determine if the main source of pollution is wastewater. Na-Cl water types have been observed in many groundwater systems that were contaminated with urban wastewaters (Bashir et al., 2015; Hassane et al., 2016; Lee et al., 2010). In our study, Na-Cl water types were observed and water quality parameters determined elevated levels of total dissolved solids, electrical conductivity, chlorides, nitrates, ammonium, and *E. coli.* These water quality parameters have been used to indicate contamination of groundwater from wastewater sources (Bajjali et al., 2015; Hassane et al., 2016; Lawrence et al., 2000; Lee et al., 2010; Nagarajan et al., 2010; Nas and Berktay, 2010). Cl/Br ratios are also used as a key parameter to determine the extent of groundwater contamination from wastewater sources (Vengosh and Pankratov, 1998). From a combination of these factors, it is determined that wastewater from local sewage canals contaminates shallow wells in the Amarapura Aquifer.

Previous studies on wastewater contamination of groundwater in other regions of the world have resulted in similar water types, for example Na-Cl (Bashir et al., 2015; Hassane et al., 2016; Lee et al., 2010). Geochemistry data yields a predominant Na-Cl water type across the Amarapura Aquifer, which is most likely the result of infiltration by urban wastewaters because there is no known local source of halite. Not being in an arid environment, it is unlikely that evaporation would play a major role in the precipitation of Na-Cl. Further, stable isotope data does not show the presence of an evaporite line (see Figure 8). All stable isotope data of δ^2H and δ^{18}O plotted on the global meteoric water line (GMWL) and local meteoric water line (LMWL), suggesting these wells are all directly recharged by recent rain events (Clark and Fritz, 1997).

In sampling of the Irrawaddy River, a $Ca\text{-}SO_4$ water type is observed towards the north side of the river during both the wet and dry seasons. During the dry season, sampling was extended farther south, revealing a change in water type to $Ca\text{-}CO_3$. It is believed this is the dominant water type because of the local calcite deposits, and the sulfate anions are influenced in these surface waters from the weathering of barite (Adamu et al., 2014; Baldi et al., 1996).

Myanmar has begun development of its industrial infrastructure with help from other countries across the region and world. The water quality data presented here will serve as a baseline prior to development. Many sources of pollution still exist within Mandalay. The water quality data and an uneven spatial distribution and high concentration of other ions such as ammonium, nitrates, and chlorides suggest that this likely results from anthropogenic wastewater sources. The presence of ammonium, nitrates above 10 ppm, and chlorides above 100 ppm typically indicates influence from domestic wastewater (Fetter, 1999). High sulfate levels are also observed but are likely from barite ($BaSO_4$) deposits in the Shan Plateau. It is expected that calcite ($CaCO_3$) and barite ($BaSO_4$) would be the dominant water types in this area because they are present in the local source rocks.

Another indicator of anthropogenic waste is *E. coli*. The presence of *E. coli* is commonly related to human waste, can cause severe diarrhea, and is often associated with other waterborne pathogens (World Health Organization, 2008). In Myanmar, it is estimated that 38 children per 1000 live births (3.8%) in Myanmar die before the age of 5, which is mainly attributed by waterborne diseases and malnutrition (Pavelic et al., 2015). During the wet season, 100% of dug wells and 33% of tube wells sampled contained unsafe levels of *E. coli* for drinking water. During the dry season, 86% of dug wells and 11% of tube wells sampled contained unsafe levels of *E. coli* for drinking water. High levels of *E. coli* in these wells may be due to wastewater canals, but may also just be from poor hygiene practices by those using the wells. DW10, being within 5 meters of the Shwe-Ta-Chaung sewage canal is more likely to have been contaminated by local wastewater. Locals using water from this well knew not to drink the water but still used it for cleaning dishes and taking baths, which could still potentially pose a health risk.

A few groundwater wells had different water types between seasons (YDB1, SVD, SA2, and DW4) and are likely due to contamination from other anthropogenic sources because of improper well construction. YDB1 changed water types between seasons from Na-SO_4 during the wet season to Ca-CO_3 during the dry season. This is likely due to overland flow of water during the wet season going directly into the well. YDB1 only has about 3 cm of stickup and is covered with a brick, which does not protect it from water flowing into it when flash floods are above 3 cm, which occurs frequently during monsoon season. $CaCO_3$ is consistent with the dominant water type suspected to be present in this system, especially in deeper wells, because there is evidence of calcite deposits in this area. SVD changed from Na-HCO_3 to Na-Cl, which may be due to changing groundwater flow directions between seasons near TTML. SA2 changed from Ca-Cl to Na-Cl between seasons, but this was a minor change that plots very close to one another on the Piper diagram and is not significant. DW4 changed from Na-Cl to Ca-Cl but was also a minor change on the Piper diagram.

Contamination of the shallow aquifer system can have a negative impact on the health of those using water from dug and tube wells in the Amarapura Township. It is possible that many of these health effects have gone unnoticed because health surveys haven’t been conducted. Local infrastructure is needed to build lined wastewater canals or underground sewers to protect water sources, and treatment plants are needed, which has been shown to reduce wastewater’s impact on shallow groundwater systems (Foster et al., 2011). Numerical modeling can be used as guidance for resource management and determining protective zones for wells (Foster et al., 2011). A safe and accessible municipal supply would also reduce the number of private wells being used and make management strategies more controlled (Foster et al., 2011). Other small things can be done as short-term solutions, such as building concrete pads that direct wash and wastewater next to a well away from it and into a lined canal (Schneider, 2014). Better construction of deeper tube wells can also help to improve the quality of the water people in the Amarapura Township are drinking (Schneider, 2014).

Well Construction

Well construction is often a major issue in the developing world when trying to provide clean water to those living there. Dug and tube wells both contain many issues with their construction that make them vulnerable to contamination. Variations and combinations of cable tool percussion, air rotary, mud rotary, auger, and reverse circulatory rotary are often used to manually construct groundwater wells (Schneider, 2014). Well construction is a very important aspect to supplying and maintaining clean water in these areas. With the proper information and materials, simple improvements can be made to improve the construction of tube wells and further the quality of groundwater. This change could impact 68% of domestic water usage in the Amarapura Township (Moe, 2013).

While dug wells are not usually used for drinking, dug wells had been created with brick liners over 50 years ago. Typically, the bottom of the dug wells were just naturally occurring sand layers. No cover existed for these dug wells, which left them vulnerable to debris collecting inside these wells. Additionally, the large diameter, heavy usage, and local hygiene practices left it vulnerable to surface contaminants. In two dug wells, fish were observed, which locals used to determine the water quality. Hence, if the fish died they knew not to use the water but otherwise considered it safe. Since the local population depend on dug wells, water quality could be improved by pumping water to the top in closed containers, where chlorination could be used as a treatment. Covering the wells and extending concrete pads on top to divert used water away from the well would also help to improve the water quality of dug wells. Tube wells did not contain any kind of sand pack, grouting, or annular surface seal to prevent infiltration of surface contaminants directly to the screen of the tube well (Schneider, 2014). Many of these did not contain a cap, and YDB1 had a stickup of only 3 cm, leaving it vulnerable to overland flow. Often, during construction unfiltered/unclean water from local ponds were dumped down the well, and no well development was attempted.

The drilling techniques and bamboo tools used in Myanmar are similar to the cable tool percussion method developed by the Chinese 4000 years ago (Driscoll, 1986). While this technique is uncommon in the modern era, modified drilling techniques are common in many other developing countries (Schneider, 2014). Modern drilling techniques are costly and often require equipment that is not accessible. The lack of access to information on proper well construction and development has caused many of these wells to be more vulnerable to surface contaminant sources (Schneider, 2014).

