Evaluation of the Kanchan™ Arsenic Filter Under Various Water Quality Conditions of the Nawalparasi District, Nepal

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ABSTRACT

In 2002, the Massachusetts Institute of Technology Department of Civil and Environmental Engineering partnered with the Environment and Public Health Organization to develop and disseminate the Kanchan™ Arsenic Filter (KAF) for the low-cost removal of arsenic from drinking water in rural Nepal. In this system, arsenic is removed via absorption onto the surface of ferric hydroxide, or rust, through the integration of locally available iron nails into a BioSand Filter setup.

Since 2002, the KAF filter has been successfully disseminated in approximately 24,000 Nepali households. However, recent studies have indicated that under certain raw water conditions, the KAF may inadequately reduce groundwater arsenic concentrations to levels below the Nepali government guideline of 50 µg/L. The present study focused on identifying and determining the impact of raw water parameters on the arsenic removal efficiency of the KAF. These parameters included arsenic, ferrous iron, dissolved oxygen, silica, phosphorous, pH, hardness, chloride, manganese, and electrical conductivity concentrations. In addition, filter flow rate, installation date, location, and user survey results were recorded. A total of 100 filters, of ages from less than one year to seven years, from 79 groundwater sources and 15 villages - primarily in the Nawalparasi District - were tested.

Data showed that poorly performing KAFs resulted from groundwater conditions that did not promote the corrosion of the iron nails. These conditions included low groundwater ferrous iron levels (<3mg/L), low ferrous iron levels after water had passed though the nails (<1.1 mg/L), low chloride concentrations (<7 mg/L), and low hardness concentrations (<350 mg/L of $CaCO_3$). In order for the filter to be promoted in areas with various groundwater conditions, it is recommended that future studies explore the incorporation of local components into the KAF system to increase iron corrosion.

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We both would also like to thank all of the parties involved in the making, execution, and publication of this study: Raju Shretha, Chintu Thapa, Hari Budhathoki, Tirta Sharma, Bipin Dangol, Susan Murcott, Tommy Ngai, Harry Hemond, Eric Adams, Pete Shanahan, the entire ENPHO Staff, the MIT MEng program, the MIT Legatum Center, and the wonderful people of Nepal.

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LIST OF ABBREVIATIONS

μg/L	– micrograms per Liter
As	– Arsenic
BOD	– Biological oxygen demand
BSF	– Bio-Sand Filter
Ca^{2+}	– Calcium ion
CAWST	– Center for Affordable Water and Sanitation
CEE	– Civil and Environmental Engineering
DMAA	– Dimethylarsinic acid
DO	– Dissolved oxygen
DWSS	– Department of Water Supply and Sewerage
EDTA	– Ethylenediaminetetraacetic acid
ENPHO	– Environment and Public Health Organization
Fe	– Iron
Fe(0) or Fe^0	– Zero valent iron
Fe(II) or Fe^{2+}	– Ferrous iron
Fe(III) or Fe^{3+}	– Ferric iron
GDP	– Gross Domestic Product
GW	– Groundwater
KAF	– Kanchan™ Arsenic Filter
L	– liters
L/hour	– Liters per hour
Lab	– Laboratory
MBA	– Master of Business Administration
mg/L	– milligrams per Liter
Mg^{2+}	– Magnesium ion
MIT	– Massachusetts Institute of Technology
MMAA	– Monomethylarsonic acid
ND	– Non-detectable
NDWQSC	– National Drinking Water Quality Steering Committee
NGO	– Non-governmental Organization
NSSC	– National Sanitation Steering Committee in Nepal
NWP	– Nepal Water Project of MIT
P	– Phosphorous (refers to phosphate in this context)
Si	– Silicon (refers to silica/silicate in this context)
VDC	– Village Development Committees
WHO	– World Health Organization

Chapter 1 – Introduction

1.1 Background on Nepal

Nepal is a landlocked country bordered by China to the north and India to the south. The country has a total population of 29.3 million people, an area of 54,363 square miles, and is a developing nation with a per capita income of about $440 US dollars (World Bank, 2009). Nepal is divided into three different regions that run from the northwest to the southeast - the mountains, the hills, and the plains, which are locally called "Terai" (**Figure 1-1**). The present-day arsenic groundwater contamination problem in the Terai Region was identified in the 1990s. About 50% of the total population of Nepal resides in the Terai, and 90% of this population depends on groundwater as their main source of water for drinking and domestic purposes (Neku & Tandukar, 2003). In addition, most of Nepal's agriculture is produced in the Terai; the region accounts for 34% of the national GDP and employs about ¾ of the total Nepali workforce, making the area vital to the country's economy (World Bank, 2009; US CIA, 2011).

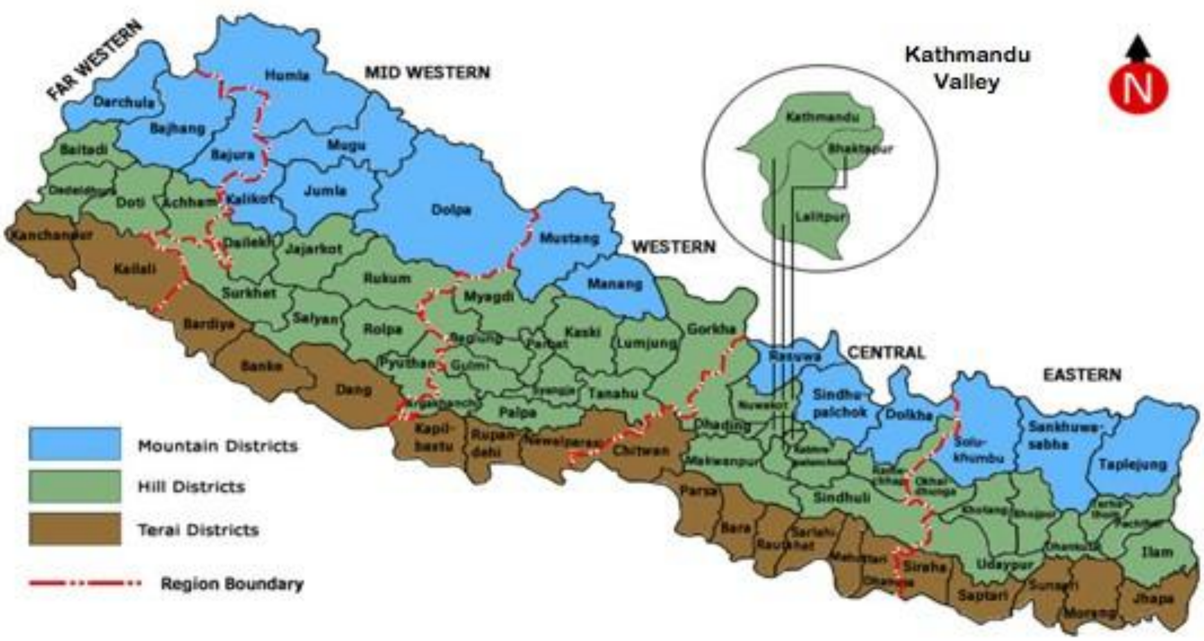

Figure 1-1: Geographic districts of Nepal – the mountains, the hills, and the plains (Terai). The circled area marks the country's capital, Kathmandu. Source: Murcott, 2010.

1.2 The Arsenic Problem

Naturally-occurring high arsenic groundwater concentrations are a recognized problem in many parts of southern and eastern Asian countries, including Bangladesh, India, China, Taiwan, Cambodia, and Nepal (see **Table 1-1** for arsenic concentrations and population affected by country). High arsenic concentrations in groundwater are dependent on the geological, hydrogeolocial, and geochemical conditions of the aquifers. Many studies have led to a greater understanding of the conditions leading to the mobilization of arsenic from the aquifer sediment, but the scale and precise causes for arsenic groundwater contamination are still uncertain. The World Health Organization (WHO) standard for allowable arsenic concentrations in drinking water is 10 μg/L, yet concentrations as high as 5,000 μg/L have been detected in groundwater tubewells in East Asian countries (Smedley, 2003; WHO: Guidelines for Drinking-water Quality, 2008).

Table 2-1: Maximum arsenic concentrations and number of people exposed in affected counties.

