Textile Dyes as a Source of Groundwater Contamination in Mandalay, Myanmar

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Textile dyeing and weaving of traditional longyi garments has traditionally occurred in the Amarapura Township of Mandalay, Myanmar, since 1822, transitioning from natural to chemical dyes in the early 1900’s. With no current wastewater treatment facilities in Mandalay, dye effluents mix with other wastewaters in unlined canals dug near peoples’ homes and discharge into local canals and groundwater. As locals rely heavily on dug and tube wells for drinking, bathing, and cooking, this industry poses a major health hazard to the people in this region. The objective of this study is to identify the previously unknown composition of the textile dyes as well as identify and quantify the concentrations of major ions and heavy metals found in dye effluents and to determine the impact on local groundwater resources. Powdered dye samples as well as water samples from each stage of the dyeing process have been identified with the combination of heavy metals used to create these color dyes. Water samples collected from tube wells and dug wells, both at dyeing sites and away from these operations, have been used to assess the geochemistry of the local waters. Sodium chloride, used in the dyeing processes, was found to have been transported the furthest away from dyeing operations. Heavy metals such as thallium, aluminum, barium, iron, nickel, lead, and antimony were observed at each stage of the dyeing process as well as in effluent waters at concentrations above the U.S. Environmental Protection Agency (EPA) Maximum Contaminant Levels (MCLs). Textile dyeing is a major
source of pollution and a health hazard to the people within the Amarapura Township; however, locals are not readily connecting dye practices to the issues with their drinking water.
TEXTILE DYES AS A SOURCE OF GROUNDWATER CONTAMINATION IN
MANDALAY, MYANMAR

BY
SURYA FREEMAN
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY AND ENVIRONMENTAL GEOSCIENCES

Thesis Director:
Melissa Lenczewski
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DEDICATION

To my parents, Mark and Michelle Freeman, for their unconditional love and support.
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CHAPTER 1: INTRODUCTION

Textile dyeing and weaving of traditional longyi garments has occurred in the Amarapura Township of Mandalay, Myanmar since a declaration by King Bagyidaw in 1822 (Grzybowski et al., 2019). Textile dyeing has been identified as a potential source of contamination in the area due to it being an unregulated industry. The industry is composed of groupings of families located along the Me-O Chaung Canal who rotate through different colors of textile dyes each day and create large batches of dyed longyi thread that are later transferred to other local families that weave the threads into the traditional garments. Textile dyeing is a year-round practice; during the monsoon or wet season some dyeing operations are relocated slightly uphill due to the homes along the Me-O Chaung Canal flooding. Those that practice the textile dyeing are unaware of the chemical compositions of the dyes that they use daily as the dyes are sourced mainly from China with a few sourced from India. Because this is an unregulated practice and the composition of the dyes themselves are unknown it is important to investigate the textile dyeing industry further and identify what is released into the local surface water and groundwater.

Effluents created through textile dyeing are dumped into unlined canals typically within a meter of peoples’ homes, which flow outwards from the community towards the Me-O Chaung Canal. The responsibility of drainage of wastewater and rainwater networks are left to the discretion of each household, instead of local city or town development committees; therefore, in most cases
drains and wastewater collection systems do not function as a connected network and are assembled with varying stretches of different materials that lead to unsuitable disposal points (Asian Development Bank, 2013). In areas where dyeing takes place these poorly connected networks allow effluents to be released into the environment nearby these communities which include agricultural fields and eventually the local canal. Effluent pipes do not directly connect to the Me-O Chaung Canal, but alternate from flowing in unlined canals to PVC piping until waste is released into the open area. When the Me-O Chaung Canal floods during the wet season low-lying lands in the area become flooded up into the ground floor of most homes, and textile dye effluents pool at the end of waste pipes and remain stagnant in the area contributing to flood water.

Currently urban infrastructure across Myanmar are deficient which include underinvestment and underdevelopment in water services, leading to poor water supply, sanitation, drainage, wastewater, and solid waste management throughout the country (Asian Development Bank, 2013). Due to the lack of proper sanitation throughout Myanmar locals have switched from drinking surface water to drinking groundwater from the Amarapura Aquifer within the last ten years (Grzybowski et al., 2019). Currently the country is investing into an integrated water resources management plan that will be implemented by 2020 as a step towards rectifying the lack of proper water supply, sanitation, personal hygiene, and environmental cleanliness (Global Water Partnership, 2016). The uses of this groundwater, primarily from dug wells and tube wells, are for daily consumption and necessity including cooking, bathing, and cleaning and are relied on heavily by the low-income locals. Dug wells inland and in the most populated areas of the
city have been used for the past 100 years, while tube wells have been installed more recently along the Me-O Chaung Canal.

Globally, the textile dyeing industry has existed for over 4,000 years, while during the last 150 years chemical dyes have been used in place of natural dyes (Ferreira et al., 2004). When dyes are used wastewaters or effluents are created, and depending on how large the dyeing operations are, varying amount of water is used, and effluents created. The main components of textile wastewaters include dyes and chemical additions with a wide range of chemicals and dyestuffs; organic compounds with complex structures (Al-Kdasi et al., 2004). These wastewaters have been identified by their high biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), and dissolved solids (DS) as typical characteristics of textile effluent water (Prabha et al., 2013; Al-Kdasi et al., 2004; Senthilnathan and Azeez, 1999). In Tirupur, Tamilnadu, India, long-term discharge of effluents has been known to cause carcinogenesis and teratogenesis (Senthilnathan and Azeez, 1999). Several countries, where textile dyeing is an essential economic industry, have introduced strict ecological standards for effluents due to the toxic effects of dyestuffs, organic compounds, alkaline and acidic contaminants which have all recently been recognized (Ramesh Babu, et al., 2007). In countries where industrial textile dyeing occurs recycling of dyes and wastewaters has become a necessary element to control pollution (Ramesh Babu, et al., 2007). Currently in Myanmar the dyeing industry is unregulated; therefore no recycling of dyes or management of effluents exists.
Previous research in Southern India where textile dyeing is a major source of economic production has found that groundwater in affected dyeing areas is unsuitable for consumption and use for irrigation (Prabha et al., 2013). In the Tirupur industrial area of Southern India polluted waters were found to have extremely high electrical conductivity (EC), total dissolved solids (TDS), chloride, nitrate and strong acids, while trace metals were found to be within permissible limits (Prabha et al., 2013). Another study in the Tirupur region found effluents sampled had similar physio-chemical characteristics in addition to high sodium levels from the addition of salts in the dyeing process as well as high potassium levels, both above permissible standards (Senthilnathan and Azeez, 1999). The heavy metals identified in this study, which include copper, zinc, chromium, and cadmium were identified at multiple stages of dyeing, but were found in low levels within permissible limits in resulting effluents (Senthilnathan and Azeez, 1999).