Many locals install tube wells because they know they provide better drinking water quality. Tube wells are safer than dug wells for drinking water purposes because they are deeper and have a screened interval. They also do not have the component of human-infected buckets being dumped directly into them to retrieve water but instead have a hand or compressor pump for obtaining water from them. However, this was not always the case. Many of the wells with varying water chemistry between seasons are tube wells. This is likely due to the way in which they were constructed. Without a proper sand pack or grout in the annulus many of these wells have open space between the surficial material and the well casing. This makes these tube wells vulnerable to contamination, especially when there is a high amount of overland flow from rain or from practices of washing and cleaning directly next to the well. During the dry season, water chemistry revealed water types similar to the surrounding geology, suggesting that a higher amount of contamination occurs during the wet season.

During the workshop in December of 2016 with professionals in the field of geology and water quality in Myanmar, YDB3 was installed at Yadanabon University to discuss and point out improvements to their current methods. Guidebooks on water supply well guidelines for use in developing countries were provided to these participants to provide a reference for future construction of tube wells (Schneider, 2014). Hopefully, by providing this information to local professionals in similar fields, the information will begin to spread and standard well construction practices will improve over time. More hands-on applications with local professionals will help, but experienced drillers are still needed to further emphasize these points in Myanmar.

Groundwater Flow

The groundwater flow models of the Amarapura area are the first of any kind in the country of Myanmar. Little is known about the local groundwater flow systems and the variability that may exist between seasons or the influences from TTML and the Irrawaddy River. The physical conditions of an aquifer play a major role in the potential contamination to the groundwater from surface contaminants because this controls the wastewater's ability to penetrate the subsurface. These models were used to provide additional information in understanding this regional groundwater system. Improvements can be made, but these models provide information on key characteristics of the Amarapura Aquifer to be investigated for a better calibration in future studies of this region.

The physical hydrogeology of an area plays an important role in the potential for surface contaminants to infiltrate into the shallow Amarapura Aquifer. The Amarapura Aquifer contains predominantly coarse-medium sands with gravels, which creates a high range of hydraulic conductivities. Its high hydraulic conductivities (67 m/day) and high average linear velocity (2.10 m/day) allow water/contaminants to flow in and out of the Amarapura Aquifer. The surface water to groundwater interaction was observed by changing heads in reaction to changing weather conditions (Haitjema, 2012). Heavy thunderstorms/prolonged rain events cause additional inflow of water from the Irrawaddy River and other surface water features in the region.

The analytical element groundwater flow models showed the conceptual model to be correct, and groundwater does predominantly flow towards the Irrawaddy River. Sensitivity analysis showed hydraulic conductivity to be a key physical characteristic of this groundwater flow system. In the model calibration, four hydraulic conductivity zones were identified (see Figure 11). Sensitivity analysis also showed the lake stage of TTML to be a major factor in the model calibration. When the head of TTML was raised 1-2 meters there was an improvement in the model calibration. This could be due to the potential 2-3 meter error in our digital elevation model in assigning these head measurements. Errors in the digital elevation model have been observed in another study, especially with smaller streams (Fredrick et al., 2006). However, in general, flow directions and groundwater divides did not change significantly with this elevated head in TTML. Measurements of recharge (R), hydraulic conductivity (K), and average linear groundwater flow velocities (v_x) in the model provided results within the same order of magnitude as the field measurements. This further validated our final model and assumptions provided by the sensitivity analysis and the PEST module.

Seasonal differences in groundwater flow existed between the dry and wet season models. The dry season model showed the influence of TTML on the shallow groundwater system, which creates a groundwater divide between TTML and the Irrawaddy River. However, this groundwater divide is not seen in the wet season model when heads are higher. Groundwater gradients also spread farther apart during the wet season and show slower average groundwater linear velocities (v_x). This groundwater divide likely disappears because of a less permeable sediment layer at a particular head or because with such a high influx of water during the wet season the influence of TTML becomes negligible. Meaning, when more water is added to the system during the wet season, groundwater and surface water heads are more consistent across the region. This could potentially allow for rapidly rising heads in TTML and the Irrawaddy River during monsoon rain events to cause reverse flow conditions for short periods of time (2-10 days).

Modeling results were also used to compare geochemical differences across the site between seasons. As presented earlier, there were very few major geochemical differences and were not suspected to be a result of physical flow differences. However, at the beginning of this project, electrical conductivity measurements were used in identifying the potential groundwater divide. During modeling, the hydraulic conductivity zones around TTML were identified and also showed similar geochemical characteristics. Wells in the low hydraulic conductivity zone (K2) near TTML typically had a lower TDS. Wells in the higher hydraulic conductivity zone (K3) near TTML typically had a higher TDS. These zones around the lake should be considered in future conceptual models of this area and tested further to determine their validity. Future models could also look into specific contaminants in specific wastewater canals to determine whether these contaminants are traveling along these groundwater flow paths and infiltrating into the local wells.

This initial model provides a general characterization of the regional groundwater flow and offers the first of its kind in the country of Myanmar. Many improvements would be needed to improve the accuracy of the calibration, such as properly surveying wells, long-term monitoring of surface water heads/stages, and a watershed model for the Irrawaddy River. Additionally, from the transient conditions observed and fast groundwater velocities, an improved time-series monitoring system of groundwater heads, surface water heads, and velocities of the rivers/streams would be needed to accurately determine the full extent to which the Irrawaddy River influences flow conditions in the Amarapura Aquifer during the wet season.

Open-Source Software

Open-source software such as GFLOW and QGIS were used in this project because they are free and don't require licenses. QGIS contains numerous instructional videos and documents that give assistance on how to use the software (www.qgis.org, 2016). GFLOW contains instructional documents that assist using the software and understanding the assumptions made in the groundwater model (Haitjema, 2016). The software is just as effective as using any other software that could have been chosen for the tasks necessary in this project but contained challenges when transferring this information to local professors in Myanmar, such as Internet access and language barriers.

Many of the challenges in a country like Myanmar concern accessibility. Myanmar is still fairly secluded and updating its local infrastructure. Even when the technology is available, other services such as Internet service are not. The Internet service in Mandalay is still very slow and often not working. This makes downloading large software files difficult and often impossible. Accessibility to Internet is only available during regular work hours at the university but is often not working due to technical reasons or blackouts. QGIS contains many help videos, but this was not an option if the 3-minute video takes 2 hours to complete loading. Open-source maps, such as Google maps, were often blocked by government Internet services or technology. QGIS is moderately technical and difficult to be taught in a short course to non-English speakers. Instructional videos and documents are also in English, which not everyone there can understand easily. GFLOW is very technical and requires a basic understanding of groundwater modeling.

However, many of the local geology professors are just receiving their first course on the basics of hydrogeology, which causes another barrier.

Improved accessibility to these materials are needed to be successful for projects such as this one to start improving research and site investigations in Myanmar. This would require a reliable Internet system that does not censor simple items, such as Google maps. During our second trip many of these problems were solved by bringing flash drives pre-loaded with all of the software and materials. Open-source software is a great starting point for universities such as Yadanabon University to start producing higher quality research, but more support is needed locally. Local investment and commitment to projects such as this are needed for them to be successful in the future and to continue to improve in the field of hydrogeology in Myanamar.

The chemical and physical properties of the Amarapura Aquifer suggest that urban wastewater in the Amarapura Township is the predominant source of contamination to the shallow groundwater system. Seasonal variations occur for both physical and chemical properties of the Amarapura Aquifer, which include varying water types, higher concentrations of chemical ions during the wet season, transient water levels, changing groundwater divides, and gradients. Its high hydraulic conductivities (67 m/day) allows for groundwater and contaminants to flow in and out of the Amarapura Aquifer with high average linear velocities (2.10 m/day). Therefore, chemical and physical data suggest wastewater plays a major role in contamination of shallow groundwater wells in the Amarapura Township.