S.No.	Country/Region	Population exposed *(Million)	Area (Km^2)	Max Conc. Range (ppb)
1	Bangladesh	30	150000	2500
2	Inda/W. Bengal	6	23000	3200
3	China	5.6	NA	NA
4	Argentina	2	1000000	5300 (7800 in some porewaters)
5	Nepal	0.46 - 0.75	30000	600 (2620 in one case)
6	Chile (North)	0.5	125000	1000
7	Mexico	0.4	32000	620
8	USA (South West)	0.35	206300	2600
9	Taiwan	0.1	4000	
10	Mongolia (Huhhot Basin)	0.1	4300	2400

Source: Panthi et al., 2006.

Prior to the 1970s, the primary source of drinking water in many South Asian countries was surface water from dug-wells, rivers, canals, or ponds. However, most of these sources were biologically contaminated due to poor sanitation practices; thus, water-borne diseases, such as cholera, diarrhea, and typhoid, were common and caused the deaths of thousands of people in this region. In the 1980s, many government and non-government agencies in Nepal promoted the use of groundwater tubewells as a clean, pathogen-free, alternative source of drinking water.

However, in the proceeding decade, arsenic contamination was identified in groundwater sources throughout South Asia (Panthi et al., 2006).

Arsenic contamination in the groundwater of the Nepali Terai was discovered in 1999 during an exploratory arsenic testing project lead by the Department of Water Supply and Sewerage (DWSS) and the WHO. Since this discovery, many efforts have been made by rural water supply agencies to assess the occurrence of arsenic in Nepali groundwater. A 2003 National Sanitation Steering Committee (NSSC) study of arsenic concentrations in 17,000 tubewells of the Terai Region showed that water in about 31% of the wells exceeded the WHO 10 µg/L standard, while water in 4% of the wells exceeded the Nepali 50 µg/L standard for arsenic in drinking water. Since 2003, several research institutions have obtained similar measurements, as displayed in **Table 1-2** and **Figure 1-2** below. As can be seen from the figure, the Nawalparasi District has the highest arsenic concentrations in the Terai (Thakur et al., 2011).

Table 2-2: Statistical summary of Nepali groundwater arsenic contamination samples, subdivided by sampling research institution.

Research Organization/ Individuals	Total no. of tests	Samples with Arsenic Concentrations		
		0–10 µg/L	>10–50 µg/L	>50 µg/L
DWSS/UNICEF/WHO	670,117	91%	7%	2%
Nepal Red Cross Society (NRCS)	42,719	79%	16%	5%
Rural Water Supply and Sanitation Support Programme (RWSSSP)/Finnish International Development Agency (FINNIDA)	3,686	86%	8%	5%
Nepal Water Supply Corporation (NWSC)	30	53%	47%	0%
Nepal Water for Health (NEWAH)	5,328	83%	14%	2%
PLAN International	6,307	59%	39%	1%
Tandukar, N.	99	60%	32%	8%
Birgunj municipality, Nepal	6,670	97%	1%	1%
Rural Water Supply and Sanitation Fund Development Board (RWSSFDB)	1,021	87%	12%	1%
Department of Irrigation, MoI, Nepal	590	83%	7%	9%
Royal Institute of Technology (KTH)	53	42%	23%	36%
Japan International Cooperation Agency (JICA)/Environment and Public Health Organization (ENPHO)	389	69%	26%	5%
Total Samples	**737,009**	**82.63%**	**7.59%**	**2.64%**

Source: Thakur et al., 2011.

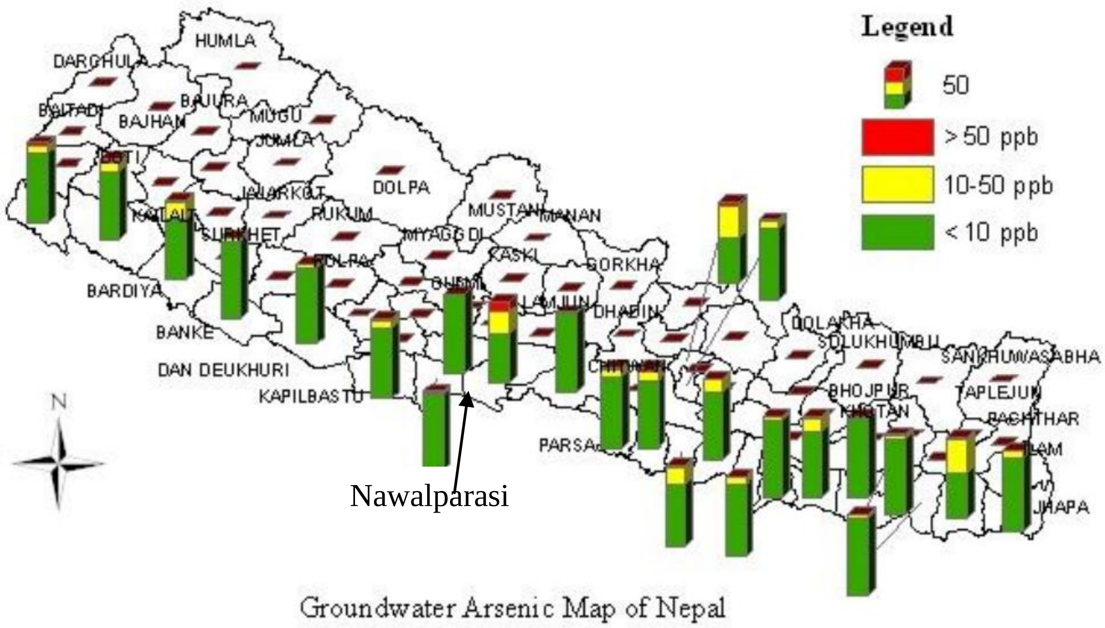

Figure 1-2: Arsenic concentrations in the Terai Region of Nepal from combined studies of over 700,000 tubewells. The Nepali standard for arsenic levels in drinking water is 50 ppb (μg/L). Source: Thakur et al., 2011.

A combination of rural conditions, a lack of infrastructure, and a lack of resources have made it difficult to install centralized water supply and treatment systems in many parts of the Terai Region. Although the fast and thorough installation of groundwater tubewells succeeded in reducing the number of deaths from microbiologically contaminated water, arsenic poisoning has become the new threat to drinking water quality in Nepal (Panthi et al., 2006).

1.3 Nepal Water Project

1.3.1 Project Motivation

The Nepal Water Project (NWP) within the Department of Civil and Environmental Engineering (CEE) at MIT began in 1999. The study was established by Senior Lecturer Susan Murcott, who was inspired by the Second International Women and Water Conference, which was held in 1998 in Kathmandu, Nepal. The NWP began with two primary objectives: (1) to quantify Nepali water quality issues with specific data and analysis, and (2) to make design recommendations for a point-of-use water treatment system that was both culturally and technically acceptable and effective (Halsey, 2000). To achieve these objectives, research was conducted in the areas of water supply and pollution control, household water treatment technologies, health and social surveys, and business plan formulations. From 1999 to 2005, over 30 MIT Master of Engineering and 8 MIT Sloan School of Management Master of Business Administration students traveled to Nepal to conduct field research (Murcott, 2010). Due to political instability and high travel risk warnings, MIT students were unable to participate in any research projects in Nepal from 2006 to 2009. In 2010, moderate travel risk levels allowed for the reestablishment of the MIT NWP for the 2010-2011 academic year.

1.3.2 Community Partner

Established in 1990 in Kathmandu, Nepal, the Environment and Public Health Organization (ENPHO)[1] is a service-oriented national Non-Governmental Organization (NGO). The mission of ENPHO is to develop and promote appropriate technologies to enable societies to become eco-friendly; to this extent, the organization primarily focuses on the areas of water, sanitation, and hygiene. ENPHO began working with the MIT Nepal Water Project in 1999 and has been one of the principal developers and distributors of the Kanchan™ Arsenic Filter (KAF). ENPHO has 73 members, 43 staff, and a well-equipped biological and chemical laboratory that has been accredited by the Nepal Bureau of Standards and Metrology (ENPHO, 2011).

[1] Main website: www.enpho.org.