The traditional garment people wear in Myanmar is the acheik longyi. This piece of clothing is worn as a sign of status in Myanmar culture. This garment has been worn since the nineteenth century where it was originally worn as part of royal dress wear (ICHCAP, 2019). Originally raw silk threads were woven into fabric, however now cotton and silk fabrics are imported for use in making the longyi garments. After these fabrics are dyed by local families within the Amarapura Township motorized weaving machines are used to create intricate patterns and color designs on the longyis, with fifty-two classic designs, before they are woven from the batch fabric materials into individual longyi garments (ICHCAP, 2019).
The objective of this study is to understand the geochemistry of waters associated with textile dyeing in the Amarapura Township of Mandalay, Myanmar. This study will: 1) identify the previously unknown compositions of the textile dye powders; 2) identify and quantify the concentrations of major ions and heavy metals found in the textile dyes, effluent waters, and water sources away from dyeing operations; and 3) assess the water quality between regions of textile dyeing and inland in tube wells and dug wells.
CHAPTER 2: STUDY AREA

The country of Myanmar, formerly known as Burma, is in Southeast Asia and borders the countries of India, Bangladesh, China, Laos, and Thailand (Zaw et al., 2017). Myanmar is 2,000 km in length from North to South and spans a total area of 676,600 km$^2$ (Besset et al., 2017). The city of Mandalay, Myanmar is in the central region of the country and sits at 70-80 meters above mean sea level (amsl) within the flood plain of the Irrawaddy River (Grzybowski et al., 2019). The Irrawaddy River is the main river in the country and provides 2/3 of the surface water volume for Myanmar, spanning 2,150 km with a river basin area of 430,000 km$^2$ (Kravtsova et al., 2009). This river originates in the Himalayas Mountains from the confluence of the Nmai River and the Mali River (Kravtsova et al., 2009). In addition to being fed by waters from the Himalayan Mountains it receives its water from precipitation during the monsoon season and melt water sourced from local glaciers and alpine snowfields (Kravtsova et al., 2009). Mandalay sits within an alluvial setting of Holocene Age sands and gravels on the Amarapura Aquifer (Grzybowski et al., 2019). Along the Me-O Chaung Canal where this study takes place the ground is primarily sand (Appendix A).

Climate

The climate in Myanmar is both temperate and subtropical in the northern region and tropical in the southern region (Zaw et al., 2017). Mandalay in the central region is considered a tropical savannah (Harris et al., 2014). Myanmar lies within an area of Asia referred to as the Monsoon
Belt (Zaw et al., 2017). There are three seasons in Myanmar; dry, rainy, and winter (Zaw et al., 2017). The dry season occurs from March to mid-May, the wet season from mid-May to September, and the winter season from October to February (Zaw et al., 2017). Within the Irrawaddy River Basin the mean annual rainfall is between 2,000 and 3,000 mm (Besset et al., 2017). During the sampling period for this study the average temperature for the dry season was 29.96°C and 33.0°C during the wet season. The average rainfall for the dry season was 154 mm while the wet season was 1,524 mm.

Hydrogeology

The Amarapura Aquifer is an unconfined shallow aquifer that lies below the Amarapura Township and Mandalay Region. This aquifer is where most locals obtain their groundwater used for drinking, cooking, cleaning, and bathing. The Amarapura Aquifer has been classified as having Na-Cl type waters which are the result of pollution through anthropogenic wastewaters (Grzybowski et al., 2019). The unconfined aquifer’s average linear groundwater flow velocity is 0.754 m/day and is recharged by precipitation events at a rate of 3.01 x 10^{-4} m/day (Grzybowski et al., 2019).

Taung Tha Man Lake (TTML) is an oxbow lake that lies within the center of the Amarapura Township, which itself lies along the South edge of Mandalay (Grzybowski et al., 2019). The outlet stream from TTML is the Me-O Chaung Canal which runs perpendicular to the South edge of TTML and connects to the Irrawaddy River. This canal floods seasonally due to the monsoon
rains during the wet season. TTML is thought to be formed by the braided Irrawaddy River or the meandering of the Myitnge River (Grzybowski et al., 2019).
CHAPTER 3: MATERIALS AND METHODS

Field Survey

Sample collection and research occurred during both wet and dry seasons in Mandalay, Myanmar on 12-23 March 2018 (dry) and 8-14 August 2018 (wet). All sample locations are shown on Figure 1. Dye sampling sites were chosen because they are historically used sites and are still currently used for textile dyeing. Sample collection occurred from 10 dug wells, 10 tube wells, 6 dye bowls, 6 dye washing bowls, and 5 effluent creeks. Each dye operation visited consisted of one to four dye bowls with one to three washing bowls being actively used each day. Families that partake in textile dyeing live along the North side of the Me-O Chaung Canal. The dyeing operations are set up in the back yards or lower levels of these homes. Effluent from dyeing operations flows out from the bases of homes and is transported into the fields and canal through unlined dug canals. Tube wells are prevalent along the canal, so the tube wells chosen for this study are ones directly adjacent to dyeing operations. The dug wells chosen for this study are located inland and away from dying operations. The dug wells chosen for sampling are not used in dyeing or by families that practice dyeing.
Textile Dye Powders

Dye powder samples being analyzed at Union College (Schenectady, NY) were collected in plastic bags. Two shops located in the Amarapura Township sell powdered textile dye colors to local dyeing operations. Nineteen different colored dye powders were collected between these two shops (SH1 and SH2). The colors that were collected include SH1_pink, SH1_violet, SH1_dark green, SH1_orange, SH1_sky blue, SH1_red, SH1_dark blue, SH1_bold yellow,
SH1_yellow, SH1_black, SH1_brown, SH1_green, SH2_bright yellow + gold, SH2_bright green, SH2_violet, SH2_burgundy, SH2_pink, SH2_red, and SH2_blue. All dyes used in the region are sourced predominantly from China and a few from India. Powdered dye samples were analyzed using the Union College Ion Beam Analysis Lab Accelerator with a 2.2 MeV proton beam (Schenectady, NY) by proton induced x-ray emission (PIXE). Samples analyzed by PIXE tested for titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), germanium (Ge), arsenic (As), selenium (Se), silver (Ag), cadmium (Cd), indium (In), tin (Sn), antimony (Sb), mercury (Hg), thallium (Tl), lead (Pb), and bismuth (Bi).

Water Quality

Samples analyzed for physio-chemical parameters were collected in rinsed polypropylene bottles. Samples for major ion chemistry were filtered through a 0.45 µm nylon syringe filter into a 50 mL or 10 mL centrifuge tube with no head space. Samples for heavy metal analysis were filtered through a 0.45 µm nylon syringe filter into a 10 mL centrifuge tube containing 1 mL of heavy metal grade nitric acid (NaOH). Samples tested for *E. coli* were collected using Aquagenx Compartment Bag Test (CBT) kits (Chapel Hill, North Carolina). Collection and analysis for CBT kits followed manufacturer instructions.

A HACH HQ 40d multi-probe (Loveland, Colorado) was used to take physio-chemical parameter measurements for temperature, pH, oxidation-reduction potential (Eh), electrical
conductivity (EC), and dissolved oxygen content (DO). An XactMicro20 photometer (Rock Hill, South Carolina) was used within 24 hours of sample collection to test for parameters including total alkalinity, total hardness, total chlorine (Cl\(^-\) total), free chlorine (Cl\(^-\) free), phosphate (PO\(_4^{3-}\)), ammonia (NH\(_3\)), sulfide (S\(^2-\)), nitrate (NO\(_3^-\)), nitrite (NO\(_2^-\)), bromine (Br), chromium (Ch), copper (Cu), sulfate (SO\(_4^{2-}\)), fluoride (F\(^-\)), manganese (Mg), chromium (Cr), iron (Fe), and turbidity.

Water samples analyzed at Northern Illinois University were collected using 50 mL and 15 mL centrifuge tubes. Samples were filtered through a 0.45 µm nylon syringe filter. Major ion chemistry was analyzed using a Dionex DX500 Aquion Ion Chromatograph (Waltham, Massachusetts) to determine both major cations including sodium (Na\(^+\)), ammonium (NH\(^+\)), potassium (K\(^+\)), magnesium (Mg\(^+\)), and calcium (Ca\(^+\)), as well as major anions including fluoride (F\(^-\)), chloride (Cl\(^-\)), bromide (Br\(^-\)), sulfate (SO\(_4^{2-}\)), nitrate (NO\(_3^-\)), nitrite (NO\(_2^-\)), and phosphate (PO\(_4^{3-}\)).