Future Research

Future research should include further chemical and physical analysis. Testing for volatile organic compounds (VOC) and additional metals should be conducted because the potential for VOCs is high. Identification of potential contamination sources, such as the textiles industry, and their effect on the water quality should be analyzed in more detail. Identification of other industrial sources of wastewater and incoming industries should be conducted. This can then be used to determine additional effects on water quality as more industries move in and tourism begins to expand. Continued drilling to develop a hydrogeologic cross-section, or map, should be done to better understand the local hydrogeology. Additional slug tests or pump tests in wells in each of the K-zones should be done to provide field measurements to support or disprove the current groundwater flow model. Proper surveying of wells should be done to eliminate an additional source of error so the model can be better calibrated and key parameters narrowed. Sampling outside of the city limits, away from wastewater influences, would provide ideal background levels of various indicator chemicals to compare current and future data with. Further, continued monitoring throughout the year of groundwater level heads, river heads, and lake heads should be conducted to further understand the seasonal variations in flow. This could also help determine if reverse flow conditions occur during intermittent times of the wet season.

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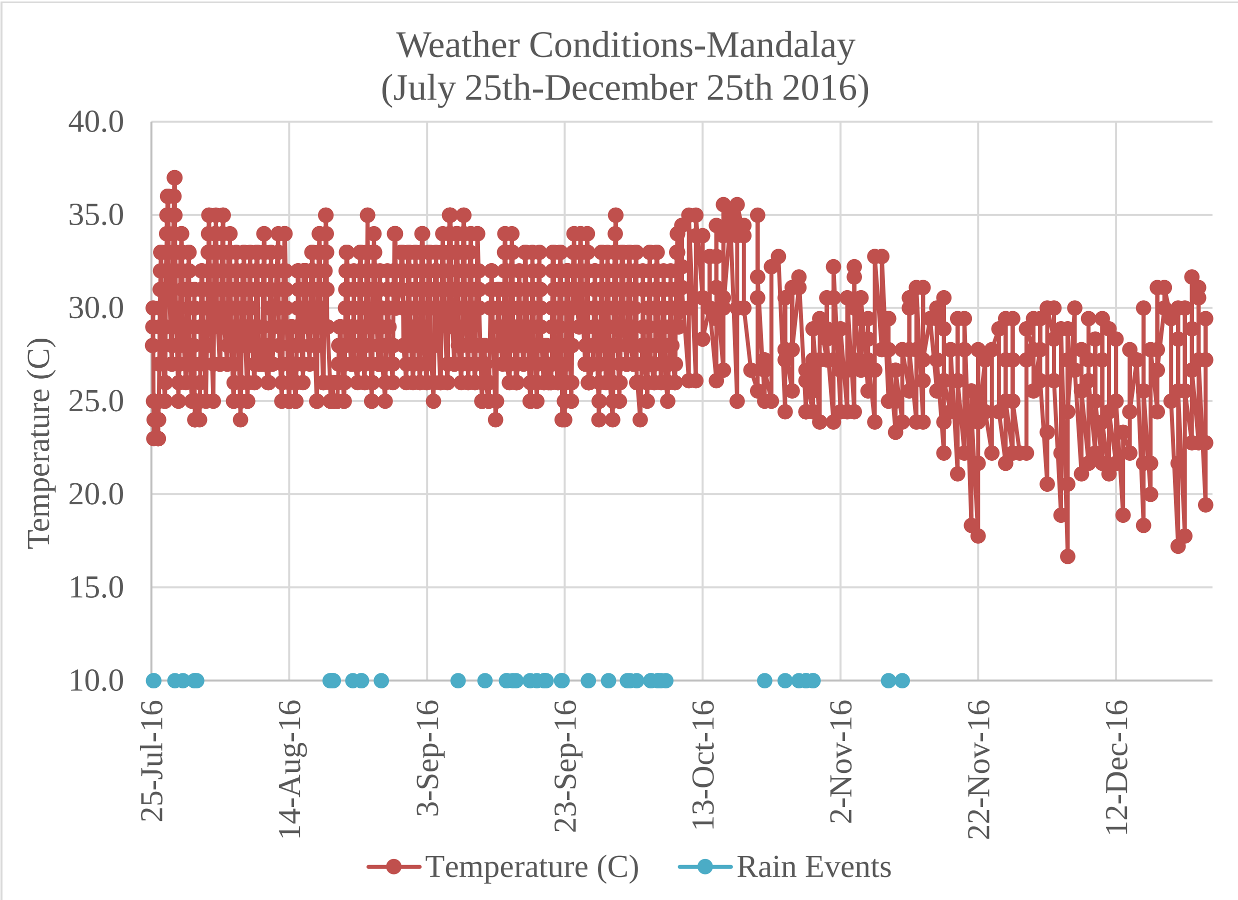
APPENDICES

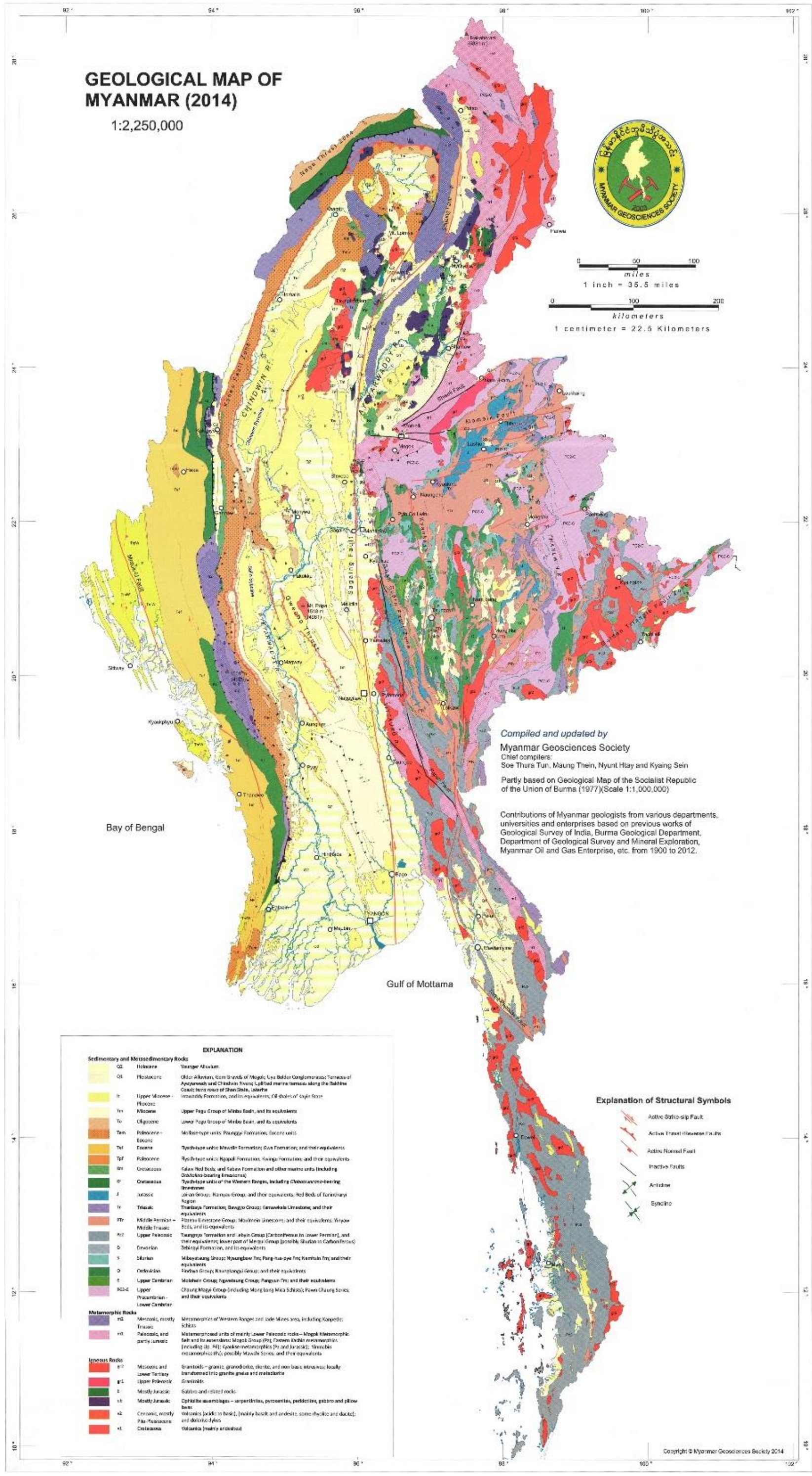
APPENDIX A

WEATHER CONDITIONS DURING DURATION OF THE STUDY (OBTAINED FROM WEATHER UNDERGROUND)