Chapter 2 – Kanchan™ Arsenic Filter

2.1 Development of the Kanchan™ Arsenic Filter

In 1999, the NWP began its work with a review of existing literature and completed field studies to identify an appropriate technology for arsenic mitigation in Nepal. Over 50 existing water treatment technologies were identified from around the world and eight of these technologies were selected for the *Phase I* pilot testing study of 2000-2002. The tested technologies included the three-gagri system, the jerry can system, activated alumina, iron-oxide coated sand, activated alumina manganese oxide, the two-Kolshi system, arsenic iron treatment plants, and the arsenic BioSand Filter (Hurd, 2001; Lee, 2001; Hwang, 2002; Poole, 2002; Ngai, 2002; Ngai, 2007). These technologies were evaluated based on arsenic removal efficacy and appropriateness for implementation in rural Nepal. Three of these technologies, the arsenic BioSand Filter, the three-gagri, and the two-kolshi progressed to *Phase II* of the pilot study from 2002-2003 (Tabbal, 2003). All three technologies were evaluated by the criteria listed in **Table 2-1**. This second phase of the study identified the arsenic BioSand Filter, which, in 2004, was branded and trademarked as the Kanchan™ Arsenic Filter, to be the most appropriate technology for the removal of arsenic in rural Nepal. From 2003 to 2004, about 1,000 KAFs were deployed throughout the country. Currently, the KAF has been disseminated to approximately 24,000 Nepali households.

Table 2-1: Technical, social, and economic criteria for arsenic removal technology evaluation in Nepal.

Technical performance	**Social Acceptability**	**Economic Affordability**
Arsenic removal	Locally available materials	Low capital cost
Iron removal	Local manufacturing	Low running cost
Microbial removal	Easy operations and maintenance	Support local economy
Filtration rate	Culturally appropriate	Scale-up potential
Environmental safety	Users perceived benefits	Financial sustainability
Durability	Users preference	

Source: Ngai et al. 2006.

2.2 KAF Design and Construction

The KAF is a trademarked slow sand filter, modified with the addition of iron nails for arsenic removal. Large-scale slow sand filters were developed and successfully introduced in Europe around the 1890s. In the 1980s, a scaled down version of this technology for intermittent, household use - called the BioSand Filter (BSF) - was developed by researchers at the University of Calgary. Similarly to a large-scale slow sand filter, the BSF was designed to maintain certain critical flow characteristics (i.e. loading rate, sand layer depth, and grain size distribution) and a layer of standing water (typically two inches above the top fine sand layer). In addition, both systems are designed for the removal of bacteria, protozoa, and viruses. The KAF can be considered a BSF because it adheres to these same design criteria, but this filter is more innovative due to its arsenic, as well as pathogen, removal capabilities. In the KAF, arsenic is removed by adsorption onto the surface of rusted iron nails, which provide ferric hydroxide for a necessary chemical reaction, detailed in **Section 2.3**. Pathogens are removed primarily through physical straining in the sand layers, attachment to previously removed particles, biological predation in the *schmutzdecke* layer occurring in the top few centimeters of the sand, and natural die-off (Ngai et al., 2006).

The KAF is constructed from simple, local materials that are readily available in Nepal: plastic containers, PVC pipes, iron nails, two types of sand grains (fine and course), gravel, and brick (**Figure 2-1**). These materials - as opposed to higher-tech components - were selected due to the distribution system in Nepal that is not adequate for supplying specialized components in an efficient manner. The KAF is manufactured locally by trained technicians using simple hardware tools (i.e. wrenches and screwdrivers). In addition, the filter's operation and maintenance does not require any external energy or chemical input (Ngai et al., 2007).

Since 2004, several models of the KAF have been developed with the aim of improving the arsenic removal performance and the social acceptability of the filter. These models include the concrete square, concrete round, plastic square, plastic round, GEM505, and the fiberglass model. The KAF plastic round and fiberglass models are not currently found in the field and are also no longer promoted by ENPHO. All of the currently deployed KAF models are shown in **Figure 2-2**.

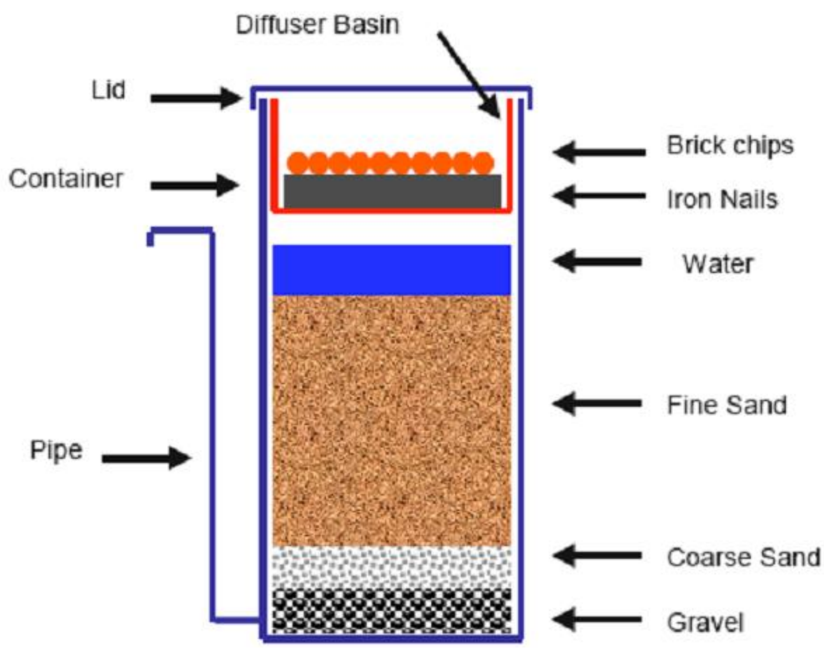

Figure 2-1: Diagram of the KAF, showing the location and arrangement of its components.
Source: Murcott, 2010.

Figure 2-2: Various KAF models developed over the years. (Left to right) concrete square, 2002; concrete round, 2003; plastic square, 2003; GEM505, 2004. Source: Ngai, 2005.

The concrete and GEM505 KAF models were designed to provide a filtration rate of 25 and 15 L/hour respectively, which are sufficient to supply water for a large family according to WHO guidelines (Howard, G. and Bartram, J., 2003). From February 2004 to February 2005, ENPHO tested 1,000 KAF systems - both concrete and plastic - over the entire Terai Region. This study revealed that the KAF has a removal efficiency of 85-99% for total coliform and of 90-93% for arsenic. In addition, 95% of the filters produced drinking water with arsenic concentrations below the Nepali guideline of 50 µg/L (Ngai et al, 2006).

2.3 Arsenic Removal Mechanism of the KAF

2.3.1 General Arsenic Chemistry

Arsenic is a highly toxic metalloid that is transparent, odorless, and tasteless when dissolved in water. As a metalloid, it is stable in the –III, 0, +III, and +V oxidation states. Arsenic forms several inorganic and organic compounds, and is commonly found in the environment. The most common species of arsenic found in aqueous environments are arsenite (H3AsO3), arsenate (H3AsO4), monomethylarsonic acid (MMAA), and dimethylarsonic acid (DMAA). For humans, the most toxic species of arsenic are arsenite and arsenate.

2.3.2 KAF Chemistry

The KAF system integrates an arsenic removal mechanism into a standard BioSand Filter by the addition of iron nails into a diffuser basin above the BioSand Filter media (see **Figure 2-1**). **Figure 2-3** shows an overview of the arsenic removal chemistry in the KAF. As water is poured into the diffuser basin, it oxidizes the iron nails from Fe(0) to Fe(II). Dissolved oxygen in the water further oxidizes Fe(II) into Fe(III), which in turn complexes as ferric hydroxide, $Fe(OH)_3$, more commonly known as rust. These dissolved ferric hydroxide particles then bind to the arsenic in the water, creating an iron-arsenic complex. Although the KAF was designed to have the arsenic adsorb onto the surface of $Fe(OH)_3$ while bonded to the nails, the iron-arsenic complex may be flushed down by the incoming water into the underlying sand layers. This complex can then bind to the sand in the filter, thus removing arsenic from the effluent water. The KAF mechanism is similar to arsenic adsorption on zero-valent iron as reported by Nikolaidis et al., 2003 and arsenic adsorption on hydrous ferric oxides as reported by Hussam et al., 2003. However, the exact location of the oxidation mechanisms and the point of complexion between the iron and the arsenic (on the nails or in the sand layers) in the KAF are not known.

