Water quality and physical hydrogeology of the Amarapura township, Mandalay, Myanmar

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Abstract

Mandalay is a major city in central Myanmar with a high urban population and which lacks a central 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 wells and tube wells, determine quantitative data on characteristics of the Amarapura Aquifer, and compare seasonal variations in groundwater flow and quality. Water samples were collected during the dry and wet seasons, then analyzed for major ion chemistry using ion chromatography to identify indicators of wastewater contamination transport to the shallow aquifer and to compare seasonal variations in groundwater chemistry. An open-source analytic 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 wells 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, chloride, nitrate, ammonium, and *E. coli*. Physical measurements and GFLOW characterize groundwater flow directions predominantly towards the Irrawaddy River and with average linear velocities 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.

Keywords Myanmar · Groundwater development · Urban groundwater · Water quality

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, which has caused both a lack of access to basic information and a clear understanding of hydrogeology (Anatomy 2013). One of the causes of the lack of knowledge of hydrogeology is that urban centers such as Mandalay 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 lacks a wastewater management system, a solid waste disposal procedure, 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). In the urban areas of the country of Myanmar, 76.38% have access to basic sanitation services, and in 2015 around 75% of the population were using lined latrines with water, 12% were using septic systems, and the remainder using sewers (JMP 2018). Open-defecation was not witnessed by the authors.

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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 50 m 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 computer software and licenses are major limiting factors when conducting this type of research. Programs such as QGIS (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.

The purpose of this research study was to gain a preliminary understanding of the physical and chemical hydrogeology of the aquifer serving Amarapura Township in Mandalay. The objectives of the study are to: (1) identify drinking water contaminants and assesses water quality between dug wells, tube wells, and surface waters; (2) compare and identify seasonal variations in groundwater flow and quality, and to yield quantitative data on the hydrogeologic properties of the Amarapura Aquifer using an analytic element model; and (3) use open-source software programs that assist in educating the locals on issues in their region as they develop in the future.

Study area

Mandalay is in central Myanmar on the west side of Southeast Asia (Fig. 1). The city is about 70–80 m above mean sea level (m amsl) in a flood plain for the Irrawaddy River between the Shan Plateau and the Sagaing Mountains (Fig. 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 km long, and its drainage basin is about 414,400 km² (Kravtsova et al. 2008).

The Amarapura Township contains about 235,000 people and is located on the south side of Mandalay (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; Fig. 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, while the Shwe-Ta-Chaung canal runs from Mandalay through the Amarapura region between TTML and the Irrawaddy River (Fig. 1). The Shwe-Ta-Chaung canal is one of the larger discharges of wastewater from the city of Mandalay into the Irrawaddy River.

Climate

Mandalay experiences monsoon rains and is considered to be a tropical savannah, averaging 1,161 mm 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 to 39 °C with an average between 20 and 30 °C. 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).

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, whereas 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; Fig. 2). The Shan Plateau is made of limestone formations containing predominantly calcite (CaCO₃), with other mineral deposits including magnesite (MgCO₃), barite (BaSO₄), and various gemstones (Myanmar Ministry of Mines, Ministry of Education, Ministry of Industry 2017).

Taung Tha Man Lake (TTML) is an oxbow lake formed by either the braided Irrawaddy River or the meandering Myitnge

Fig. 1 Map of Mandalay and the Amarapura Township, in Myanmar

River, which contains channel and bar deposits (Kyi 2005). 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).

Materials and methods

Research was conducted during the wet and dry seasons in Mandalay, Myanmar. Wet-season sampling was conducted from 20 July–12 August 2016. Dry-season sampling was conducted from 10 to 21 December 2016 (see Fig. 3 for sampling locations).

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 (Fig. 3). These water sources were tested for physico-chemical parameters, major ion chemistry, selected metals, and *E. coli*.