Analysis for heavy metals occurred at First Environmental Laboratories (Naperville, Illinois) using EPA Method 6010C. Each sample tube contained a 1:10 ratio of 10% nitric acid (HNO\(_3\)) for heavy metal preservation. Heavy metals that were tested for include aluminum (Al), antimony (Sb), arsenic (As), barium (Be), beryllium (Be), cadmium (Cd), calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese
(Mn), nickel (N), potassium (K), selenium (Se), silver (Ag), sodium (Na), thallium (Tl), vanadium (V), zinc (Zn).
CHAPTER 4: RESULTS

Field Survey

Within the Amarapura Township, locals rely on dug wells, tube wells, or bottled water for daily uses. The dug wells and tube wells in the area draw groundwater from the shallow unconfined Amarapura Aquifer. Due to the lack of a local wastewater management system, local wells are susceptible to wastewater contamination from anthropogenic sources. The dug wells range in depth from 10 to 14.6 m with a radius of 1 m. The tube wells range in depth from 24 to 47 m with a radius of 1.15 cm. Dug well water is primarily used for bathing, cooking, and cleaning while tube well water is primarily used for drinking in tandem with cooking, cleaning and bathing.

There are no covers on the dug wells, thus trash is commonly found in the wells. To extract water from the dug wells, a bucket is attached to a rope and lowered and raised from the well. Tube wells extract water with the aid of a handpump. The tube wells are generally rerouted from the wellhead with PVC piping to various parts of the household. Some of these PVC routings end suspended above ground while others end with the PVC at ground level.

Potential sources of groundwater contamination in the Amarapura Township include the local unregulated dyeing industry which disposes of dye effluent into the unlined canals that are, in
most cases, within 1 m of tube wells. The dug wells sampled for this study are inland from the Me-O Chaung Canal and uphill from the textile dyeing area and are used as a representative of groundwater not directly impacted by the local textile dyeing industry. The results of this study were compared to 10 sampling points from Grzybowski et al., (2019).

Dye Powder Analysis

**PIXE**

Powdered dye samples were collected for elemental analysis using proton induced x-ray emission (PIXE) for nineteen different colors of dye. The PIXE method uses non-destructive simultaneous elemental analysis of samples using a proton beam to stimulate x-ray emissions. Grouping of electron energy levels differ by a factor of ten with the inner-most energy level being the K-shell then the next level is the L-shell (Arizona State University Department of Physics and Astronomy, 2000). Of the elements analyzed for through PIXE the elements identified include chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), and lead (Pb). Aluminum (Al), sodium (Na), and beryllium (Be) were not tested for using the PIXE due to limitations with the accelerator and beam. Table 1 shows the results of the PIXE analysis by dye color in parts per million and each dye’s respective country of origin. Appendix B shows two spectra for SH1_Red and SH1_Black dyes representative of the other 17 colors. Each peak on the spectra is labeled based on the element identified and transition to K (to \(n=1\) shell) or to \(L\) (to \(n=2\) shell) while \(\alpha, \beta, \text{and } \gamma\) denote the initial state of the falling electron (\(n+1, n+2, n+3\)). Figure 2 shows the number of samples each element identified occurred within, where
Fe was found in all 19 samples while Cu was found in 17, Zn in 14, Cr in 5, Co in 2 and Mn and Pb each found in one. Figure 3 is a histogram representation of the elemental occurrences of each identified element by the color family it appeared within. The color families chosen are reds, oranges, yellows, greens, blues, violets, browns, and black. All elements appeared within each family group except for Pb and Mn which occurred exclusively in the greens and reds, respectively.

Water Quality

Major Ion Chemistry

Piper Diagrams are used as a classification of water based on major ion chemistry (Figure 4 and Figure 5). The major ions that were analyzed for include the cations sodium (Na$^+$), ammonium (NH$^+$), potassium (K$^+$), magnesium (Mg$^+$), and calcium (Ca$^+$), as well as anions including fluoride (F$^-$), chloride (Cl$^-$), bromide (Br$^-$), sulfate (SO$_4^{2-}$), nitrate (NO$_3^-$), nitrite (NO$_2^-$), and phosphate (PO$_4^{3-}$). The dry season in Myanmar (March to mid-May) shows that the water type is primarily Na-Cl type (Figure 4) as well as during the wet season (mid-May through September) (Figure 5). Na-Cl is the predominate type of water for both tube wells and dug wells as well as the wastewater sampled at the textile dye effluent release points. Both wet and dry season Piper Diagrams include the 10 sampling points from Grzybowski et al., (2019), which also identified the primary type of water for this region as predominantly Na-Cl. Away from the sampling sites the water type observed for the Irrawaddy River is Ca-SO$_4$ to the north and Ca-HCO$_3$ to the south (Grzybowski et al., 2019). Full major ion chemistry results are shown in Appendix C.
Table 1. Concentrations of Elements Identified within Colored Dye Powders

<table>
<thead>
<tr>
<th>Color Name</th>
<th>Country of Origin</th>
<th>CrK (ppm)</th>
<th>MnK (ppm)</th>
<th>FeK (ppm)</th>
<th>CoK (ppm)</th>
<th>CuK (ppm)</th>
<th>ZnK (ppm)</th>
<th>PbL (ppm)</th>
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<tr>
<td>SH1 Bright Green</td>
<td>China</td>
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<td>322.3</td>
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<td>80.92</td>
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<td>SH1 Black</td>
<td>China</td>
<td></td>
<td></td>
<td>147.2</td>
<td></td>
<td>277.8</td>
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<td>47.9</td>
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<td>SH1 Brown</td>
<td>China</td>
<td></td>
<td></td>
<td>27.87</td>
<td>21.49</td>
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<td>52.7</td>
</tr>
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<td></td>
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<td>SH1 Dark Blue</td>
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<td></td>
<td></td>
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<td>India</td>
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<tr>
<td>SH1 Orange</td>
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<td></td>
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<td>387.7</td>
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<td>97.68</td>
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<td>China</td>
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<td></td>
<td>124.6</td>
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<td>14599</td>
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<td></td>
<td>19.68</td>
<td></td>
<td>494.3</td>
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<td></td>
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<td>919.5</td>
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<td>11587</td>
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<td>91.86</td>
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<tr>
<td>SH2 Burgundy</td>
<td>China</td>
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<td></td>
<td>178.6</td>
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<td>37.71</td>
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<td>30.46</td>
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<tr>
<td>SH2 Bright Yellow with Gold</td>
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<td></td>
<td></td>
<td>282.3</td>
<td></td>
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<tr>
<td>SH2 Pink</td>
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<td>407.1</td>
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<td>70.13</td>
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<td>629.5</td>
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<td>360.7</td>
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<td>35.68</td>
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<td>China</td>
<td></td>
<td></td>
<td>46.26</td>
<td></td>
<td>35.35</td>
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<td>224.3</td>
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</table>
Figure 2. Histogram of Number of Occurrences of each Element in Dye Samples when N=19.
Figure 3. Histogram of Number of Occurrences of each Element per Color Family when N=19.
Figure 4. Piper Diagram - Dry Season. Colors indicate the source of water sampled. Green represents textile dyeing and washing bowls. Yellow represents effluent release points. Black represents sampling sites from Grzybowski et al., 2019.
Figure 5. Piper Diagram - Wet Season. Colors indicate the source of water sampled. Blue represents communal dug wells. Orange represents tube wells. Green represents textile dyeing and washing bowls. Yellow represents effluent release points. Black represents sampling sites from Grzybowski et al., 2019.
Heavy Metals