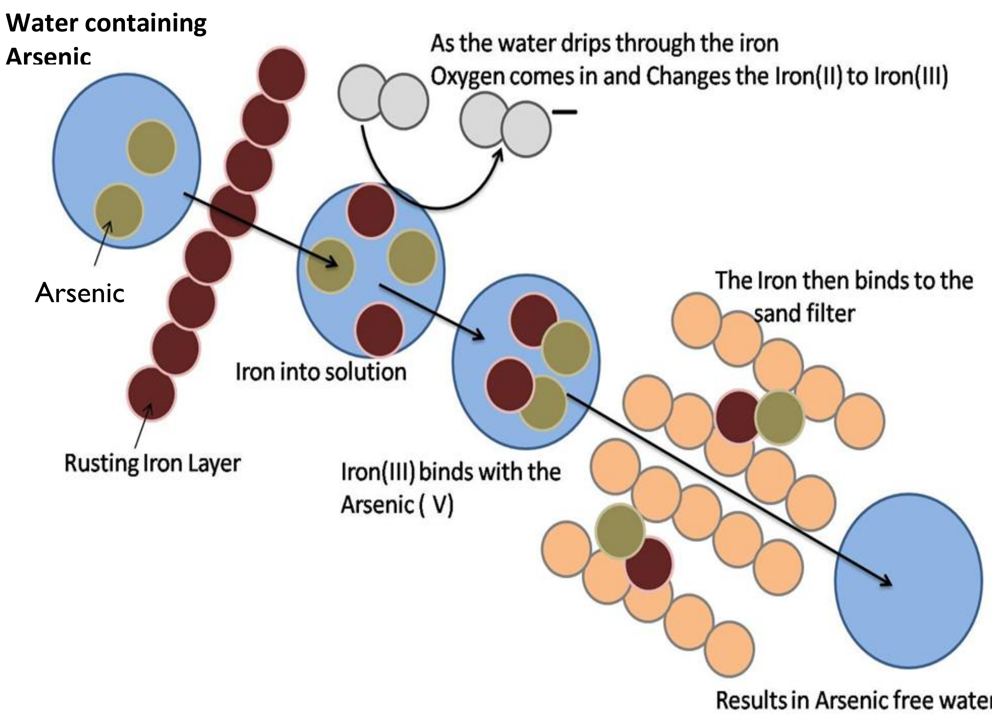

Figure 2-3: Diagram of the series of reactions used to remove arsenic from groundwater in the KAF. Note: the exact locations of these reactions in the KAF are not known.

2.4 Problems with the KAF

In 2009, the National Drinking Water Quality Steering Committee (NDWQSC) of Nepal issued a third party evaluation study of 703 KAFs. The objective of the study was to assess the arsenic removal performance of the KAF, with a focus on determining the filter breakthrough point and evaluating the filter's performance under high arsenic loads. Data was collected and analyzed by the CEMAT Laboratory of Kathmandu, Nepal, and is presented in **Appendix A**. Overall, researchers determined that the arsenic removal efficiency of the KAF was about 99% for influent arsenic concentrations less than 100 µg/L (**Figure A-1** and **A-2**). However, for inlet arsenic concentrations greater than 100 µg/L, effluent arsenic concentrations were typically above the Nepali arsenic drinking water standard of 50 µg/L (**Figure A-3** and **A-4**). In addition, the age of the KAF was observed to influence the arsenic removal performance of the filter (**Figure A-5**). KAFs operating for less than one year had an arsenic removal efficiency of about 95%; however, 30% of the KAFs operating for 1-3 years and about 15% of the KAFs operating after 3 years had efficiency levels of <75%. Nonetheless, the study found that the KAF was well performing (with effluent arsenic concentrations below the Nepali 50 µg/L drinking water standard) in 95% of the 703 tested filters. Researchers observed that well performing and poorly performing filters were typically found in the same geographic areas. Furthermore, many "clusters" of poorly performing filters were located in the Nawalparasi District.

Another third party study conducted by Chiew et al., 2009 in Cambodia examined the arsenic removal performance of three concrete square KAFs over the course of five-and-a-half months. The study found that none of the tested filters removed inlet arsenic concentrations to levels below the Nepali standard. This poor arsenic removal performance of the KAF was attributed to a combination of high influent phosphate concentrations and low influent iron concentrations (**Figure 2-4**). Other internal studies of the KAF in Bangladesh showed percent arsenic removal performance between 76% and 90 % in six GEM505 KAF models with influent groundwater with iron concentrations of 6 mg/L and arsenic concentrations between 200 and 400 µg/L.

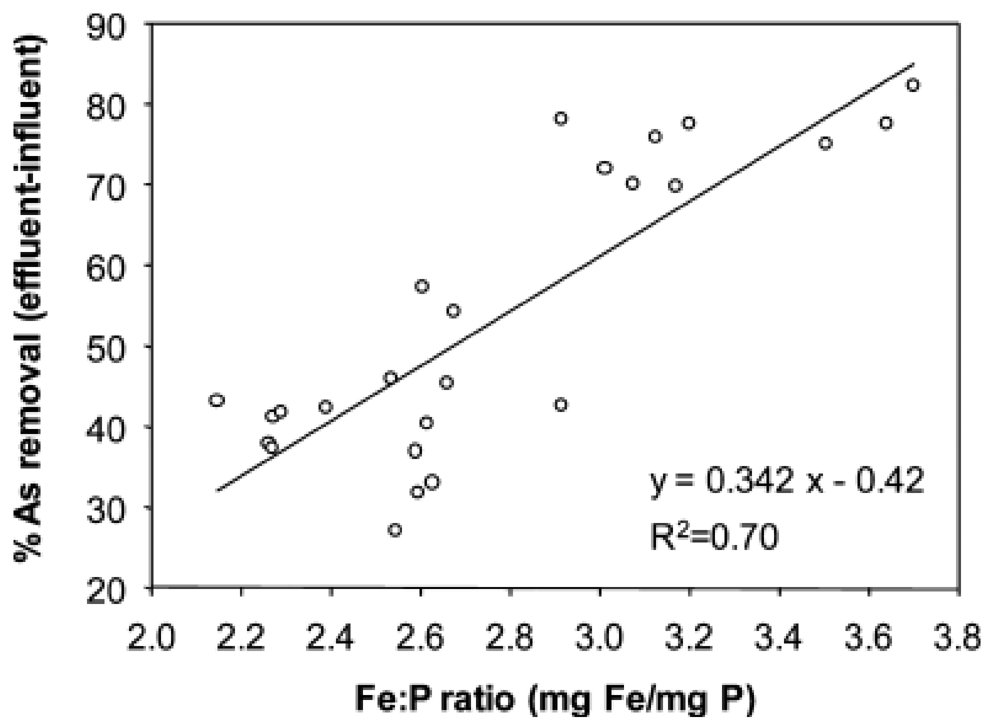

Figure 2-4: Graph depicting the relationship between the iron:phosphorus (Fe:P) ratio and percent arsenic removal in Cambodian groundwater. If the inlet iron concentration is high or increases, and/or if the inlet phosphorus concentration is low, there is a high Fe:P ratio and arsenic removal efficiency increases dramatically. Source: Chiew et al., 2009.

Chapter 3 – Design of Study

3.1 Objectives of the Study

The present study was developed in response to the reported poor performance of the KAF in particular areas of Nepal (i.e. the Nawalparasi district) and also in other South Asian countries, as described in **Section 2.3**. The uncertain performance of the KAF is presumed to be due to the different chemical composition of influent groundwater from location to location. The Nawalparasi District, in addition to having clusters of poorly performing filters, has some of the highest arsenic groundwater concentrations in all of Nepal (**Figure 1-2**). Thus, the first objective of this study was to evaluate the arsenic removal performance of the KAF under the different groundwater conditions of the Nawalparasi district to determine if the influent groundwater was impeding the KAF mechanism in this area. The second objective was to make recommendations on design improvements and operating limits for the dissemination of the KAF within and outside of Nepal based on the findings of the evaluation.

3.2 Studied Groundwater Factors

3.2.1 Arsenic

Since arsenic removal is the focus of this study, influent groundwater and effluent filtered water was tested for total arsenic concentration levels. A filter will be labeled as poorly performing if effluent arsenic water concentrations exceed the Nepali guideline of 50 μg/L. In the 3rd party study described above (**Section 2.3**), it was found that higher influent arsenic can lead to higher effluent arsenic levels. This would make inlet arsenic levels a known variable in filter performance. In Nepal, arsenic concentrations can be found to exceed 500 μg/L, while most contaminated water is in the 100-250 μg/L range **(**Ngai et al., 2002**)**. The KAF was previously studied by ENPHO, who determined that it performed poorly with inlet arsenic concentrations above 500 μg/L, so the KAF is expected that filters will fail in these conditions. This study was more interested to see if the KAF still continued to fail under groundwater arsenic concentrations <500µg/L.