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 sampled facility before filling. A Hach HQ40D multi-probe (Loveland, Colorado, USA) was used to take physio-chemical measurements including temperature, pH, reduction–oxidation potential (Eh), electrical conductivity (EC), and dissolved oxygen (DO) at each sampling site. Industrial Test Systems eXact Micro 20 photometers (Rock Hill, South Carolina, USA) and test strips were used in initial screening of these water samples. All samples were tested for turbidity, total alkalinity, total hardness, cyanide (CN^-), nitrite (NO_2^-), sulphide (S^{2-}), copper (Cu^{2+}), 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).

Samples for analysis at Northern Illinois University (USA) were collected in sterile 50-ml centrifuge tubes. Each was filtered ($0.2\ \mu\text{m}$) 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. Analysis was conducted to determine major cations including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), ammonium (NH_4^+), and lithium (Li^+), and anions including fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}).

Legend

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

Fig. 2 Geologic map of Mandalay

Testing for *E. coli* was conducted using Aquagenx Compartment Bag Test (CBT) kits (Chapel Hill, North Carolina), as this method 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 min, before the water was transferred into a five-column Whirl-Pak bag, where the water separated into 5, 10, 15, 20, and 25-ml columns, and was allowed to sit for 24–48 h, 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). The detection for the kit is 1 MPN/100 ml with an upper 95% confidence limit of 5.14 MPN/100 ml (see manufactures instructions). For the purpose of this research, any result greater than 1 MPN/100 ml was considered positive, which, according to the World Health Organization (WHO), is considered intermediate risk/probably safe (WHO 2008).

Physical hydrogeology

During the dry and wet seasons, 18 wells were examined (Fig. 3), including 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-ft water-level-meter tape (Dundas, Ontario, Canada). 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 observations at YDB 3 (tube well) provided information on local tube well construction. The method used is called manual ‘sludging’, which is common in Asia (Danert 2009).

Fig. 3 Mandalay study site sampling locations (Amarapura Township)

The well was constructed of 2 in (5 cm) PVC pipe. A 10 ft (3 m) screen was constructed by sawing slits into the PVC approximately every half inch (1 cm).

Grain size analysis

Grain size analysis was conducted for sediments collected from the drilling of YDB3. 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), coarse 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).

Hydraulic conductivity measurements

Hydraulic conductivity (K) was determined by conducting falling and rising head slug tests in two tube wells (YDB1

and YDB2) in the Amarapura Aquifer during the wet season and three tube wells (YDB1, YDB2 and 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 (USA) 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 contradicted common assumptions used in the Hvorslev method (Butler et al. 2003). The Hvorslev 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 contradict other assumptions in the Hvorslev method (Fetter 2001).

Groundwater level measurements

Depth to groundwater from the top of the casing, the stick up, and the total depth were measured using a Heron Instruments 150-ft water level meter tape accurate to 0.01 decimal feet in all dug wells, as well as tube wells YDB1, YDB2, and YDB3. All other tube wells were in use and total depths reported by their owners. An In-Situ Inc. Rugged TROLL 100 (Fort

Collins, Colorado) and Solinst Levellogger 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 two-dimensional (2D) numerical code based on the analytic 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 Climate Research Unit (CRU; Harris et al. 2014). Data from the International Water Management 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 (Eq. 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 using the Quantum Geographic Information System's (QGIS) program using an open-source plug-in map from Google (Quantum Geographic Information System 2016). Digital elevation models were downloaded for the country of Myanmar from the 2000 Shuttle Radar Topography Mission (SRTM) in 2016 at a resolution of three arc seconds. These shaded relief maps were then interpolated into 1-m contour maps on QGIS (Quantum Geographic Information System 2016). 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 wells 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. 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 the potentiometric surface of groundwater levels across the study site.

Results

Field survey

The city of Mandalay has access to piped water, while the population in the Amarapura Township obtains their water supply from groundwater by access to dug wells and tube wells. Dug wells are about a meter in diameter and range from 7 to 15 m deep in mixed medium-coarse sand and gravel layers (Fig. 4). The dug wells are lined with bricks 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 who use these on a daily basis is unknown but is estimated to be from 50 to 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. Water from dug wells is primarily used for cooking, cleaning, and bathing, activities which directly occur next to the well and the buckets are not sanitary. Buckets were usually made of excess rubber from tires or steel; additionally, from conversations with well owners, most people report their water tastes salty.