Weather Conditions-Mandalay
(July 25th-December 25th 2016)
Temperature (C)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
25-Jul-16
14-Aug-16
3-Sep-16
23-Sep-16
13-Oct-16
2-Nov-16
22-Nov-16
12-Dec-16
Temperature (C)
Rain Events

APPENDIX B

GEOLOGIC MAP OF MYANMAR (Htay et al., 2014)



GEOLOGICAL MAP OF MYANMAR (2014)
1:2,250,000
1 inch = 35.5 miles
1 centimeter = 22.5 Kilometers
Bay of Bengal
Gulf of Mottama
Compiled and updated by
Myanmar Geosciences Society
Chief compilers:
Soe Thura Tun, Maung Thein, Nyunt Htay and Kyaing Sein
Partly based on Geological Map of the Socialist Republic of the Union of Burma (1977)(Scale 1:1,000,000)
Contributions of Myanmar geologists from various departments, universities and enterprises based on previous works of Geological Survey of India, Burma Geological Department, Department of Geological Survey and Mineral Exploration, Myanmar Oil and Gas Enterprise, etc. from 1900 to 2012.
EXPLANATION
Explanation of Structural Symbols
Active Strike-slip Fault
Active Normal Fault
Inactive Faults
Syncline
Copyright © Myanmar Geosciences Society 2014

APPENDIX C

YDB3 CORE LOG

Interval (m)	Sediment	Color	Other
0.31	Sand & Gravel Conglomerate/ Some clay material	Light Brown, yellow, some gray	Roots and organic matter
2.13	Sandy-clay	Light Brown	
3.10	Silty-clay/ rock fragments	Light Brown	
3.66	Gravel-loam	Light Brown	
4.27	Gravel, angular, poor sorting/ 5-10% loam mixture	Light Brown	
4.88	Gravel, subangular, poorly sorted/ <5% loam mixture	Light Brown	
5.49	Sandy/ <5% gravel/ 10% clay	Light Brown	
6.10	Medium sand and silt/ <5% gravels	Light Brown	
6.71	Sands and gravels, angular, poorly sorted	Light Brown	
7.01	Sand/ <10% angular gravels/ <5% clays	Brown	
7.62	Medium sand/ some gravels	Light Brown	Silicate material
8.23	Medium sand	Dark Brown/ black mixing	Increased water content

APPENDIX D

HEAD MEASUREMENTS

Name	Well Type	Stickup (m)	Elev. (m)	TD (m)	Date	DTW (m)	Head (mamsl)
SVS	Dug Well	0.55	79	6.45	27-Jul	4.61	74.95
					21-Dec	4.86	74.70
OVS	Dug Well	1.16	79	7.64	10-Aug	2.02	78.14
					21-Dec	4.88	75.28
YDB1	Tube Well	0.03	71	22.37	25-Jul	4.17	66.86
					26-Jul	4.05	66.98
					27-Jul	3.95	67.08
					28-Jul	3.86	67.17
					10-Aug	-0.06	71.09
					13-Dec	2.96	68.07
					16-Dec	3.05	67.98
					19-Dec	3.12	67.91
					21-Dec	3.17	67.86
YDB2	Tube Well	0.96	71	24.84	26-Jul	4.58	67.39
					27-Jul	3.95	68.01
					28-Jul	4.36	67.60
					10-Aug	0.72	71.24
					13-Dec	3.69	68.27
					16-Dec	3.75	68.21
					19-Dec	3.84	68.12
YDB3	Tube Well	0.52	71	7.93	16-Dec	3.38	68.13
					19-Dec	3.44	68.07
SA1	Dug Well	0.81	80	13.32	28-Jul	8.38	72.43
					22-Dec	10.55	70.26
MYA1	Dug Well	1.00	75	5.64	8-Aug	0.60	75.40

					10-Dec	5.37	70.63
DW1	Dug Well	1.36	79	11.99	11-Aug	5.50	74.85
					10-Dec	8.56	71.80
					16-Dec	8.77	71.58
DW2	Dug Well	0.94	80	14.84	11-Aug	7.95	73.00
					10-Dec	11.31	69.63
					16-Dec	11.55	69.40
DW3	Dug Well	0.78	78	8.53	28-Jul	3.85	74.93
					2-Aug	1.65	77.13
					8-Aug	2.05	76.73
					11-Aug	2.44	76.34
					10-Dec	5.34	73.44
DW4	Dug Well	1.43	77	7.26	28-Jul	4.06	74.37
					2-Aug	2.69	75.74
					11-Aug	3.13	75.30
					10-Dec	5.79	72.64
DW5	Dug Well	0.92	73	8.93	11-Aug	1.86	72.06
					10-Dec	5.30	68.62
					16-Dec	5.44	68.48
DW6	Dug Well	1.19	80	14.59	30-Jul	8.82	72.37
					5-Aug	7.45	73.74
					11-Aug	7.77	73.42
					10-Dec	11.43	69.76

DW7	Dug Well	0.70	80	10.26	11-Aug	3.70	76.99
					10-Dec	7.45	73.25
					16-Dec	7.68	73.02
DW8	Dug Well	1.08	81	14.67	30-Jul	8.64	73.43
					5-Aug	7.62	74.46
					11-Aug	7.70	74.38
					10-Dec	11.45	70.62
DW9	Dug Well	0.82	76	11.72	30-Jul	5.20	71.62
					5-Aug	4.18	72.64
					11-Aug	4.26	72.57
					10-Dec	7.83	69.00
					16-Dec	8.11	68.72
DW10	Dug Well	1.12	74	7.74	1-Aug	4.68	70.44
					11-Dec	4.77	70.35
					16-Dec	4.87	70.25
DW11	Dug Well	1.17	73	9.02	2-Aug	1.15	73.02
					8-Aug	2.29	71.88
					11-Aug	2.91	71.26
					10-Dec	6.24	67.93
					16-Dec	6.35	67.82
DW12	Dug Well	0.93	78	9.48	2-Aug	2.07	76.86
DW13	Dug Well	1.37	76	10.55	5-Aug	3.61	73.77
					8-Aug	3.39	73.98

					19-Dec	6.76	70.61
DW14	Dug Well	1.07	80	-	11-Aug	6.02	75.04
DW15	Dug Well	1.73	75	11.03	11-Dec	6.09	70.64
DW16	Dug Well	2.11	76	10.16	11-Dec	6.22	71.88