3.2.2 Iron

The arsenic removing mechanism of the KAF depends on the formation of ferric hydroxides from the nails, the zero valent iron source (Fe^0). The corrosion of Fe^0 by water is an electrochemical process where Fe^0 is oxidized to form ferrous iron (Fe^{2+}), releasing electrons into the system and reducing dissolved oxygen or other species with high electropotential. In neutral pH and with the availability of water, the cathodic and anodic reactions for the overall iron corrosion reaction is show below:

$$Fe^0 \Leftrightarrow Fe^{2+} + 2e^- \tag{1}$$

$$O_2 + 2H_2O + 4e^- \Leftrightarrow 4OH^- \tag{2}$$

$$2Fe^0 + O_2 + 2H_2O \Leftrightarrow 2Fe(OH)_2 \tag{3}$$

Ferrous iron hydroxide ($Fe(OH)_2$) can be further oxidized into ferric iron or ferric hydroxide ($Fe(OH)_3$) in the presence of oxygen and water:

$$4Fe(OH)_2 + O_2 + 4H^+ + 4OH^- \Leftrightarrow 4Fe(OH)_3 + 2H_2O \tag{4}$$

These reactions indicate that the formation of ferric iron (Fe^{3+}) is highly dependent on the availability of water and oxygen. Also, the pH of the influent water governs the chemical reactions and species of iron present. In reaction (1) higher concentrations of H^+ ions will consume the electrons in this reaction (combining with oxygen and producing water) thus driving the reaction towards the right. In addition, other factors such as hardness (detailed in section 3.2.7) can impede the corrosion process by the deposit of calcium ions onto the surface of the nails.

3.2.3 Phosphate

Phosphate (PO_4^{3-}) is a phosphorus (P) bearing a tetrahedral anion compound. Due to their similar structure, both arsenic and phosphate form inner-sphere complexes with functional groups at the surface of iron oxides. Competition for adsorption sites in the iron oxides decreases the sorption of either anion when both are present. Chiew et al., 2009 found that poor arsenic removal by KAF in Cambodia was due to a combination of high influent P concentrations (>0.5 mg/L) and low Fe concentrations (<5 mg/L). Other studies suggest that high phosphate concentrations (>1.8 mg/L) alone or in the presence of other competing anions significantly decrease rate of removal of arsenic by iron (Meng et al., 2002; Roberts et al., 2004; Su and Puls, 2001).

3.2.4 Silicate

Silicate (SiO_4^{4-}) is a silicon (Si) bearing a tetrahedral anion compound. Similar to phosphate, silicate forms inner-sphere complexes with functional groups at the surface of iron oxides; thus it also competes with arsenic for adsorption sites in the iron oxides. Meng et al., 2000 showed that silicate significantly decreased As(III) removal by ferric chloride when Si concentrations were higher than 1 mg/L and the pH was greater than 5. In addition, this study shows that a Si concentration of 10 mg/L and a pH of 6.8 caused the adsorption capacity of ferric hydroxide for both As(V) and As(III) to be reduced by 200% and 400% respectively. Furthermore, Meng et al., 2002 found that the adverse effects of phosphate on As(V) adsorption were magnified in the presence of silicate and bicarbonate. Silicon dioxide, more commonly known as silica, refers to the combination of silicon and oxygen. Since a great majority of silicate species are oxides in natural water, we can quantify silicate concentrations in groundwater by measuring silica concentrations.

3.2.5 pH

The influent water pH level can affect the filter by promoting various solubility reactions. For arsenic and iron, the pH level determines the dominant species present in the influent water. At higher pH levels the As(V) and Fe(III) ion species dominate, while at lower pH levels the As(III) and Fe(II) species dominate (shown for arsenic in **Figure 3-1**). The As(V) and Fe(III) species have low solubility and tend to precipitate out, whereas the As(III) and Fe(II) species have high solubility. For the removal of arsenic via adsorption, low soluble conditions are preferable. The effects of pH are also related to the oxidation-reduction potential (Eh) of the chemical species to acquire electrons (**Figure 3-2**). A higher Eh will require a lower pH to shift the equilibrium of iron and arsenic ions towards their more soluble forms.

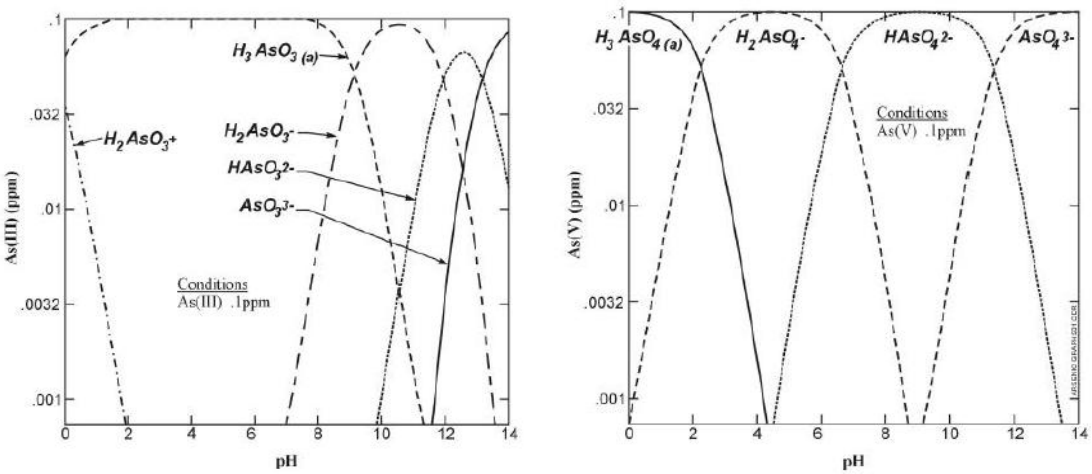

Figure 3-1: Solubility diagrams for As(V) and As(III). Source: Fields et al., 2000.

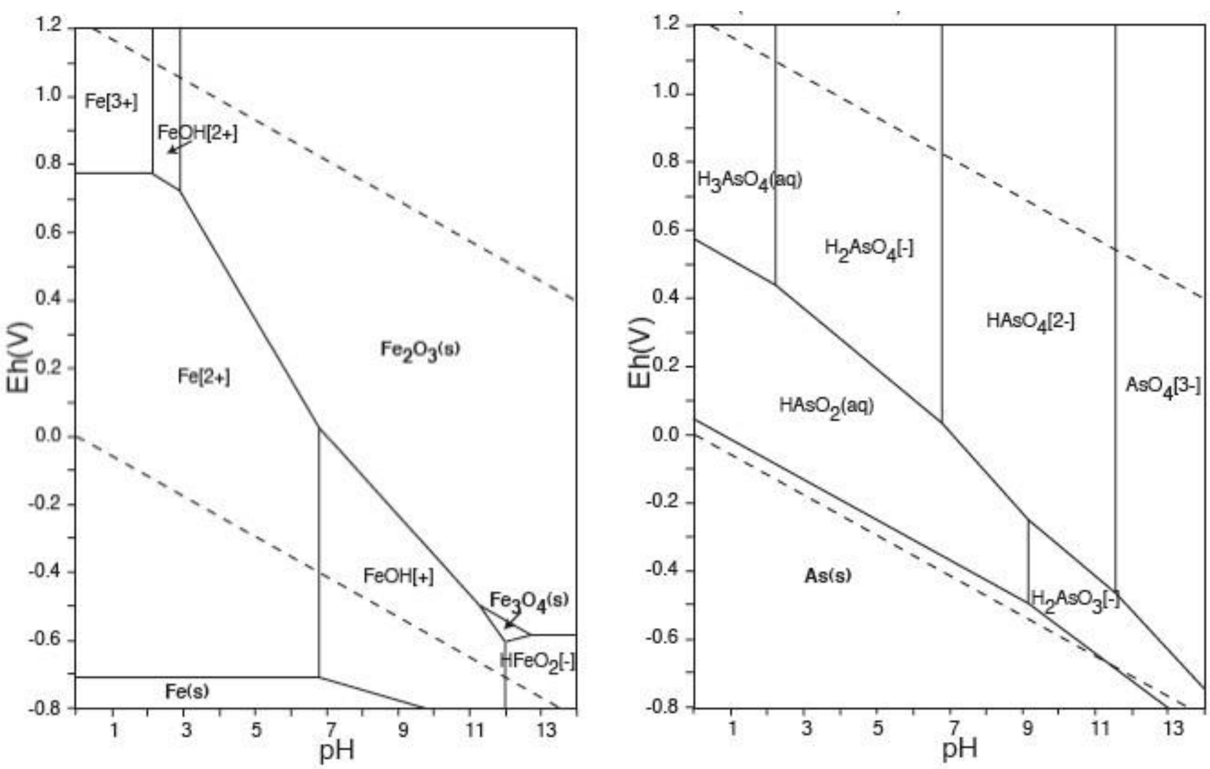

Figure 3-2: Eh-pH diagrams of arsenic and iron species. Source: Geological Survey of Japan, 2005.