Fig. 4 Dug well construction diagram (DW10 adjacent to Shwe-Ta-Chaung canal)

Many people have access to tube wells, which are shared among individual families or for private business purposes. The tube wells range from 15 to 60 m deep and are usually installed by local drillers using a manual ‘sludging’ drilling method (Danert 2009). Often these wells were installed next to an old dug well. Most tube wells had hand pumps, but a few had compressors.

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 (Fig. 3). Subsidiary canals connect with it at various intersections. A wastewater treatment plant is in the Shwe-Ta-Chaung canal between Mandalay and Amarapura but has not been operational; 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 overflowed by rising water levels during the wet season. The disposal process

is unknown but is suspected to be collected and piled in local landfills, which are open pits that are unlined and uncovered.

Water quality

Geochemistry

Results indicate that chloride, nitrate, ammonium, total dissolved solids, electrical conductivity, and *E. coli* are key indicators of wastewater contamination to the Amarapura Aquifer (Tables 1, 2, and 3). Chloride-bromide ratios were compared for similar signals from other studies indicating anthropogenic contamination from wastewater sources (Table 2; Vengosh and Pankratov 1998).

Major ion chemistry

Piper diagrams are used to classify water types (Fig. 5), whereby major ion chemistry revealed the water types in this system to be predominantly Na-Cl. The predominant water

Table 1 Comparison of wells exceeding background levels of potential wastewater indicators during dry and wet seasons

Parameter	Units	Background levels		Wells exceeding background levels (%)			
		Dry	Wet	Dry		Wet	
				Dug	Tube	Dug	Tube
Electrical conductivity	$\mu\text{S}/\text{cm}$	713.5	502.3	81	44	82	63
Total dissolved solids	ppm	209.4	174.68	81	44	82	63

type in dug wells, tube wells, and TTML in both seasons were Na-Cl type and 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 (Fig. 5) are used to compare proportions of key geochemical parameters in the major ion chemistry used to determine water types. A charge balance error for the chemical analyses was calculated and ranged from 7.87 to 87.57% CBE, indicating an excess amount of cations which is due to dilution and some constituents that precipitated out during transport (Fritz 1994). The dominant anions in most groundwater samples contain a high proportion of sulfate and chloride (40–95%) and there are lower proportions of carbonate and bicarbonate ions (5–60%). The dominant cations in most groundwater samples contained a high proportion of sodium (20–90%), calcium (0–60%), and 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; however, this was a minor shift.

Wastewater indicators

Electrical conductivity

Electrical conductivity (EC) is a common measurement used to evaluate water quality. During the dry season, EC values in groundwater samples ranged from 305 to 2,590 $\mu\text{S}/\text{cm}$ and averaged 1,385 $\mu\text{S}/\text{cm}$, while during the wet season, EC values in groundwater samples ranged from 183 to 2,950 $\mu\text{S}/\text{cm}$ and averaged 1,168 $\mu\text{S}/\text{cm}$. 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 and 502.33 $\mu\text{S}/\text{cm}$, respectively, which 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; however, 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 (>1,200 $\mu\text{S}/\text{cm}$) were located on the west side (closer to the Shwe-Ta-Chaung canal) and lower values (<1,200 $\mu\text{S}/\text{cm}$) were observed on the east side (closer to TTML). This was identified as a potential groundwater flow divide.