Samples tested for heavy metals were analyzed using EPA Method 6010C - inductively coupled plasma atomic emission spectrometry (ICP-AES), at First Environmental Laboratories (Naperville, IL). All samples were filtered with a 0.45 µm nylon syringe filter and acidified with 10% heavy metal grade nitric acid (HNO₃) during collection. The heavy metals that were analyzed for include aluminum (Al), antimony (Sb), arsenic (As), barium (Be), beryllium (Be), cadmium (Cd), calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), potassium (K), selenium (Se), silver (Ag), sodium (Na), thallium (Tl), vanadium (V), zinc (Zn). Tables 2-5 show the results of the heavy metal analyses based on origin of tested groundwater; (Table 2) groundwater tube wells, (Table 3) dyeing and washing bowls, (Table 4) effluent release pipes, and (Table 5) groundwater dug wells. Samples were compared to the Environmental Protection Agency (EPA) Drinking Water Standards 2018 and World Health Organization (WHO) Drinking Water Guidelines 2017. Values that were above the EPA maximum contaminant level (MCL) or WHO Guideline are shown in red as “dangerous”, values below the reported detection limit (RDL) which are still potentially above the MCL or WHO Guidelines are shown in yellow as “cautionary”, and values without color are above the RDL and below the MCL or WHO Guidelines, indicating that the heavy metals, if any identified, are within “safe” ranges.

The heavy metals identified at dangerous levels in the groundwater tube wells include aluminum, iron, lead, and thallium. The only heavy metal identified in the groundwater dug wells as dangerous was sodium. The heavy metals identified during the textile dyeing process as
dangerous include aluminum, barium, iron, lead, and sodium; while the heavy metals identified in the post-dyeing washing stage include aluminum, iron, lead, manganese, nickel, sodium, and thallium. Between the dyeing stage and following washing stage the heavy metals of manganese, nickel, and thallium were introduced to the water, likely from the colored textile dyes themselves. The heavy metals identified at the culmination point of the effluent release pipes include aluminum, antimony, iron, lead, nickel, sodium, and thallium. Between the washing stage and the effluent release of multiple dye operations antimony was introduced to the groundwater as well.

Two hotspot maps were created using QGIS 3.6.1 to display the results of heavy metals present that are above current MCLs and WHO Guidelines (Figure 6 and Figure 7). The number of heavy metals above these set limits and guidelines ranged from 0 to 5 at each site. The graduated symbol hot spots indicate how many heavy metals were identified above these values, where the larger circle indicates more heavy metals present. Figure 6 displays the hot spots for the dry season while Figure 7 displays the wet season. In both seasons the largest hot spots are located along the Me-O Chaung Canal where the textile dyeing operations and effluent pipe openings are located.
Table 2. Heavy Metal Concentrations in Groundwater Tube Wells

<table>
<thead>
<tr>
<th>Heavy Metals</th>
<th>Units</th>
<th>RDL</th>
<th>MCL/WHO</th>
<th>PG1-C1</th>
<th>PG1-C1</th>
<th>PG1-C2</th>
<th>PG1-C3</th>
<th>M2-C1</th>
<th>M3-C1</th>
<th>M6-C1</th>
<th>M2-C2</th>
<th>M5-C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>mg/L</td>
<td>0.1</td>
<td>0.2*</td>
<td>0.22</td>
<td>&lt;0.20</td>
<td>0.25</td>
<td>&lt;0.20</td>
<td>0.14</td>
<td>&lt;0.20</td>
<td>5.9</td>
<td>0.19</td>
<td>&lt;0.50</td>
</tr>
<tr>
<td>Antimony</td>
<td>mg/L</td>
<td>0.006</td>
<td>0.02</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
<td>&lt;0.006</td>
<td>&lt;0.030</td>
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</tr>
<tr>
<td>Arsenic</td>
<td>mg/L</td>
<td>0.01</td>
<td>0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.050</td>
</tr>
<tr>
<td>Barium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.3</td>
<td>0.007</td>
<td>&lt;0.010</td>
<td>0.008</td>
<td>0.011</td>
<td>0.01</td>
<td>0.014</td>
<td>0.044</td>
<td>0.11</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Beryllium</td>
<td>mg/L</td>
<td>0.004</td>
<td>0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.008</td>
<td>&lt;0.004</td>
<td>&lt;0.008</td>
<td>&lt;0.008</td>
<td>&lt;0.008</td>
<td>&lt;0.008</td>
<td>&lt;0.004</td>
<td>&lt;0.020</td>
</tr>
<tr>
<td>Cadmium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.003</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Chromium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.05</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>0.015</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/L</td>
<td>0.005</td>
<td>2*</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>0.023</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Iron</td>
<td>mg/L</td>
<td>0.05</td>
<td>0.3</td>
<td>0.26</td>
<td>0.22</td>
<td>0.31</td>
<td>0.13</td>
<td>0.14</td>
<td>&lt;0.10</td>
<td>5.35</td>
<td>0.43</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>Lead</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.01*</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>0.126</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
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<tr>
<td>Manganese</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.4*</td>
<td>0.008</td>
<td>&lt;0.010</td>
<td>0.071</td>
<td>0.021</td>
<td>0.031</td>
<td>0.010</td>
<td>0.093</td>
<td>0.017</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Nickel</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.02*</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Selenium</td>
<td>mg/L</td>
<td>0.01</td>
<td>0.01</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.050</td>
</tr>
<tr>
<td>Silver</td>
<td>mg/L</td>
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<td>0.1</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
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<td>200*</td>
<td>81.7</td>
<td>66.3</td>
<td>55.1</td>
<td>34.3</td>
<td>31</td>
<td>47.6</td>
<td>183</td>
<td>31.9</td>
<td>35.3</td>
</tr>
<tr>
<td>Thallium</td>
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<td>0.002</td>
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<td>&lt;0.020</td>
<td>&lt;0.003</td>
<td>&lt;0.020</td>
<td>&lt;0.002</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
<td>&lt;0.002</td>
<td>&lt;0.050</td>
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<tr>
<td>Zinc</td>
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<td>0.022</td>
<td>&lt;0.02</td>
<td>0.067</td>
<td>0.048</td>
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</table>

Table 2. Heavy metals identified in groundwater tube wells located near textile dyeing practices. Values in red indicate those above the MCL (EPA 2018) or WHO Drinking Water Guidelines (WHO 2017) as “dangerous”. Values in yellow indicate cautionary concentrations of contaminants that are below the recognized detection limit but are still potentially above MCL and WHO values. Values not colored indicate the “safe zone” of contaminants that are below the MCL and WHO values.
Table 3. Heavy Metal Concentrations in Dye Baths and Washing Bowls