A low pH can also cause the iron nails to rust more readily, thus providing more adsorption sites over the lifetime of the filter. Thus, a balance between a low enough pH to facilitate nail rusting, yet a high enough pH to promote arsenic precipitation and deposition in the nails and sand layers, would be ideal. Furthermore, pH also has an influence on solubility of calcium (see **Section 3.2.7**).

3.2.6 Dissolved Oxygen

Dissolved oxygen (DO) levels in groundwater are typically low due to the laminar nature of groundwater flow. However, the KAF arsenic removal mechanism favors oxygen-rich source water conditions for the oxidation of the nail iron and the presence of the lower soluble As(V) and Fe(III) species. By pouring the source water over the nails and through the diffuser basin, some aeration is generated despite the low inlet groundwater DO levels. Also, oxygen may diffuse into the sand layers at the top of the standing water layer. As discussed in **Section 2.2** the KAF was designed to grow a biofilm layer in the first few centimeters of the sand layer for the removal of pathogens. Thus, low DO levels in the effluent filtered water may be an indication of large bacterial growth within the sand. Oxygen is the primary electron receiver for many bacteria during respiration; therefore, bacteria can lower the DO levels during the process of metabolism, causing a more reducing environment that favors the presence of the more soluble As(III) and Fe(II).

3.2.7 Hardness

Hardness is defined as the sum of all polyvalent cations, such as Ca^{2+} Mg^{2+}, and is typically expressed as mg/L of $CaCO_3$ (Davis, 2010). Therefore, a higher measured hardness means that there is more calcium in the water sample, which in turn is more likely to precipitate out onto the iron nails and create a thin layer coating on the nails. Even a very thin layer of calcium precipitate on the nails can drastically reduce the amount of iron that is dissolving and oxidized into Fe(III), thus reducing the KAF's arsenic removal performance (Columbia Analytical Services, Web: 12/5/10). Studies show that high hardness concentrations (612.5 mg/L $CaCO_3$) significantly decreased arsenic adsorption efficiencies, while low hardness concentrations (51.5 mg/L $CaCO_3$) had no apparent effect (Yuan et al., 2002; Zhang et al., 2002).

3.3 Additional Measured Factors

Though this study tries to minimize all other factors outside of the discussed groundwater parameters that could affect the KAF's performance, there are still many filter properties and social factors that could not be removed or ignored. To account for these factors a user survey (**Appendix B**) was created to record and identify any significant location or social trends related to the arsenic removal performance of the KAF, as discussed in the proceeding sub-sections.

3.3.1 Filter Properties

As observed in the NDWQSC, 2009 study, the length of time the KAFs have been operating, or filter age, played a role in the arsenic removing performance of the filter. Thus, the installation date of the filters was recorded to see if there were any similar trends with filter performance and length of time used. In addition, the ENPHO 2008 study showed that filter flow rates above 30 L/hour could lead to a significant decrease in filter performance. Therefore, flows rates were also recorded to identify any similar new trends. The quality of the nails was another filter property measured in the survey because of the importance iron rusting plays in the arsenic removal mechanism. Nails were visually observed and recorded as being either: (1) not rusted, (2) moderately rusted, and (3) well rusted. Lastly, the filter model was recorded to confirm any discrepancies in the efficiency between the types of KAFs used.

3.3.2 Location and Social Influences

Also observed in the NDWQSC, 2009 study were clusters of well performing and poorly performing filters. Thus, the location of each filter was recorded to see if within particular regions of the study there were clusters of well or poorly performing filters. The survey recorded the District, Village Development Committees (VDC), Ward Number, and Tole (an individual village) of each tested filter. Also, the person or organization that provided the filter was documented to see if the poorly or well performing filters originated from the same manufacturer or distributer. In addition, questions specific to the use and maintenance of the filter were noted to observe any influences on the filter's performance due to the everyday use by the locals. These factors included: the number of households serviced by the filter, the number of people in each household, the volume of water filtered per day, the frequency of use, and the frequency of cleaning. Yet, it should be noted that this survey was not anonymous; therefore, the results may be biased.

Chapter 4 – Execution of Field Study

4.1 Timeline Summary

Literature reviews and project logistics were conducted from September through December 2010. The authors traveled to Nepal for the month of January 2011 to collect the field data. The first week of the trip was spent in Kathmandu to calibrate the field equipment using standards provided by the ENHPO Laboratory (Lab), and also to finalize project logistics with the ENPHO team. In addition, local testing materials were purchased and KAF distribution logs were obtained. The proceeding 16 days focused on fieldwork data collection in the Districts of Nawalparasi and Rupandehi. The concentrations of the interested parameters in the groundwater and filtered water sources were tested. Also, water samples were collected and returned to the ENPHO lab for the analysis of hardness and phosphate concentrations, as well as the analysis of a few split sample measurements on arsenic, iron, dissolved oxygen, and silica concentrations. Upon returning from the field to Kathmandu, preliminary data analyses were initiated for a short project presentation to our community partner ENPHO.

Table 4-1: Nepal fieldwork timeline.

Activities	**Jan. 2011**			
	Week 1	**Week 2**	**Week 3**	**Week 4**
Two MIT students arrive in Kathmandu				
Meetings and coordination with ENPHO				
Lab calibration and material collection				
Carry out research in the field				
Preliminary data analysis and presentation				

4.2 Field Study Team

The MIT NWP 2011 team consisted of members from the MIT Department of CEE and ENPHO. In addition to the authors, the following ENPHO members collaborated in the fieldwork study:

Raju Shrestha – ENPHO Program Officer
Hari Budhathoki – ENPHO Field Officer
Tirtha Raj Sharma Dhungana – ENPHO Nawalparasi Field Officer
Chintu Thapa – ENPHO Driver

In addition, the following program advisors were key in the development and logistical coordination of the fieldwork project:

Bipin Dangol – ENPHO Program Manager of the Water Quality Program
Susan Murcott – Project Supervisor**,** Senior Lecturer in the Department of CEE at MIT
Tommy Ka Kit Ngai – Project Supervisor, Director of Research Learnings, CAWST[2]

Figure 4-1: Nepal KAF study 2011 field team: (from left to right) Claudia Espinoza, Raju Shrestha, Maclyn O'Donnell, Chintu Thapa, Hari Budhathoki, and Tirtha Raj Sharma Dhungana.

[2] Centre for Affordable Water and Sanitation Technology (Calgary, Canada)

4.3 Selection of Field Site

The Nawalparasi District has some of the highest reported arsenic levels in Nepal; thus, it is a targeted region for filter distribution by many NGOs. Also, the NDWQSC study in 2009 identified this District as having clusters of poor performing filters. Individual villages within Nawalparasi were identified based on archived filter distribution lists recorded by ENPHO during their blanket study KAF testing in 2004-2005. In addition, sale lists provided by local entrepreneurs of the KAF and contacts from ENPHO team members who previously distributed the KAF via non-affiliated parties were an aid to our study. The targeted villages were in areas where the reported KAF effluent arsenic concentrations were above 50 µg/L. In total, filters and groundwater sources in 15 different villages in the Nawalparasi District and 3 villages in the Rupandehi District were tested (**Table 4-2**).

Table 4-2: KAF testing locations (*VDC = Village Development Committees).