Total dissolved solids

Total dissolved solids (TDS) is a commonly used water quality parameter to describe the presence of inorganic salts in the

Table 2 Comparison of wells exceeding wastewater indicator levels during dry and wet seasons (Vengosh and Pankratov 1998). WIL wastewater indicator level

Parameter	Units	WIL	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 3 Percentage of dug and tube wells exceeding the WHO drinking water standard for *E. coli* during dry and wet seasons

Parameter	Units	WHO drinking water standard	Dug wells		Tube wells	
			Dry	Wet	Dry	Wet
<i>E. coli</i>	MPN/100 ml	<1	86%	100%	11%	33%

Fig. 5 **a** 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 represents

wells between TTML and the Irrawaddy River on the south side. Black represents wells further north of the Amarapura Township near one of the major wastewater canals. Black bordered represents wastewater from the Shwe-Ta-Chaung canal. Light blue represents surface waters. **b** Wet season. Colors represent different regions of the study site

water. The World Health Organization (WHO 2008) sets a limit on TDS of 1,000 ppm as reasonable quality but specifies 300 ppm as the preferred limit for drinking water. TDS values during the dry season ranged from 59 to 1,039 ppm and averaged 497 ppm. TDS values during the wet season ranged from 79 to 1,326 ppm and averaged 467 ppm. Only DW10 exceeded the WHO limit of 1,000 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, whereas 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 m of the Shwe-Ta-Chaung canal. Background TDS was estimated using the six tube wells (YDB1, LS1, SVD, YY1, SA2, and MYA2); the background values for the dry and wet seasons were 209.4 ppm and 174.68 ppm, respectively. TDS values that exceeded background levels for both seasons followed the same pattern as EC values.

Chloride

A high chloride concentration in groundwater has been shown to be indicative of wastewater contamination (Lawrence et al. 2000). Background chloride concentrations for the Amarapura Aquifer were estimated from the six deep uncontaminated 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 exceeded the average, and 56% exceeded the range maximum.

Nitrate and ammonium

Nitrate and ammonium contaminations has been documented in a number of areas from anthropogenic sources (Fetter 1999). Nitrate (NO_3 as N) above 10 ppm and the presence of ammonium in urban areas often indicates 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. Nitrate concentration ranged from 0.10–331.07 ppm and averaged 55.68 ppm; 56% of nitrate exceeded 10 ppm during the wet season, and 61% during the dry season.

Cl/Br ratio

The chloride–bromide ratio (Cl/Br) has 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, while they are greater than 150 for groundwater contaminated with domestic wastewater (Vengosh and Pankratov 1998). During both the wet and dry seasons, 70% of dug wells exceeded the Cl/Br ratio of 150 indicating

wastewater contamination, while in tube wells, 38 and 63% exceeded this ratio during the wet and dry seasons, respectively.

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 US Environmental Protection Agency (2012) recreational or contact limit. Only two wells (DW7 and DW15) during the dry season did not contain any *E. coli*, whereas *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.

Physical hydrogeology

Grain size analysis

Drilling was conducted to install tube well YDB3 in December 2016. Sediments collected from the drilling of YDB3 are used to determine grain sizes in the upper 8 m 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 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 m, indicating thin flood plain deposits. This provides a wide range of porosities estimates from 20 to 35%. Hazen approximations provided hydraulic conductivity estimates between 4.98 and 726.62 m/day.

Hydraulic conductivity measurements

Slug tests of tube wells were conducted to determine the hydraulic conductivities at YDB1, YDB2, and YDB3 at Yadanabon University. High hydraulic conductivities were observed at wells with screening intervals at approximately 25 m below ground surface (bgs). The hydraulic conductivity result at YDB1 was 54.86 and 67.06 m/day at YDB2. Lower

hydraulic conductivity (1.31 m/day) was observed at YDB3 at a shallower screening interval of 7–8 m bgs.

Groundwater 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. Water levels generally declined between the wet and dry seasons and often spiked 1–2 m during rain events. Heads varied from approximately 66 to 71 m amsl.

During both seasons, heads in the Amarapura Aquifer were relatively shallow, ranging from 64 to 71 m across the Amarapura Aquifer. Heads were approximately 2–6 m higher during the wet season than the dry season, showing the effect of 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 velocity (9.25 m/day) causing quick water level fluctuations during rain events.