APPENDIX E

HACH HQ 40D RESULTS

Sample	Season	Lat.	Long.	Date	Temp	pH	Eh	Elec. Cond.	DO
Units					Celsius	[H+]	mV	µS/cm	mg/L
WHO Standard					-	6.5-8.0	-	-	-
YDB1	Wet	21.8919	96.0700	29-Jul	30.0	7.55	250	183	5.00
	Dry	21.8919	96.0699	21-Dec	27.8	7.74	166	305	2.78
SVD	Wet	21.8930	96.0639	27-Jul	28.0	7.12	185	751	2.81
	Dry	21.8930	96.0640	21-Dec	27.7	7.19	207	1369	3.27
SVS	Wet	21.8929	96.0640	27-Jul	29.0	7.54	203	1321	2.93
	Dry	21.8929	96.0639	21-Dec	28.1	7.73	177	1513	3.47
Ohbo 1	Wet	21.8944	96.0753	10-Aug	29.2	7.28	268	1258	4.38
	Dry	21.8936	96.0751	21-Dec	27.6	7.30	174	2074	4.03
OVS	Wet	21.8944	96.0753	10-Aug	30.1	7.68	265	1935	4.93
	Dry	21.8945	96.0752	21-Dec	27.3	7.49	185	2028	3.33
TTML1	Dry	21.8913	96.0556	22-Dec	27.5	7.44	214	679	1.67
LS1	Wet	21.9106	96.0597	2-Aug	28.1	7.65	224	587	8.38
	Dry	21.9107	96.0597	20-Dec	28.1	7.69	159	575	8.30

YY1	Wet	21.9094	96.0507	3-Aug	28.2	7.83	220	430	8.05
	Dry	21.9095	96.0506	19-Dec	27.5	8.02	170	430	8.41
MYA1	Wet	21.9033	96.0775	8-Aug	27.4	7.43	230	501	2.48
MYA2	Wet	21.9094	96.0508	8-Aug	28.7	7.75	233	699	8.01
	Dry	21.9043	96.0773	22-Dec	28.9	7.82	203	660	8.77
SA1	Wet	21.9133	96.0519	28-Jul	29.8	7.23	223	1376	1.39
	Dry	21.9009	96.0490	22-Dec	25.9	7.69	226	1979	3.43
SA2	Wet	21.9133	96.0519	28-Jul	29.6	7.65	215	364	7.71
	Dry	21.9009	96.0490	22-Dec	27.0	7.69	175	838	8.47
DW1	Dry	21.9075	96.0499	10-Dec	26.8	7.20	209	1346	1.99
DW2	Wet	21.9075	96.0497	3-Aug	28.7	7.60	224	1396	4.85
	Dry	21.9012	96.0466	10-Dec	26.7	7.31	206	1703	4.48
DW3	Wet	21.9095	96.0556	8-Aug	27.7	7.25	257	2380	2.77
	Dry	21.9096	96.0556	10-Dec	26.0	7.40	195	1961	3.54
DW4	Wet	21.9108	96.0600	2-Aug	29.7	7.17	244	948	3.33
	Dry	21.9107	96.0599	10-Dec	27.3	7.41	199	729	3.54

DW5	Dry	21.9054	96.0536	10-Dec	27.4	7.10	236	417	3.10
DW6	Wet	21.8981	96.0425	5-Aug	26.5	7.44	233	2069	5.08
	Dry	21.8981	96.0426	10-Dec	25.7	7.43	228	2590	4.57
DW7	Dry	21.8964	96.0499	10-Dec	27.0	6.64	230	1108	1.61
DW8	Wet	21.8972	96.0414	5-Aug	28.2	7.23	235	2137	4.26
	Dry	21.8972	96.0413	10-Dec	26.6	8.14	187	2250	4.75
DW9	Wet	21.8986	96.0408	5-Aug	26.5	7.30	236	1589	4.97
	Dry	21.8987	96.0407	10-Dec	26.7	7.42	225	1901	3.86
DW10	Wet	21.9294	96.0672	1-Aug	28.4	7.65	230	2950	4.30
	Dry	21.9294	96.0678	11-Dec	24.6	7.41	236	1826	2.23
DW11	Wet	21.9103	96.0603	8-Aug	27.1	7.65	233	267	4.16
	Dry	21.9102	96.0603	10-Dec	26.6	7.10	223	372	2.52
DW12	Wet	21.9092	96.0553	2-Aug	28.7	6.93	267	1807	2.43
DW13	Wet	21.9103	96.0500	8-Aug	28.0	7.46	238	1744	4.75
	Dry	21.9102	96.0499	19-Dec	27.0	7.53	195	2350	4.38
DW15	Dry	21.8988	96.0369	11-Dec	26.5	7.18	207	1959	3.33

WWTP2	Wet	21.9250	96.0633	1-Aug	28.4	6.86	251	1510	1.79
	Dry	21.9250	96.0634	19-Dec	27.0	7.09	215	1657	2.77
WWTP-SW	Dry	21.9252	96.0630	19-Dec	27.0	8.48	161	697	9.81
Sewage-DW10	Dry	21.9294	96.0676	22-Dec	25.8	7.42	-319	888	0.06
SW1	Wet	21.8922	96.0544	30-Jul	NA	9.21	185	160	8.99
	Dry	21.8920	96.0548	11-Dec	27.7	7.93	187	616	8.62
AYE1	Wet	21.9856	96.0550	9-Aug	27.0	7.47	203	70	7.68
AYE2	Wet	21.9667	96.0517	9-Aug	26.5	7.13	247	61	7.58
AYE5	Dry	21.9493	96.0418	17-Dec	21.9	8.09	282	192	8.91
AYE6	Dry	21.9085	96.0174	17-Dec	21.9	8.27	212	240	8.96
AYE7	Dry	21.8854	95.9987	17-Dec	22.0	8.15	199	105	8.90
AYE8	Dry	21.8305	95.4546	17-Dec	23.5	8.10	203	263	8.74