SN	DISTRICT	VDC*	WARD No.	TOLE
1	Nawalparasi	Tilakpur	7	Patkhauli
2	Nawalparasi	Devgaun	1	Patkhouli
3	Nawalparasi	Pratappur	1	Khaireni/Tharu
4	Nawalparasi	Sunwal	3	Naduwa
5	Nawalparasi	Swathi	8	Swathi
6	Nawalparasi	Bhutaha	9, 6	Panchanagar
7	Nawalparasi	Sarawal	1	Goini
8	Nawalparasi	Makar	8	Laghuna
9	Nawalparasi	Ramgram Municipality	12	Kasiya
10	Nawalparasi	Ramgram Municipality	8	Unwanch
11	Nawalparasi	Ramgram Municipality	8	Baikunthapur
12	Nawalparasi	Ramgram Municipality	13	Kanchanha
13	Nawalparasi	Ramgram Municipality	13	Shiwangadh
14	Nawalparasi	Ramgram Municipality	13	Paratikar
15	Nawalparasi	Sukrauli	9	Naduwa
16	Rupandehi	Rudrapur	4	Gargare
17	Rupandehi	Rudrapur	4	Bargadhawa
18	Rupandehi	Dudharakshya	3	Budhanagar

4.4 Selection of Filter Types

This study focused on the arsenic removal performance of the KAF for different groundwater parameters; therefore, to avoid the influence of structural or mechanical failures on the KAF's performance, filters were chosen based on the following criteria:

(1) *No cracks or leakage*: Structural failures in the KAF could disrupt the arsenic removal mechanism of the filter by allowing inflows of untreated water. Also, leakages could affect the filter flow rate, which is an indication of filter performance, as discussed below.

(2) *Groundwater arsenic concentration greater than 50 µg/L*: The Nepali standard for arsenic concentrations in drinking water is 50 µg/L; therefore, filters were only tested with groundwater concentrations above this standard.

(3) *Maximum flow rate of 30 liters/hour*: The blanket study of the KAF by ENPHO in 2004-2005 indicated that filter flow rates above 30 L/hour can lead to significant decreases in the percentage of arsenic removal by the KAF. This is presumed to be due to low water contact time with the nails or sand layers.

(4) *Sufficient sand*: The KAF was designed to have a 2-inch gap between the diffuser basin and the top sand layer. The consumer sometimes removes too much sand during cleaning or to increase flow rate, but this is not recommended and can lead to decreased filter life and increased filter flow rate.

(5) *Nails present and evenly spread*: The contact of iron nails with the groundwater is essential for the arsenic removal mechanism of the KAF, especially with naturally low levels of iron in the groundwater. Therefore, large gaps in the iron layer, or the absence of nails altogether, will let the groundwater drip through the diffuser basin and out the effluent without the proper arsenic treatment.

(6) *No tap*: Many consumers of the KAF like to install a tap into the outlet of the filter to control the volume of source water that is filtered or stored inside the KAF. This alteration allows them to collect the filtered water as needed throughout the day without adding in more source water continuously. However, this alteration will also inadvertently increase the standing water level above the sand, which is designed to be 2-inches such that sufficient oxygen from the air cannot diffuse into the biofilm layer in the sand. As previously discussed, a lack of oxygen in the KAF can change the oxidation state of arsenic and iron in the sand layers to its more soluble forms, As(III) and Fe(II), thus possibly leading to “spiked” arsenic concentrations in the effluent water.

Figure 4-2: Tested KAF models (left to right) concrete square, concrete round and GEM505.

From these criteria, only the KAF concrete square, concrete circle and GEM505 models were tested in this study (**Figure 4-2**). KAF model 3 (plastic square) was widely distributed in the Nawalparasi District but it was not included in this study due to structural failures noted in the side bulging of the plastic container. Also, it is no longer promoted or distributed by ENPHO.

4.5 Testing Instruments and Methods

4.5.1 Arsenic

Arsenic concentrations in the influent groundwater and effluent filtered water were measured using the Wagtech Arsenator® Digital Arsenic Test Kit[3]. Studies show that the Arsenator can measure reliable arsenic concentration readings with a correlation of 0.95 and 0.96 with laboratory measurements of arsenic concentrations 0-100 µg/L (Sankararamakrishnan et al. 2008) and 0-250ug/L (Shukla et al., 2010) respectively. Testing methodology followed the Arsenator's instructional manual attached in **Appendix B**. The Arsenator used in the present study was borrowed from the Center for Affordable Water and Sanitation Technology (CAWST) of Canada.

Figure 4-3: Wagtech Arsenator® Digital Arsenic Test Kit. Source: Wagtech, 2011

In addition, 16 samples were preserved for split sample arsenic concentration analysis in the ENPHO Lab. Samples were preserved down to a pH <2 using hydrochloric acid in accordance to standard methods ("Standard Methods," 1995). The ENPHO lab measured the samples for arsenic using the hydride generation method and an atomic absorption spectrometer.

[3] Product number: WAG-WE10500. Web: http://www.wagtech.co.uk/

4.5.2 Iron

Ferrous iron concentrations (Fe(II)) were measured in the influent groundwater, the water passing through the nails and dripping out of the diffuser basin ("nail water", **Figure 4-4**), and the effluent filtered water. Ferrous iron concentrations were measured using the HACH DR 27000 Portable Spectrophotometer[4] and HACH Ferrous Iron Reagent Powder Pillows[5]. The composition of the HACH reagent is about 10% 10-Phenanthroline and 90% sodium bicarbonate (MSDS, 2009). If ferrous iron concentrations were present, the solution would turn orange and the spectrophotometer would calculate the concentration of Fe(II) from the color intensity within a range of 0.02 to 3.00 mg/L. If the solution surpassed the detection limit, the sample would be diluted by ½ (since our measurements of Fe(II) never exceeded 6 mg/l) using purchased bottled water, which indicated that it was reverse osmosis treated. Testing methodology followed the HACH Method 8186.

Figure 4-4: Collecting water sample after it has passed through the nails and is dripping from the diffuser basin into the sand layers. Hari Budhathoki (left) and Tirtha Raj Sharma Dhungana (right).

[4] Product number: DR2700-01B1. Web: http://www.hach.com/
[5] Product number: 103769. Web: http://www.hach.com/

In addition, 16 split samples for total iron concentrations were preserved and brought back to the ENPHO lab for testing. Samples were preserved down to a pH <2 using hydrochloric acid in accordance to standard methods ("Standard Methods," 1995). The lab measured the preserved iron concentrations using an atomic absorption spectrometric instrument.

4.5.3 Silica

Silica concentrations were measured from only the groundwater sources using the HACH DR 2700 Portable Spectrophotometer and three silica reagents: citric acid, sodium molybdate, and the acid reagent[6]. The latter reagent has a composition of sulfamic acid and sodium chloride (HACH: MSDS-Acid Reagent, 2010). In the presence of silica concentrations, the sample will turn green with the reagents and the spectrophotometer would then calculate the concentration within a range of 1 to 100 mg/L using the color intensity. Samples did not surpass the detection limit for silica, so dilution was not necessary. Testing methodology followed the HACH Method 8185.

In addition, 15 split samples for silica concentrations were preserved and brought back to the ENPHO lab for testing. Samples were collected in polyethylene bottles and stored in accordance to standard methods ("Standard Methods", 1995). The lab measured the stored silica concentrations using a molybdosilicate reagent and a spectrophotometric instrument.

4.5.4 Phosphate

Phosphate concentrations were only measured for the groundwater sources. Previous studies indicate that field kits for measuring phosphate concentrations do not prove to be very accurate. Therefore, groundwater samples were collected for each source and brought to ENPHO for laboratory analyses of phosphate concentrations. In the lab, phosphate was measured using an ammonium molybdate ascorbic acid reagent and a spectrophotometric instrument. Samples did not need to be preserved according to standard methods ("Standard Methods," 1995).

[6] Product number (for all three reagents): 2429600. Web: http://www.hach.com/

4.5.5 Dissolved Oxygen (DO)

DO concentrations were measured for the effluent water from each of the filters of interest. This testing took place in the field using the HACH Dissolved Oxygen Test kit, model OX-2P[7]. This field kit measures dissolved oxygen concentrations using the drop count titration method. The detection range is 0.2-4 mg/L (in increments of 0.2 mg/L) and 1-20 mg/L (in increments of 1mg/L). Testing methodology followed the HACH Method 8215.