Groundwater modeling

Conceptual model

The initial groundwater flow conceptual model of this groundwater 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 (>1,200 $\mu\text{S}/\text{cm}$) towards the west side and low (<1,200 $\mu\text{S}/\text{cm}$) towards the east side (Fig. 6). 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 1,100 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

Fig. 6 Conceptual groundwater flow model. Values displayed are electrical conductivities in ($\mu\text{S}/\text{cm}$) and the dashed line represents the potential groundwater divide. Arrows represent suspected groundwater flow direction

flow velocities ranged from 3.38×10^{-2} to 9.25 m/day and averaged 7.54×10^{-1} m/day.

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; see Fig. 7 also for model calibration results). Average linear groundwater flow velocities calculated from the modeled heads ranged from 1.76×10^{-2} to 2.10 m/day and averaged 3.20 m/day in the dry season model (Fig. 7). These optimized parameters were used in creating the wet season model (Fig. 7; see also Table 4 for a summarized comparison of field and modeling data).

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 (m amsl) are represented in Fig. 7 by solid black lines, while dashed black polygons represent the different hydraulic conductivity zones (K1, K2, K3, and K4); also the outer black polygon (K1) represents the area that recharge is applied to. Boundaries between white and gray fills represent surface waters/line elements with specified heads and

Fig. 7 **a** Model features. K1, K2, K3, and K4 are hydraulic conductivity zones; solid black lines represent surface-water features/line elements with specified heads; **b** 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. **c** Dry season model, study site, **d** wet season model, study site

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

Table 4 Model calibration with field data

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)	3.04×10^{-1}	1.76×10^{-2}
Average linear velocity (v_x) (K3-zone)	9.25	2.10

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, whereas 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 Fig. 7).

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 Fig. 7).

Discussion

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.

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 this study, Na-Cl water types were observed, and water quality parameters determined elevated levels of total dissolved solids, electrical conductivity, chloride, nitrate, 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 Berktaş 2010). The Cl/Br ratio has also been 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 yield 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.

In sampling of the Irrawaddy River, a Ca-SO₄ 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-CO₃. 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 can serve as a baseline for future 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, nitrate, and chloride suggest that this likely results from anthropogenic wastewater sources. The presence of ammonium, nitrate above 10 ppm, and chloride above 100 ppm typically indicates influence from domestic wastewater (Fetter 1999). High sulfate levels are also observed but are likely from barite (BaSO₄) deposits in the Shan Plateau. It is expected that calcite (CaCO₃) and barite (BaSO₄) 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*, whose presence is commonly related to human waste, can cause severe diarrhea, and is often associated with other waterborne pathogens (WHO 2008). In Myanmar, it is estimated that 38 children per 1,000 live births (3.8%) die before the age of 5, which is mainly attributed to 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 or poor hygiene practices by those using the wells. DW10, being within 5 m 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-SO₄ during the wet season to Ca-CO₃ during the dry season, likely due to overland flow of water during the wet season going directly into the well. YDB1 only has about 3 cm of stick up and is covered with brick, which does not protect it from water flowing into it when flash floods are above 3 cm, which occurs frequently during the monsoon season. CaCO₃ 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. The water type in SVD changed from Na-HCO₃ to Na-Cl, which may be due to changing groundwater flow directions between seasons near TTML. The water type in 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. The water type in 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 have not 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; Danert 2009). 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; Danert 2009).

One of the goals of this project was to determine if inexpensive and easy-to-use chemical analysis kits could be used in the developing or low-income countries. The advantages of these kits are that many analyses could be performed for tens of dollars versus the multi-thousands of dollars needed for laboratory analyses, especially in a country with limited electricity, Internet, and access to reagents. While the kits' results were not an exact match for the IC results, the same trends were observed. The kits allow one to determine water samples that have high concentrations of specific ions which could then be sent to a laboratory. The kits were also easy to use and allowed for many different faculty and graduate students at universities to learn more about geochemistry and their water supply.