<table>
<thead>
<tr>
<th>Heavy Metals</th>
<th>Units</th>
<th>RDL</th>
<th>MCL</th>
<th>M2-E1</th>
<th>M2-E2</th>
<th>M2-E3</th>
<th>M2-E4</th>
<th>M2-F1</th>
<th>M2-F2</th>
<th>M2-F3</th>
<th>M3-E1</th>
<th>PG1-D</th>
<th>PG1-D</th>
<th>M2-D1</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>mg/L</td>
<td>0.1</td>
<td>0.2*</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
</tr>
<tr>
<td>Antimony</td>
<td>mg/L</td>
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<td>0.02</td>
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<td>&lt;0.006</td>
<td>&lt;0.006</td>
<td>&lt;0.006</td>
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<td>&lt;0.006</td>
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<td>&lt;0.006</td>
<td>&lt;0.012</td>
<td>&lt;0.006</td>
<td>&lt;0.012</td>
</tr>
<tr>
<td>Arsenic</td>
<td>mg/L</td>
<td>0.01</td>
<td>0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
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<tr>
<td>Barium</td>
<td>mg/L</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.745</td>
<td>0.01</td>
<td>0.008</td>
<td>0.007</td>
<td>0.016</td>
<td>1.33</td>
<td>0.093</td>
<td>0.28</td>
<td>0.013</td>
</tr>
<tr>
<td>Beryllium</td>
<td>mg/L</td>
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<td>0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.004</td>
<td>&lt;0.008</td>
<td>&lt;0.004</td>
<td>&lt;0.008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.003</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Chromium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.05</td>
<td>0.018</td>
<td>&lt;0.005</td>
<td>0.007</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.11</td>
<td>&lt;0.010</td>
<td>0.012</td>
<td>0.03</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/L</td>
<td>0.005</td>
<td>2*</td>
<td>0.006</td>
<td>0.006</td>
<td>0.013</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>0.019</td>
<td>0.061</td>
</tr>
<tr>
<td>Iron</td>
<td>mg/L</td>
<td>0.05</td>
<td>0.3</td>
<td>0.3</td>
<td>0.17</td>
<td>0.56</td>
<td>0.16</td>
<td>0.18</td>
<td>0.35</td>
<td>0.41</td>
<td>0.46</td>
<td>4.66</td>
<td>16</td>
<td>0.37</td>
</tr>
<tr>
<td>Lead</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.01*</td>
<td>&lt;0.005</td>
<td>0.013</td>
<td>0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>0.008</td>
<td>0.031</td>
</tr>
<tr>
<td>Manganese</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.4*</td>
<td>0.03</td>
<td>0.005</td>
<td>0.027</td>
<td>0.014</td>
<td>0.021</td>
<td>0.006</td>
<td>0.01</td>
<td>0.024</td>
<td>0.117</td>
<td>0.44</td>
<td>0.111</td>
</tr>
<tr>
<td>Nickel</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.02*</td>
<td>0.007</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.008</td>
<td>0.008</td>
<td>0.031</td>
</tr>
<tr>
<td>Selenium</td>
<td>mg/L</td>
<td>0.01</td>
<td>0.01</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
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</tr>
<tr>
<td>Silver</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.1</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
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</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
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<td>200*</td>
<td>1150</td>
<td>1180</td>
<td>1720</td>
<td>29</td>
<td>62</td>
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<td>339</td>
<td>485</td>
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<tr>
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<td>&lt;0.002</td>
<td>&lt;0.002</td>
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</table>

Table 3. Heavy metals identified in textile dyeing and washing bowls. Values in red indicate those above the MCL (EPA 2018) or WHO Drinking Water Guidelines (WHO 2017) as “dangerous”. Values in yellow indicate cautionary concentrations of contaminants that are below the recognized detection limit but are still potentially above MCL and WHO values. Values not colored indicate the “safe zone” of contaminants that are below the MCL and WHO values.
Table 4. Heavy Metal Concentrations at Effluent Release Points

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tr>
<td>Aluminum</td>
<td>mg/L</td>
<td>0.1</td>
<td>0.2*</td>
<td>5.12</td>
<td>0.24</td>
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<td>Antimony</td>
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<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
</tr>
<tr>
<td>Barium</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.3</td>
<td>0.109</td>
<td>0.17</td>
<td>0.042</td>
<td>0.026</td>
<td>0.068</td>
<td>0.033</td>
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<tr>
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<td>0.004</td>
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<td>&lt;0.004</td>
<td>&lt;0.008</td>
<td>&lt;0.004</td>
<td>&lt;0.008</td>
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<tr>
<td>Cadmium</td>
<td>mg/L</td>
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<td>0.003</td>
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<td>&lt;0.005</td>
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<tr>
<td>Chromium</td>
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<td>0.05</td>
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<td>0.006</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
</tr>
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<tr>
<td>Iron</td>
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<td>8.69</td>
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<td>1.58</td>
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<tr>
<td>Lead</td>
<td>mg/L</td>
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<td>0.01*</td>
<td>0.271</td>
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<td>&lt;0.010</td>
<td>0.046</td>
<td>&lt;0.010</td>
<td>0.045</td>
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<tr>
<td>Manganese</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.4*</td>
<td>0.159</td>
<td>0.006</td>
<td>0.052</td>
<td>0.045</td>
<td>0.08</td>
<td>12.9</td>
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<tr>
<td>Nickel</td>
<td>mg/L</td>
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<td>0.02*</td>
<td>0.01</td>
<td>&lt;0.005</td>
<td>0.122</td>
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<td>0.01</td>
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<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.010</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
</tr>
<tr>
<td>Silver</td>
<td>mg/L</td>
<td>0.005</td>
<td>0.1</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.005</td>
<td>&lt;0.010</td>
<td>&lt;0.010</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
<td>0.5</td>
<td>200*</td>
<td>523</td>
<td>1090</td>
<td>2960</td>
<td>373</td>
<td>44.3</td>
<td>624</td>
</tr>
<tr>
<td>Thallium</td>
<td>mg/L</td>
<td>0.01</td>
<td>0.002</td>
<td>0.002</td>
<td>&lt;0.002</td>
<td>&lt;0.020</td>
<td>&lt;0.002</td>
<td>&lt;0.020</td>
<td>&lt;0.020</td>
</tr>
<tr>
<td>Zinc</td>
<td>mg/L</td>
<td>0.01</td>
<td>3*</td>
<td>0.247</td>
<td>0.041</td>
<td>0.038</td>
<td>0.072</td>
<td>0.031</td>
<td>0.066</td>
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</tbody>
</table>

Table 4. Heavy metals identified in waters from dye effluent release points. Values in red indicate those above the MCL (EPA 2018) or WHO Drinking Water Guidelines (WHO 2017) as “dangerous”. Values in yellow indicate cautionary concentrations of contaminants that are below the recognized detection limit but are still potentially above MCL and WHO values. Values not colored indicate the “safe zone” of contaminants that are below the MCL and WHO values.
Table 5. Heavy Metal Concentrations in Groundwater Dug Wells