APPENDIX F

EXACT MICRO 20 AND HACH TEST KIT RESULTS

Sample	Season	Date	Turbidity	T. Alk.	T. Hardness	Ca (as CaCO3)	CO3	HCO3	SO4	S(2-)	F	Br	Cl	T. Cl	F. Cl	PO4	NO3	NO2	NH3	CN	T. Mn	T. Fe	Al	Cu	As
Units			NTU	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Range			4-900	9-210	1-600	20-400	-	-	2-210	0.01-1.6	0.01-1.5	0.01-12	3-300	0.01-6.2	0.01-6.2	0.03-4.4	0.1-30	0.01-1.8	0.02-2.4	0.01-1.1	0.01-1.5	0.03-6.0	0.01-1.2	0.01-11	10-500
WHO Standards			5	200	100	75	-	-	250	0.05	0.8	-	200	-	0.6	-	50	3	1.5	0.01	0.1	0.3	0.1	1	0.01
	Wet	29-Jul	21.00	74.00	17	23.00	2.47	4.39	54	0.07	0.85	0.09	10	0.04	0.05	0.44	1.77	0.01	0.04	<0.01	10.00	0.28	<0.01	0.02	0.01
YDB1	Dry	21-Dec	16.00	124.00	417	65.00	4.13	7.36	<2	<0.01	1.01	0.03	<3	0.05	<0.01	0.81	<0.1	<0.01	0.53	<0.01	<0.01	1.27	<0.01	0.02	ND
	Wet	27-Jul	<4	207.00	58	115.00	6.90	12.29	94	0.04	0.56	0.06	246	0.03	0.15	0.05	4.52	<0.01	<0.02	<0.01	<0.01	1.45	<0.01	0.03	ND
SVD	Dry	21-Dec	<4	188.00	289	156.00	6.27	11.16	117	<0.01	1.36	0.04	109	0.03	<0.01	<0.03	6.10	<0.01	<0.02	<0.01	<0.01	0.49	<0.01	0.02	ND
	Wet	27-Jul	9.00	210.00	77	52.00	7.00	12.46	179	0.04	0.96	0.10	229	0.06	0.06	<0.03	3.27	<0.01	<0.02	<0.01	<0.01	<0.03	0.02	0.02	ND
SVS	Dry	21-Dec	94.00	201.00	417	41.00	6.70	11.93	114	0.02	>1.5	0.15	240	0.05	0.03	1.68	9.20	<0.01	<0.02	<0.01	<0.01	0.27	0.17	0.02	<10
	Wet	10-Aug	<4	194.00	500	112.00	6.47	11.51	80	0.02	1.10	0.04	239	0.03	0.03	<0.03	7.50	0.05	<0.02	<0.01	<0.01	0.23	<0.01	0.04	ND
Ohbo 1	Dry	21-Dec	116.00	209.00	52	90.00	6.97	12.41	101	0.03	1.26	0.07	<3	0.04	0.03	0.07	<0.1	0.03	<0.02	<0.01	<0.01	0.17	<0.01	0.02	ND
	Wet	10-Aug	6.00	408.00	660	53.00	13.60	24.22	232	0.02	1.30	0.06	378	0.04	0.03	0.32	6.40	0.05	<0.02	<0.01	<0.01	0.57	<0.01	0.02	0.01
OVS	Dry	21-Dec	<4	790.00	455	154.00	26.33	46.89	186	<0.01	1.48	1.96	460	0.04	0.04	<0.03	7.00	<0.01	<0.02	<0.01	<0.01	0.16	<0.01	0.03	ND
TTML1	Dry	22-Dec	<4	161.00	217	62.00	5.37	9.56	15	<0.01	1.00	0.04	68	0.03	<0.01	0.08	4.15	0.10	<0.02	<0.01	<0.01	<0.03	<0.01	0.02	ND
	Wet	2-Aug	<4	152.00	395	103.00	5.07	9.02	54	<0.01	0.58	<0.01	43	<0.01	<0.01	0.11	2.19	<0.01	<0.02	<0.01	0.04	0.04	<0.01	<0.01	ND
LS1	Dry	20-Dec	22.00	187.00	324	146.00	6.23	11.10	13	<0.01	0.67	0.04	186	0.05	0.02	<0.03	<0.1	<0.01	<0.02	<0.01	<0.01	0.13	<0.01	0.02	ND
	Wet	3-Aug	8.00	134.00	76	59.00	4.47	7.95	3	<0.01	1.12	<0.01	<3	<0.01	<0.01	0.20	<0.1	<0.01	<0.02	<0.01	<0.01	0.30	<0.01	<0.01	ND
YY1	Dry	19-Dec	8.00	156.00	105	47.00	5.20	9.26	<2	<0.01	0.58	<0.01	22	0.05	0.03	0.06	<0.1	<0.01	<0.02	<0.01	<0.01	0.37	<0.01	<0.01	<10
MYA1	Wet	8-Aug	129.00	158.00	225	71.00	5.27	9.38	<2	<0.01	0.72	<0.01	75	0.05	0.05	<0.03	<0.1	<0.01	0.62	<0.01	<0.01	0.36	<0.01	0.03	0.01
	Wet	8-Aug	50.00	172.00	456	100.00	5.73	10.21	<2	4.00	0.36	0.04	191	0.05	0.03	<0.03	<0.1	<0.01	0.12	<0.01	<0.01	0.14	<0.01	0.02	ND
MYA2	Dry	22-Dec	6.00	198.00	249	77.00	6.60	11.75	<2	<0.01	0.95	0.08	68	0.05	0.03	<0.03	<0.1	<0.01	<0.02	0.02	<0.01	<0.03	<0.01	<0.01	ND
	Wet	28-Jul	14.00	>210	595	140.00	>7	>12.46	194	0.02	0.99	0.20	300	0.04	0.05	1.14	930.00	98.00	0.05	<0.01	<0.01	1.48	<0.01	0.03	0.02
SA1	Dry	22-Dec	99.00	940.00	113	113.00	31.33	55.79	156	<0.01	1.27	<0.01	243	0.05	0.04	<0.03	<0.1	<0.01	<0.02	<0.01	<0.01	<0.03	0.20	<0.01	ND
	Wet	28-Jul	<4	190.00	292	95.00	6.33	11.28	22	0.06	0.85	0.03	53	0.03	0.03	0.29	6.40	0.23	<0.02	<0.01	<0.01	0.86	0.02	0.02	ND
SA2	Dry	22-Dec	<4	180.00	181	181.00	6.00	10.68	67	<0.01	1.10	0.10	249	0.09	0.03	0.05	24.20	0.10	<0.02	<0.01	<0.01	<0.03	<0.01	<0.01	ND
DW1	Dry	10-Dec	<4	175.00	276	109.00	5.83	10.39	92	<0.01	2.22	0.05	141	0.03	<0.01	<0.03	3.20	0.02	<0.02	<0.01	<0.01	0.47	<0.01	0.01	ND
	Wet	3-Aug	6.00	182.00	229	51.00	6.07	10.80	134	<0.01	2.60	0.04	161	<0.01	0.03	0.40	14.90	0.08	<0.02	<0.01	0.04	0.05	<0.01	0.01	ND
DW2	Dry	10-Dec	<4	156.00	254	66.00	5.20	9.26	164	22.00	1.44	0.04	211	<0.01	<0.01	0.18	17.80	<0.01	<0.02	<0.01	<0.01	<0.03	<0.01	0.01	ND
	Wet	8-Aug	6.00	147.00	475	217.00	4.90	8.73	356	<0.01	1.62	0.04	314	<0.01	<0.01	0.08	8.60	0.06	<0.02	<0.01	<0.01	<0.03	<0.01	<0.01	ND