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 present 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 construct groundwater wells (Schneider 2014), while commonly used in Myanmar's rural area is manual percussion and the sludging method (Danert 2009). 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 improve the quality of groundwater used, a change that could impact 68% of domestic water usage in the Amarapura Township (Moe 2013).

While dug wells are not usually used for drinking, they had been constructed with brick liners for over 50 years ago. Typically, the bottom of the dug wells was just naturally occurring sand layers with no existing covers for the wells, leaving them vulnerable to debris collecting inside them. Additionally, the large diameter, heavy usage, and local hygiene practices left dug wells vulnerable to surface contaminants. Since the local population depends on dug wells, water quality could be improved by pumping water from the well and collecting it in closed containers, where chlorination could be used as a treatment. Covering the dug wells and extending concrete pads on top to divert used water away from the well would also help to improve the water quality.

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; Danert 2009). Many of these did not contain a cap, and YDB1 had a stick up of only 3 cm, leaving it vulnerable to overland flow. Often, during construction, unfiltered/unclean water from local ponds was dumped down the well, and no well development was attempted.

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 buckets being dumped directly into them to retrieve water but instead have a hand or compressor pump, although this was not always the case. Many of the wells with varying water chemistry between seasons are tube wells, which is likely due to the way in which they were constructed. More importantly is the utilization of a well pad/apron, particularly as the drilling method may have made installation of a sanitary seal in the annulus difficult. 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, making 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.

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 of the

groundwater from the surface because this controls the wastewater's ability to penetrate the subsurface. These models were used to provide additional understanding of this regional groundwater system. Improvements can be made, but these models provide information on key characteristics of the Amarapura Aquifer, which can be further investigated for a better calibration in future studies.

The physical hydrogeology of an area plays an important role regarding 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 wide range of hydraulic conductivities. Its high average hydraulic conductivity (67 m/day) and high average linear velocity (2.10 m/day) allow water/contaminants to flow in and out of the aquifer. The surface water to groundwater interaction was observed by changing heads in response to changing weather conditions (Haitjema 2012). Heavy thunderstorms and prolonged rain events cause additional inflow of water from the Irrawaddy River and other surface-water features in the region.

The analytic 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 Fig. 7). 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 m, there was an improvement in the model calibration, which could be due to the potential 2–3 m error in the digital elevation model in assigning these head measurements. Errors in the digital elevation model have been observed in another study, especially with smaller streams (Frederick et al. 2006). However, in general, flow directions and groundwater divides did not change significantly with this elevated head in TTML. Results for recharge, hydraulic conductivity, and average linear groundwater flow velocities in the model provided results within the same order of magnitude as the field measurements, which further validated the 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. 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. This means that

when more water is added to the system during the wet season, groundwater and surface-water heads are more consistent across the region, potentially allowing 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 these 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 showed similar geochemical characteristics. Wells in the low hydraulic conductivity zone (K2) near TTML typically had a lower TDS, whereas 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 investigate specific contaminants in specific wastewater canals to determine whether the 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. 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 do not require licenses. QGIS contains numerous instructional videos and documents that give assistance on how to use the software (Quantum Geographic Information System 2016), while 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 in regards to Internet access and language barriers.

Many of the challenges in a country like Myanmar concern accessibility. 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 nonfunctioning, which makes downloading large software files difficult and often impossible. Access to the Internet is only available during regular work hours at the university but technical problems and blackouts mean that the Internet often does not work. QGIS contains many help videos, but prohibitive loading times prevent viewing. Open-source maps such as Google maps, are often blocked by government Internet services or technology. QGIS is moderately technical and difficult to teach in a short course to non-English speakers; additionally, the instructional videos and documents are in English, which not everyone can understand. 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 is needed to be successful for projects such as this one to start improving research and site investigations in Myanmar. During the 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 Myanmar.

Conclusion

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 average hydraulic conductivity (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. In addition, workshops within the universities in the region have increased knowledge of groundwater resources, resulting in local studies by regional professors and graduate students.

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