| Heavy Metals | Units | RDL | MCL | DW1 8/7/2018 | DW2 8/7/2018 | DW4 8/7/2018 | DW6 8/7/2018 | DW7 8/7/2018 | DW8 8/7/2018 | DW9 8/7/2018 | DW1 8/8/2018 | DW2 8/8/2018 | DW4 8/8/2018 | DW6 8/8/2018 | DW7 8/8/2018 | DW8 8/8/2018 | DW9 8/8/2018 |
|--------------|------|-----|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Aluminum     | mg/L | 0.1 | 0.2*| <0.50       | <0.20       | <0.50       | <0.20       | <0.20       | <0.50       | <0.20       | <0.50       | <0.20       | <0.50       | <0.20       | <0.50       | <0.20       | <0.50       | <0.20       |
| Antimony     | mg/L | 0.006| 0.02 | <0.030     | <0.012      | <0.030      | <0.012      | <0.012      | <0.030      | <0.012      | <0.030      | <0.012      | <0.030      | <0.012      | <0.030      | <0.012      | <0.030      | <0.012      |
| Arsenic      | mg/L | 0.01 | 0.005| <0.050     | <0.020      | <0.050      | <0.020      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      |
| Barium       | mg/L | 0.005| 0.3  | 0.026       | 0.019       | 0.036       | 0.021       | 0.047       | 0.025       | 0.050       | <0.025       | 0.082       | <0.025       | 0.050       | <0.025       | 0.082       | <0.025       | 0.050       |
| Beryllium    | mg/L | 0.004| 0.004| <0.020     | <0.008      | <0.020      | <0.008      | <0.008      | <0.020      | <0.008      | <0.020      | <0.008      | <0.020      | <0.008      | <0.020      | <0.008      | <0.020      | <0.008      |
| Cadmium      | mg/L | 0.005| 0.003| <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Chromium     | mg/L | 0.005| 0.05 | <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Copper       | mg/L | 0.005| 2*   | <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Iron         | mg/L | 0.05 | 0.3  | <0.25       | 0.15       | <0.25       | <0.10       | <0.10       | <0.25       | <0.10       | <0.25       | <0.10       | <0.25       | <0.10       | <0.25       | <0.10       | <0.25       | <0.10       |
| Lead         | mg/L | 0.005| 0.01*| <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Manganese    | mg/L | 0.005| 0.4* | <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Nickel       | mg/L | 0.005| 0.02*| <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Selenium     | mg/L | 0.01 | 0.01 | <0.050     | <0.020      | <0.050      | <0.020      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      |
| Silver       | mg/L | 0.005| 0.1  | <0.025     | <0.010      | <0.025      | <0.010      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      | <0.025      | <0.010      |
| Sodium       | mg/L | 0.5  | 200* | 406        | 11         | 118         | 308         | 51.9        | 320         | 13.1        | 320         | 13.1        | 320         | 13.1        | 320         | 13.1        | 320         | 13.1        |
| Thallium     | mg/L | 0.01 | 0.002| <0.050     | <0.020      | <0.050      | <0.020      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      | <0.050      | <0.020      |
| Zinc         | mg/L | 0.01 | 3*   | <0.05       | <0.02       | <0.05       | <0.02       | <0.02       | <0.05       | <0.02       | <0.05       | <0.02       | <0.05       | <0.02       | <0.05       | <0.02       | <0.05       | <0.02       |

Table 5. Heavy metals identified in waters from groundwater dug wells located inland and away from local textile dyeing operations. Values in red indicate those above the MCL (EPA 2018) or WHO Drinking Water Guidelines (WHO 2017) as “dangerous”. Values in yellow indicate cautionary concentrations of contaminants that are below the recognized detection limit but are still potentially above MCL and WHO values. Values not colored indicate the “safe zone” of contaminants that are below the MCL and WHO values.
Figure 6. Hotspot Map of Heavy Metals - Dry Season. Graduated symbol map indicates heavy metals above EPA set MCLs and WHO Drinking Water Guidelines. The larger the circle the more heavy metals that are present at concentrations above set standards and guidelines. Overlapping circles indicate multiple sampling points closely located to one another.
Figure 7. Hotspot Map of Heavy Metals - Wet Season. Graduated symbol map indicates heavy metals above EPA set MCLs and WHO Drinking Water Guidelines. The larger the circle the more heavy metals that are present at concentrations above set standards and guidelines. Overlapping circles indicate multiple sampling points closely located to one another.
Wastewater in the Amarapura Township of Mandalay, Myanmar was identified by the presence of elevated *E. coli*, electrical conductivity, total dissolved solids, nitrates and ammonium as indicators of contamination (Table 6). Chloride was found to not exceed wastewater indicator levels in either dug wells or tube wells, a commonly used wastewater indicator (Vengosh and Pankratov, 1998). Chloride-bromide ratios were also included and compared to previous work by (Grzybowski et al., 2019) for similarities caused by anthropogenic sources (Table 7). High electrical conductivity was recorded in both dye bath mixtures and local tube wells, due to the addition of sodium sulfide in one of the initial steps of the dyeing process to strengthen color fastness (Appendix D). Heavily reducing environments were also identified in the main dye mixtures and nearby tube wells, resulting from the high basicity of the dye mixtures (Appendix D).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Background Levels</th>
<th>Wells exceeding background levels (%)</th>
<th>Dug</th>
<th>Tube</th>
<th>Dug</th>
<th>Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity</td>
<td>µS/cm</td>
<td>231 407</td>
<td>Dry 60 50 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>ppm</td>
<td>224 186</td>
<td>Dry 60 56 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>mg/L</td>
<td>4.06 3.03</td>
<td>Dry 40 44 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cl/Br Ratio

A chloride-bromide (Cl/Br) ratio is used as a method of tracing the source of groundwater contamination in areas that are not directly influenced by seawater, where the origins of wastewater are categorized by their anthropogenic source (Vengosh and Pankratov, 1998). All wells sampled during the wet season were below the wastewater indicator level of 150 for Cl/Br ratios. During the dry season all but two wells were below the wastewater indicator level for this ratio. Results from this study are compared to results from Grzybowski et al., (2019) in Table 7. The average Cl/Br ratio for the dry season is 215 mg/L while the average Cl/Br ratio for the wet season is 54 mg/L. Although the Cl/Br ratio for this study was not indicative of anthropogenic sources chloride and bromide were identified in a lesser amount from samples taken at the textile dyeing operations and effluent pipes, indicating the source of the elevated ratio (Appendix E).

Table 7. Percentage of Wells Exceeding Wastewater Indicator Levels by Seas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Wastewater Indicator Level</th>
<th>Wells exceeding wastewater indicator levels (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>Chloride</td>
<td>ppm</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Nitrate as N</td>
<td>ppm</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Ammonium</td>
<td>ppm</td>
<td>&gt; 0</td>
<td>100</td>
</tr>
<tr>
<td>Cl/Br Ratio</td>
<td>Unitless</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Cl/Br Ratio</td>
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<td></td>
<td>67</td>
</tr>
</tbody>
</table>

(Grzybowski et al., 2019)
**E. coli**

*Escherichia coli* (*E. coli*) is identified as a wastewater indicator for groundwater in the Amarapura Township. Aquagenx Compartment Bag Tests (CBT) are used for quantitative analysis of *E. coli* in groundwater. CBT results are calculated by concentration of fecal bacteria by a Most Probable Number (MPN) estimate per 100 mL. *E. coli* at any level is considered unsafe in drinking water. The MPN is representative of World Health Organization Guidelines for Drinking Water Quality 4th Edition. *E. coli* levels are separated into risk categories of drinking water ranging from Safe 0/100 mL to Intermediate Risk 1-10/100 mL, to High Risk 11-100/100 mL, and Very High Risk >100/100 mL (WHO, 2017).

During the dry season 100% of sampled tube wells contained unsafe levels of *E. coli* at >100 MPN/100 mL (Table 8). During the wet season 20% of sampled tube wells and 78% of dug wells contained unsafe levels of *E. coli*. For the wet season 80% of the tube wells sampled tested at 0 MPN/100 mL and 22% of dug wells tested at <1 MPN/100 mL. CBT results are shown in Appendix F. *E. coli* is seen to be higher in dug wells than tube wells, which is potentially due to dug wells being open and uncovered while tube wells are sealed except for at the pump or PVC pipe opening. Most likely the *E. coli* contamination to the groundwater wells is due to anthropogenic sources, as a result of the absence of any solid waste disposal, open defecation practices, and wild animals roaming around Amarapura Township.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>WHO Drinking Water Standard</th>
<th>Dug Wells</th>
<th>Tube Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td><em>E. coli</em></td>
<td>MPN/100 mL</td>
<td>&lt;1</td>
<td>–</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Grzybowski et al., 2019)</td>
<td>67</td>
<td>100</td>
</tr>
</tbody>
</table>
CHAPTER 5: DISCUSSION

This study provides the first characterization of the textile dyeing industry in Mandalay, Myanmar and the effects on local groundwater and resulting contamination. Through this study contaminated groundwater has been identified as a major pollutant in the dyeing region and poses a threat to human health through prolonged consumption.