DW3	Dry	10-Dec	<4	155.00	466	351.00	5.17	9.20	190	<0.01	0.93	0.08	422	0.03	0.02	<0.03	1.40	0.02	<0.02	<0.01	<0.01	0.26	<0.01	<0.01	ND
	Wet	2-Aug	<4	162.00	360	265.00	5.40	9.62	154	0.02	1.20	0.05	172	0.03	0.03	0.56	5.80	0.02	<0.02	<0.01	0.13	<0.03	<0.01	0.02	ND
DW4	Dry	10-Dec	<4	156.00	239	174.00	5.20	9.26	9	<0.01	0.67	0.08	34	0.04	0.03	0.34	11.70	0.03	<0.02	<0.01	<0.01	0.26	<0.01	0.02	ND
DW5	Dry	10-Dec	<4	144.00	114	58.00	4.80	8.55	15	<0.01	0.66	0.04	14	0.03	<0.01	0.71	<0.1	<0.01	<0.02	<0.01	<0.01	2.70	<0.01	0.01	0.01
	Wet	5-Aug	<4	193.00	567	55.00	6.43	11.46	160	<0.01	11.50	0.06	239	0.04	0.05	<0.03	<0.1	<0.01	<0.02	<0.01	<0.01	1.43	<0.01	0.02	ND
DW6	Dry	10-Dec	<4	172.00	214	47.00	5.73	10.21	186	<0.01	5.95	0.05	246	0.07	0.03	<0.03	6.30	<0.01	<0.02	<0.01	<0.01	0.20	<0.01	0.02	ND
DW7	Dry	10-Dec	<4	162.00	223	271.00	5.40	9.62	45	<0.01	0.52	0.03	179	0.03	<0.01	0.07	2.38	0.05	<0.02	<0.01	<0.01	3.80	<0.01	0.03	ND
	Wet	5-Aug	<4	193.00	454	57.00	6.43	11.46	132	<0.01	10.50	0.06	642	0.04	0.06	<0.03	12.90	<0.01	<0.02	<0.01	<0.01	1.16	<0.01	0.01	ND
DW8	Dry	10-Dec	5.00	1260.00	520	40.00	42.00	74.79	163	<0.01	6.10	0.09	192	0.07	0.03	<0.03	<0.1	0.01	<0.02	<0.01	<0.01	<0.03	0.07	0.02	ND
	Wet	5-Aug	<4	171.00	539	164.00	5.70	10.15	128	<0.01	8.90	0.07	315	<0.01	0.03	0.12	113.00	0.14	0.05	<0.01	<0.01	2.00	<0.01	0.01	ND
DW9	Dry	10-Dec	<4	144.00	562	214.00	4.80	8.55	197	<0.01	5.60	0.05	256	0.04	0.02	0.07	9.10	0.02	<0.02	<0.01	<0.01	0.27	<0.01	0.02	ND
	Wet	1-Aug	10.00	186.00	424	45.00	6.20	11.04	400	0.03	2.22	<0.01	514	<0.01	<0.01	2.66	167.00	0.08	0.10	<0.01	<0.01	0.43	<0.01	<0.01	0.03
DW10	Dry	11-Dec	6.00	179.00	369	66.00	5.97	10.62	131	<0.01	0.87	0.06	119	0.06	0.05	<0.03	<0.1	<0.01	<0.02	<0.01	<0.01	0.62	<0.01	<0.01	0.03
	Wet	8-Aug	10.00	110.00	104	44.00	3.67	6.53	4	<0.01	13.80	0.06	12	<0.01	0.11	0.55	<0.1	0.02	0.07	<0.01	<0.01	0.10	<0.01	<0.01	ND
DW11	Dry	10-Dec	<4	140.00	129	68.00	4.67	8.31	<2	<0.01	0.34	0.05	10	0.03	<0.01	0.53	0.06	0.01	<0.02	<0.01	<0.01	0.16	<0.01	0.01	ND
DW12	Wet	2-Aug	6.00	-	-	-	-	-	127	-	-	-	-	-	-	-	11.60	-	-	-	-	-	-	-	-
	Wet	8-Aug	5.00	162.00	494	167.00	5.40	9.62	142	<0.01	1.82	0.04	188	<0.01	<0.01	<0.03	16.30	0.10	<0.02	<0.01	<0.01	0.06	<0.01	<0.01	ND
DW13	Dry	19-Dec	<4	162.00	438	307.00	5.40	9.62	162	<0.01	3.60	<0.01	268	0.04	0.04	<0.03	196.00	0.07	<0.02	<0.01	<0.01	0.23	<0.01	0.02	ND
DW15	Dry	11-Dec	<4	155.00	415	350.00	5.17	9.20	199	<0.01	0.70	0.04	244	0.03	<0.01	<0.03	2.60	0.01	<0.02	<0.01	<0.01	0.29	<0.01	<0.01	ND
	Wet	1-Aug	<4	183.00	232	323.00	6.10	10.86	115	0.05	0.94	0.03	200	<0.01	<0.01	<0.03	3.71	0.27	<0.02	<0.01	0.23	0.19	<0.01	<0.01	ND
WWTP2	Dry	19-Dec	<4	174.00	228	334.00	5.80	10.33	176	<0.01	1.17	0.05	189	<0.01	<0.01	<0.03	3.86	0.03	<0.02	<0.01	<0.01	0.60	<0.01	0.03	0.02
WWTP-SW	Dry	19-Dec	123.00	197.00	272	70.00	6.57	11.69	<2	<0.01	1.44	0.17	40	0.05	0.05	0.37	22.90	1.62	1.31	<0.01	<0.01	0.21	<0.01	0.10	ND
Sewage-DW10	Dry	22-Dec	61.00	202.00	122	74.00	6.73	11.99	<2	<0.01	0.93	0.04	65	0.04	<0.01	3.60	2.44	0.05	<0.02	<0.01	<0.01	0.12	<0.01	<0.01	0.01
	Wet	30-Jul	28.00	105.00	157	36.00	3.50	6.23	<2	0.01	1.23	0.11	124	0.11	0.02	0.22	<0.1	0.03	<0.02	<0.01	0.02	0.17	<0.01	<0.01	ND
SW1	Dry	11-Dec	64.00	152.00	242	89.00	5.07	9.02	3	<0.01	1.08	0.06	14	0.07	0.04	0.83	<0.1	<0.01	<0.02	<0.01	<0.01	0.67	<0.01	<0.01	0.01
AYE1	Wet	9-Aug	73.00	28.00	24	17.00	0.93	1.66	<2	<0.01	1.07	0.07	3	0.04	0.17	<0.03	1.18	<0.01	<0.02	<0.01	<0.01	2.40	<0.01	<0.01	ND
AYE2	Wet	9-Aug	78.00	25.00	28	19.00	0.83	1.48	<2	<0.01	0.72	0.08	6	0.04	0.17	0.04	1.02	<0.01	<0.02	<0.01	<0.01	0.72	<0.01	<0.01	ND
AYE5	Dry	17-Dec	42.00	46.00	67	<20	1.53	2.73	<2	<0.01	0.75	0.09	<3	0.05	0.04	0.08	<0.1	<0.01	<0.02	<0.01	<0.01	0.17	<0.01	0.02	0.01
AYE6	Dry	17-Dec	42.00	43.00	65	20.00	1.43	2.55	<2	<0.01	0.23	0.05	13	0.05	0.05	<0.03	<0.1	<0.01	<0.02	<0.01	<0.01	0.17	<0.01	0.01	0.01
AYE7	Dry	17-Dec	56.00	56.00	67	25.00	1.87	3.32	<2	<0.01	0.81	<0.01	18	0.07	0.04	0.17	<0.1	<0.01	<0.02	<0.01	<0.01	0.94	<0.01	<0.01	0.01
AYE8	Dry	17-Dec	53.00	93.00	92	40.00	3.10	5.52	<2	<0.01	0.37	0.08	32	<0.01	<0.01	<0.03	<0.1	<0.01	<0.02	<0.01	0.06	0.75	<0.01	<0.01	-