Water Quality

The water sampled within the Amarapura Township of Mandalay, Myanmar is contaminated by the local textile dyeing industry due to its absence of regulation on how dye effluents are disposed of and the composition of dyes used. This contamination comes in the form of heavy metals in the powdered dyes which infiltrate into the sand and gravel ground, unconfined shallow Amarapura Aquifer groundwater, and Me-O Chaung Canal as effluent is released. This region of Mandalay is historically known for textile dyeing and weaving and it will continue to occur in this specific area for the foreseeable future. Although textile dyeing is the main source of contamination in this area other wastewater indicators have been identified and indicate anthropogenic sources of contamination as well. These indicators include the observed Na-Cl type waters across the study area, elevated *E. coli*, electrical conductivity, total dissolved solids, nitrates, and ammonium.
The heavy metals that have been identified in this study that exceed EPA set MCLs and WHO Drinking Water Guidelines include aluminum, antimony, barium, iron, lead, manganese, nickel, sodium, and thallium. The only heavy metals identified that has any beneficial effect in a controlled amount are iron and manganese (Goyer 2004). Table 9 indicates the health risks associated with excess consumption of the heavy metals identified in this study (EPA 2004; EPA 2009; Järup, 2003; Martin et al., 2009, WHO 2017). There is an abundance of tube wells and dug wells in the area, so locals currently do not have to travel far to collect water. Local dyeing is conducted every day and tube wells adjacent to these operations are at the highest risk of contamination and unsafe for use. However, sodium has appeared as far away from dyeing operations as the dug wells that are uphill and inland into Mandalay. Sodium sulfide is one of the main components of the dye mixture used to increase color fastness and is present in all colored mixtures used in all sampled dyeing operations. Conservative tracers are those that are not produced in or degraded by the subsurface (Cook et al., 2018) A commonly used conservative tracer is chloride (Cl-) which is found in table salt (Fetter et al., 2018). Sodium sulfide, used in textile dyeing, is also a salt and therefore will move with the groundwater into which it has percolated. In this study, the sodium sulfide has appeared furthest away from dyeing operations in dug well waters.
Table 9. Health Effects of Excess Consumption of Heavy Metals

<table>
<thead>
<tr>
<th>Name of Contaminant</th>
<th>MCL/WHO Guideline (mg/L)</th>
<th>Health Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.2</td>
<td>Increase blood pressure and cholesterol</td>
</tr>
<tr>
<td>Antimony</td>
<td>0.006</td>
<td>Increase in blood cholesterol, decreases in blood sugar</td>
</tr>
<tr>
<td>Barium</td>
<td>2</td>
<td>Increase in blood pressure</td>
</tr>
<tr>
<td>Iron</td>
<td>0.3</td>
<td>Increase risk of arthritis and liver problems</td>
</tr>
<tr>
<td>Lead</td>
<td>0.015</td>
<td>Children and infants – delays in physical and mental development, with potential learning disabilities. Adults – kidney issues and high blood pressure</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.4</td>
<td>Elderly – mental disturbances Adults - lethargy and tremors</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.02</td>
<td>Attacks the lungs, causing chronic bronchitis or lung cancer</td>
</tr>
<tr>
<td>Sodium</td>
<td>200</td>
<td>Increase in blood pressure and can increase the risk of stroke and heart failure</td>
</tr>
<tr>
<td>Thallium</td>
<td>0.002</td>
<td>Hair loss, changes in blood, kidney, liver, and or intestinal issues</td>
</tr>
</tbody>
</table>
In addition to human exposure to these heavy metals through drinking water, heavy metals in groundwater used for irrigation are of concern as they can decrease crop yield by the metal’s potential bioaccumulation and biomagnification within the food chain (Wuana and Okieimen, 2011). In addition to contaminating the crops themselves, the contaminants have the ability, in small doses, will bio-accumulate into those who consume the crops (Wuana and Okieimen, 2011). If water from tube wells along the Me-O Chaung Canal are used for irrigation, it is possible to contaminate soil and crops directly with the heavy metals that have been introduced to the system through dyeing. One instance of this is when local farms noticed that their rice crops near textile dyeing areas were turning an abnormal yellow color (Personal Communications). With the influence of dye effluent runoff and contaminated water use for irrigation not only is the water resources contaminated, but the crop yields are as well.

Conceptual Models

Figures 8 and Figure 9 are conceptual models indicating how groundwater moves through the local system in the Amarapura Township textile dyeing region. Water from the shallow unconfined Amarapura Aquifer is extracted from either inland dug wells or tube wells along the Me-O Chaung Canal. Water pumped from local tube wells is used, in addition to household uses and drinking, in textile dyeing and washing bowls before being dumped into unlined canals as effluent. Effluent waters move through the unlined canals until they are released into the open environment at effluent pipe openings. These pipe openings are the convergence point for multiple unlined canals, so multiple dye operation’s effluents pass through these pipes before being released. Once water is released from the effluent pipes it either infiltrates back into the
sand and gravel ground or flows out and eventually into the Me-O Chaung Canal. Groundwater flow in this region is to the Northwest or inland in both the wet and dry seasons (Grzybowski et al., 2019, Appendix G). These waters are moving from the canal inland and towards the dug wells. The hydraulic conductivity of the sand in this region has been identified as 65 m/day (Grzybowski et al., 2019). Below each of the stages of water used, are listed the heavy metals that have been identified to be above the EPA set MCL and WHO Drinking Water Guidelines (EPA 2018; WHO, 2017). The largest variety of heavy metals are seen at the effluent release point and then dissipate as groundwater moves inland, due to the mobility properties of each heavy metal within sand. Appendix H lists the head measurements (elevation of groundwater) for all sampled dug and tube wells. During the dry season (Figure 8) the average head for dug wells is 69.66 m while the average head for tube wells is 73.81 m. During the wet season (Figure 9) this relationship is observed again where the average head is lower within the dug wells at 73.38 m than at the tube wells at 77.12 m. The wet season is influenced by heavy monsoon rains and flooding of the Me-O Chaung Canal (Sen Roy and Kaur, 2000).
Figure 8. Conceptual Model – Dry Season. From left to right how groundwater is utilized in the Amarapura Township – from being collected in dug wells and tube wells to being used for textile dyeing and then being released into the environment to flow into the Me-O Chaung canal as dye effluents. Below each utilization of water is listed the heavy metals that were present. Groundwater is flowing inland from the Me-O Chaung Canal towards the inland portion of the Amarapura Township.
Figure 9. Conceptual Model – Wet Season. From left to right how groundwater is utilized in the Amarapura Township – from being collected in dug wells and tube wells to being used for textile dyeing and then being released into the environment to flow into the Me-O Chaung canal as dye effluents. Below each utilization of water is listed the heavy metals that were present. Groundwater is flowing inland from the Me-O Chaung Canal towards the inland portion of the Amarapura Township.
Textile Dyes

Textile dye powders and their wastewaters have been used to identify the previously unknown composition of the colored dyes used in the Amarapura Township. Multiple heavy metals are part of the complex composition of the dyes being used. It is assumed however, that the heavy metals are not the only components of each color dye and that they are an amalgamation of multiple inorganic components. As an initial step of the dyeing process the powdered dyes are dissolved and mixed into boiling water and a measured amount of sodium sulfide, with the resulting solution being in the aqueous phase from when it is used for dyeing and then consequently being released as effluent.

Contaminant Migration and Mobility

Through heavy metal analysis of local groundwater and surface water, components of the dye solution have been found both directly around textile dyeing operations as well as in dug wells inland and away from where dyeing takes place. Groundwater flow is moving inland from the Me-O Chaung Canal towards the Irrawaddy River during both the wet and dry seasons (Appendix H). Due to the direction of groundwater flow and the mobility of the heavy metals in the sand and gravel ground and unconfined shallow aquifer, these contaminants are mobile as effluent is infiltrating the ground and local groundwater. The mobility of these contaminates is also exacerbated by monsoon rains during the wet season where flooding of the Me-O Chaung Canal occurs. Sodium is present in dug wells inland in the Amarapura Township while aluminum, iron, lead, and thallium have appeared in tube wells within 1 m of dyeing operations (Figure 8). The migration of these contaminant is towards the most densely populated
community, which lies between the Irrawaddy River and the Me-O Chaung Canal, consisting of resettlement areas that are the result of housing programs in the 1960s and 1990s (Asian Development Bank, 2013).

The mobility of each heavy metal identified in the local geologic media and groundwater is imperative to identifying which contaminants will stay stagnant around the dyeing operations versus which heavy metals will migrate towards the Irrawaddy River and affect inland locals’ groundwater. The chemical form of each metal contaminant influences the solubility, mobility, and toxicity in a groundwater system (Evanko and Dzombak, 1997). The heavy metals here are dissolved into the aqueous phase and different reactions may be occurring that influence the speciation and mobility of the contaminants, such as sorption, ion exchange, oxidation/reduction, and precipitation/dissolution (Evanko and Dzombak, 1997). The total concentration of the heavy metal contaminants in the aqueous phase is dependent on its ionic strength within solution and the concentrations of other ions with which the heavy metals may form complexes with (Deverel et al., 2012). Although the heavy metal composition within these select dye colors has been identified, the overall composition is most likely more complex, with some components still being unknown, therefore a full assessment of contaminant mobility is not yet possible. To further assess mobility of these contaminants, core logs of the surrounding dyeing area and near dug wells away from textile dyeing operations would be beneficial to identify the concentrations of heavy metals within the soils and a model of contaminant mobility can be created.
Each heavy metal contaminant identified at unsafe levels have different properties that influence the solubility and mobility within the sand and groundwater characteristic of the area. Aluminum mobility depends on whether organic compounds or complexes are formed, most which are soluble (WHO, 2003). Aluminum can occur in multiple forms in water causing the mobility of this contaminant to be dependent on pH. In pure water aluminum has low solubility around the pH range of 5.5-6.0, so concentrations of total dissolved aluminum will increase at higher and lower pH values (WHO, 2003). Soluble forms of antimony are very mobile in waters, while less soluble forms are adsorbed onto soil or clay particles and sediments (WHO, 2003). The solubility of barium increases as pH decreases, therefore areas with low pH groundwater are expected to have higher levels of barium. Concentration of barium ions are limited in natural aquatic systems by naturally occurring anions and adsorption of the anions to metal oxides and hydroxides (WHO, 2004). Dissolution of iron can occur due to decrease in pH and oxidation (WHO, 2003). Lead solubility and mobility as well as bioavailability increase as the pH of soil decreases (Ahmad et al., 2005). The total content of lead in soil depends on the pH, organic matter content, clay content, and biota type (Ahmad et al., 2005). Lead mobility in soils is limited and is the least mobile heavy metal, especially in reducing or alkaline conditions (Ahmad et al., 2005). Manganese mobility and partitioning is dependent on the solubility of the manganese form (EPA, 2004). In the dissolved form, such as in textile dyeing, manganese mobility is dependent on pH, the anions present, and the oxidation-reduction potential present, however manganese often settles into suspended sediments in water (EPA, 2004). Nickel is somewhat mobile in soil (Minnesota Pollution Control Agency, 1999). When nickel is compounded as a salt it is soluble in water, such as in textile dyeing mixtures (Rathor et al., 2014). Thallium itself and thallium
compounds are more soluble in water and more mobile in soil compared to other heavy metals (Karbowska, 2016). Thallium is toxic at low concentrations and tends to bioaccumulate in organisms and is generally more bioavailable than other heavy metals (Karbowska, 2016).

Recommendations

To protect local public health for those living in Mandalay, routine water quality testing for inorganic contaminants is a necessity (Bacquart et al., 2015). The health effects of short-term and long-term heavy metal consumption can take years to decades to become obvious, and a single contaminant is hard to identify on its own by generalized adverse health effects (Bacquart et al., 2015). One recommendation from this study is to seal off the tube wells that are directly influenced by the textile dyeing industry, those tube wells within the homes of the families who practice the dyeing. Another recommendation is to separate the textile dyeing effluents after dyeing occurs. The separated effluents should not be released out into the open environment but should be contained in a lined receptacle.

Most importantly, the local citizens should be informed of the heavy metals and sources of contamination that have been identified in the Amarapura Township region. By informing the locals of the potential health risks of the identified contaminants it will be up to the citizens to choose if they will continue to use the contaminated wells or not and travel to access less contaminated water. Other sources of water that are further away from the homes, such as dug wells that are more inland and upgradient are recommended for use over the local tube wells nearby dyeing operations.
Conclusion

Through this study the composition of nineteen colored textile dye powders have been identified. In addition to the identification and quantification of the major ions and heavy metals present in waters affected by dyeing, as well as waters away from dyeing operations, and an assessment of the local water quality in the Amarapura Township within Mandalay, Myanmar. The unregulated textile dyeing industry has been identified as a source of contamination to local groundwater within the shallow unconfined Amarapura Aquifer and the contamination has spread from areas of dyeing inland towards the Irrawaddy River and most densely populated areas of Mandalay. The differences in migration and mobility of the heavy metals within dyes and their effluent waters dictate how far inland contamination will spread through groundwater flow, and which wells will be affected by textile dyeing. Without proper regulation the groundwater in the Amarapura Aquifer and surface water within the Me-O Chaung Canal will continue to be contaminated, and locals who rely on this water will be at risk of serious health effects.


APPENDICES
APPENDIX A

GEOLOGIC MAP OF MYANMAR
(HTAY ET AL., 2014)
APPENDIX B

SPECTRA FOR SH1_RED AND SH1_BLACK POWDERED DYES
<table>
<thead>
<tr>
<th>Sample</th>
<th>Season</th>
<th>Date</th>
<th>TDS ppm</th>
<th>Br ppm</th>
<th>Cl ppm</th>
<th>F ppm</th>
<th>NO3 ppm</th>
<th>NO2 ppm</th>
<th>PO4 ppm</th>
<th>SO4 ppm</th>
<th>NH4 ppm</th>
<th>Ca ppm</th>
<th>Mg ppm</th>
<th>K ppm</th>
<th>Na ppm</th>
</tr>
</thead>
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<tr>
<td>PG1-B</td>
<td>Dry</td>
<td>12-Mar</td>
<td>5.49</td>
<td>0.31</td>
<td>42.011</td>
<td>1.642</td>
<td>40.066</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>54.27</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
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<td>4.49</td>
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<td>28.052</td>
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<td>0.608</td>
<td>50.289</td>
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<td>137.15</td>
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<td>136.49</td>
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APPENDIX E

EXACT MICRO 20 PHOTOMETER RESULTS
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APPENDIX F

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APPENDIX G

GROUNDWATER FLOW MAP
(GRZYBOWSKI ET AL., 2019)
APPENDIX H

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