APPENDIX G

MAJOR ION CHEMISTRY

Sample	Season	Date	TDS	Li	Na	NH4	K	Mg	Ca	F	Cl	NO3	PO4	SO4
Units			ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limits			-	0.01	1.5	0.01	1	1	1	0.05	0.2	0.02	0.05	0.5
WHO Standard			600.0	-	-	-	-	30	75	0.8	200	50	-	250
YDB1	Wet	29-Jul	103.7	ND	34.77	ND	2.01	1.11	12.03	0.15	3.74	3.33	0.33	33.77
	Dry	21-Dec	58.9	ND	11.98	3.14	2.71	5.59	22.31	0.13	1.43	0.66	0.54	1.10
LS1	Wet	2-Aug	237.6	ND	41.26	ND	1.12	19.22	64.57	0.06	22.62	272.60	ND	18.14
	Dry	20-Dec	167.5	ND	37.72	ND	1.19	18.24	62.88	0.09	19.61	4.59	ND	15.38
SVD	Wet	27-Jul	241.6	ND	147.14	ND	1.80	46.32	21.92	0.08	4.25	1.49	ND	5.16
	Dry	21-Dec	457.3	0.01	187.98	ND	1.82	53.45	65.15	0.68	57.46	19.32	ND	74.58
SVS	Wet	27-Jul	547.8	0.01	391.88	ND	51.81	45.20	26.27	0.07	7.33	1.28	ND	12.44
	Dry	21-Dec	482.7	0.01	263.08	ND	42.42	24.07	20.05	0.62	34.61	18.58	1.40	79.11
Ohbo1	Wet	10-Aug	371.7	ND	197.42	0.49	1.14	37.44	27.63	0.61	57.47	21.76	ND	32.85
	Dry	21-Dec	613.7	ND	343.16	ND	1.12	44.04	46.84	0.74	90.71	57.72	ND	61.41
OVS	Wet	10-Aug	763.7	0.01	315.24	ND	52.37	54.45	29.16	0.70	139.74	36.30	1.24	137.48
	Dry	21-Dec	770.4	ND	316.52	ND	40.08	66.80	56.48	0.81	120.94	23.00	ND	115.16
YY1	Wet	3-Aug	131.9	0.00	66.22	ND	1.96	9.06	26.51	0.23	12.32	0.15	0.07	7.03
	Dry	19-Dec	129.6	ND	61.88	0.05	1.92	9.31	27.41	0.22	11.87	0.25	ND	6.88
SA1	Wet	28-Jul	889.4	0.02	375.57	0.06	10.55	37.38	63.01	0.39	137.15	115.85	1.43	136.49
	Dry	22-Dec	805.4	ND	373.12	ND	7.00	37.44	53.60	0.80	137.51	49.91	0.99	127.67
SA2	Wet	28-Jul	176.2	ND	45.43	0.21	1.76	20.74	46.66	0.48	26.00	13.28	ND	18.69
	Dry	22-Dec	286.8	ND	90.30	ND	2.02	25.58	61.06	0.40	50.26	46.57	ND	35.75
MYA2	Wet	8-Aug	157.1	ND	80.38	0.57	2.15	26.60	26.77	0.29	2.66	0.07	ND	3.17
	Dry	22-Dec	156.3	ND	78.44	ND	2.04	25.82	32.40	0.32	2.51	0.32	ND	2.80
DW2	Wet	3-Aug	539.0	0.04	276.76	1.30	2.04	17.36	27.74	0.84	101.76	73.00	ND	83.69
	Dry	10-Dec	702.8	ND	336.00	ND	1.08	23.08	37.80	0.94	136.23	92.71	ND	115.41
DW3	Wet	8-Aug	1064.0	0.01	303.84	0.09	16.38	81.94	99.32	0.23	270.42	80.47	1.23	263.86
	Dry	10-Dec	758.6	ND	227.35	ND	9.15	74.30	114.45	0.20	189.21	5.85	0.75	132.21
DW4	Wet	2-Aug	275.6	ND	65.98	0.02	7.56	30.17	35.08	0.12	52.52	10.63	ND	72.19
	Dry	10-Dec	215.3	ND	48.64	ND	3.68	20.30	77.53	0.21	27.77	35.15	0.20	19.25
DW9	Wet	5-Aug	582.6	ND	174.22	ND	1.02	68.36	79.96	1.15	112.08	153.66	ND	97.15
	Dry	10-Dec	725.1	ND	241.16	ND	2.40	74.04	75.52	1.72	155.25	134.12	ND	135.57
DW10	Wet	1-Aug	1326.0	ND	569.84	ND	72.32	42.93	30.92	0.50	276.34	243.89	1.82	264.19
	Dry	11-Dec	668.6	ND	334.76	ND	56.76	34.64	33.84	0.35	100.61	17.43	1.11	90.88
DW11	Wet	8-Aug	79.1	ND	20.44	0.39	4.83	8.16	23.01	0.15	8.08	0.04	0.46	6.82
	Dry	10-Dec	111.1	ND	25.75	0.05	5.94	12.76	34.83	0.15	15.30	0.60	0.37	7.43
DW13	Wet	8-Aug	665.1	0.02	247.08	ND	29.00	43.29	68.02	0.77	124.82	153.11	0.16	107.62
	Dry	19-Dec	934.2	ND	310.91	ND	32.64	61.25	114.75	0.82	213.06	331.07	ND	115.73
WWTP2	Wet	1-Aug	553.6	0.01	170.36	ND	3.92	49.66	122.44	0.13	77.34	18.20	ND	114.47
	Dry	19-Dec	585.9	ND	164.96	ND	3.32	54.92	140.88	0.12	85.49	37.88	ND	116.41
SW1	Wet	30-Jul	60.8	ND	17.16	1.08	3.75	5.00	14.77	0.16	6.25	0.26	0.39	5.14
	Dry	11-Dec	193.3	ND	66.20	1.69	12.46	18.38	43.10	0.38	24.27	2.63	1.15	14.68
AYE1	Wet	9-Aug	21.9	ND	2.48	0.06	1.27	2.57	7.08	0.06	0.51	0.04	ND	1.63
AYE2	Wet	9-Aug	18.1	ND	2.40	0.05	1.22	2.50	6.91	0.06	0.48	0.08	ND	1.62
AYE5	Dry	17-Dec	28.0	ND	4.38	0.12	1.18	4.23	11.45	0.08	0.92	0.13	ND	2.34
AYE6	Dry	17-Dec	31.6	ND	5.00	0.14	1.50	4.33	11.98	0.08	1.34	7.61	ND	2.48
AYE7	Dry	17-Dec	30.6	ND	4.50	0.09	1.22	4.29	11.67	0.08	0.99	0.45	ND	2.39
WWTP-SW	Dry	19-Dec	237.1	ND	95.89	3.18	12.42	13.62	34.54	0.34	46.75	4.89	2.00	13.20
Sewage-DW10	Dry	22-Dec	289.7	ND	125.83	28.82	13.07	10.93	33.61	0.65	50.77	0.11	6.70	15.80

APPENDIX H

E. COLI RESULTS

Sample	**Season**	***E. coli*** **(MPN/100 mL)**
YDB1	Wet	-
	Dry	>100
LS1	Wet	1.1
	Dry	<1
SVD	Wet	<1
	Dry	<1
SVS	Wet	48.3
	Dry	-
Ohbo1	Wet	<1
	Dry	<1
OVS	Wet	>100
	Dry	>100
YY1	Wet	<1
	Dry	<1
SA1	Wet	-
	Dry	>100
SA2	Wet	-
	Dry	<1
MYA2	Wet	<1
	Dry	<1
DW2	Wet	>100
	Dry	-
DW3	Wet	13.6
	Dry	>100
DW4	Wet	48.3
	Dry	13.6
DW9	Wet	-
	Dry	>100
DW10	Wet	>100
	Dry	>100
DW11	Wet	>100
	Dry	2.4
DW13	Wet	48.3
	Dry	>100
WWTP2	Wet	3.2
	Dry	<1
SW1	Wet	-

	Dry	>100
WWTP-SW	Dry	>100

APPENDIX I

STABLE ISOTOPE DATA

Sample ID	Type	δ2H	δ18O
ISO1	Rain	-48.7557	-7.5043
ISO2	Rain	-89.3878	-13.0253
ISO3	Rain	-126.8082	-17.8571
AYE1	SW	-61.1830	-9.3079
AYE2	SW	-61.0389	-9.2164
SW1	SW	-52.5074	-7.7777
DW10	GW	-60.5906	-9.0123
DW11	GW	-54.4201	-8.0964
DW13	GW	-36.7378	-5.5832
DW2	GW	-40.3832	-5.9765
DW3	GW	-50.1678	-7.4673
DW6	GW	-46.3949	-7.1627
DW8	GW	-49.5963	-7.6067
DW9	GW	-52.9851	-8.0904
MYA1	GW	-59.6363	-8.3855
OVS	GW	-47.2183	-6.9299
SA1	GW	-45.0052	-6.9315
SVS	GW	-41.9085	-6.0689
SA2	GW	-36.6656	-5.5349
MYA2	GW	-53.0699	-8.2953
SVD	GW	-37.1941	-5.4773
LS1	GW	-35.2036	-5.2861
OHBO1	GW	-30.6108	-4.3924
WWTP2	GW	-51.4385	-7.7961
YDB1	GW	-83.5202	-11.9979
YY1	GW	-30.1364	-4.6484