In addition, 14 split samples for DO concentrations were preserved and brought back to the ENPHO lab for testing. The samples were collected in glass BOD bottles and were preserved using the Azide Modification procedure in accordance to standard methods ("Standard Methods," 1995). The ENPHO lab then performed a sodium thiosulfate titration to measure the oxygen concentration of the sample when initially collected.

4.5.6 Hardness

Hardness concentrations were measured for the influent groundwater and the effluent filtered water. Samples were collected from each source and brought back to ENPHO for more accurate and precise measurement ranges than field kits can provide. Samples did not need to be preserved according to standard methods ("Standard Methods," 1995). In the lab, hardness was measured using the ethylenediaminetetraacetic acid (EDTA) titrimetric method. In addition, in the field, hardness measurements were estimated using the HACH 5 in 1 Water Quality Test strips[8] for total hardness concentrations as $CaCO_3$ (0, 250 or 425 mg/L).

4.5.7 pH

The pH levels for both the influent groundwater and effluent filtered water were measured using the WaterWorksTM Extended Range pH Check Strips. The WaterWorksTM strips have a detection sensitivity of pH 1-5 and 10-12 in increments of 1 and pH 6-9.5 in increments of 0.5. The total test time per sample is 30 seconds. In addition, the HACH 5 in 1 Water Quality Strips were also used to measure pH with a detection range pH 6.2-8.4 in increments of pH 0.6.

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[7] Product number: 146900. Web: http://www.hach.com/
[8] Product number: 2755250. Web: http://www.hach.com/

4.6 Sampling Methodology

After the filters were evaluated based on the criteria described in **Section 4.4**, a systematic sampling procedure was followed to minimize sampling time and error from inconsistencies in sampling collection, as shown in **Figure 4-5** and described below:

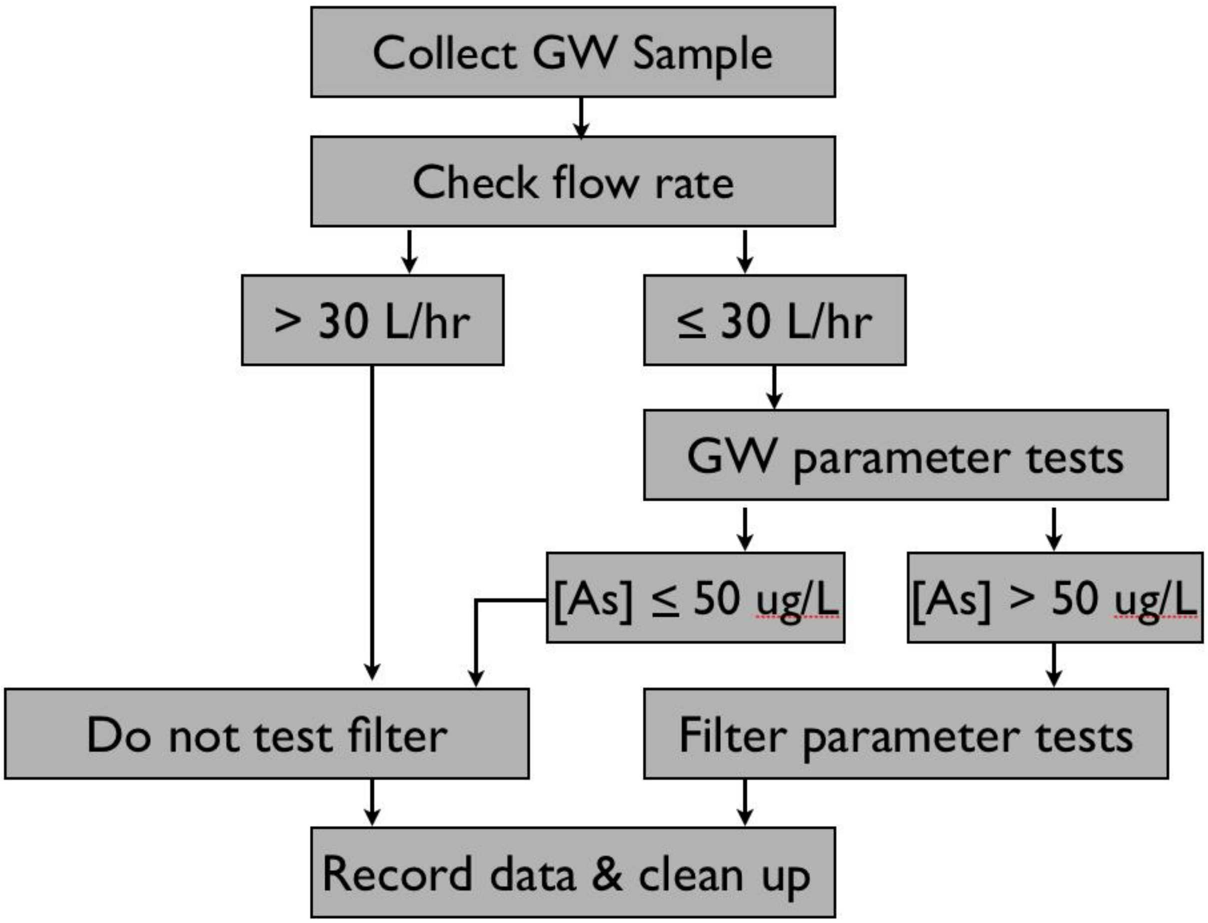

Figure 4-5: Flowchart of the Nepal 2011 field study sampling methodology. Note: GW = groundwater.

Groundwater collection

Groundwater was collected directly from private or public tubewells. Some tubewells needed to be "primed" prior to use, meaning prepared by pouring in a small amount of water into the pump and applying suction so that the mechanism of the tubewell would work. However, groundwater samples collected directly after the priming procedure would be a poor representation of the groundwater conditions, since it would contain a mixture of the "priming water". Thus, for consistency each tubewell was pumped for a minimum of 60 seconds prior to collecting the groundwater sample in 500 mL plastic beakers.

Measuring flow rate

The groundwater sample would then be used to measure the corresponding filter flow rate. To measure the filter's flow rate, a 500 mL plastic graduated cylinder and a stopwatch was used. If the flow rate was above 30 L/hour (or above 500mL/minute) the filter would not be included for testing. If the flow rate was less than or equal to 30 L/hour field testing for the concentrations of different groundwater parameters would proceed.

Testing parameters in groundwater

The parameters tested in each groundwater sample were: arsenic, pH, ferrous iron and silica concentrations. In addition, groundwater samples would be collected and stored in 500 mL polyethylene bottles for hardness and phosphate testing in the ENPHO lab. All groundwater tests per tubewell would take an estimated 25 minutes to complete, with the arsenic test results (~20 minutes to complete) being the determining factor in order to continue testing. If the arsenic concentrations in the groundwater were less than the Nepali Standard for drinking water (50 μg/L), all further testing for the corresponding filter would discontinue. On the other hand, if the groundwater concentration of arsenic was above 50 μg/L then we would proceed to collect the filtered water sample

Filtered water collection

For direct comparison of the arsenic removal performance of the KAFs, it was important to let flush the filter out completely before collecting the filtered water sample, so that it corresponded to the tested groundwater source and not old sitting water. Due to the plug flow nature of bio-sand filters, the volume of water poured into the filter would need to be greater than the filter pore volume in order to collect newly filtered water. Since both the GEM505 and the concrete square KAF models have a pore volume of about 5L, the filtered water sample would be collected after at least 5 L of the groundwater sample had passed though. The measured flow rate of each filter would allow us to know when enough time had passed (corresponding to 5 L of filtered water) before collecting the filter samples in 500 mL plastic beakers. The “nail water” sample would be taken by lifting up the basin holding the nails and collecting the dripping water (**Figure 4-4**). For comparison, a second nail water sample was taken for a few filters by “scooping” up the top water from the filter after the basin had been lifted. The nail water sample would be collected after the filtered water sample so that it would not factor into the tested performance of the filter.

Testing parameters in filtered water

The parameters tested from the filtered water sample were: arsenic, pH, and ferrous iron concentrations. The water sample for dissolved oxygen would be collected directly from the filter outlet and tested immediately. In addition, a filtered water sample would be collected and stored in a 250 mL polyethylene bottle for hardness testing in the ENPHO lab.

If a tube well source was servicing more than one KAF filter, the groundwater from the source would be tested only once and the filtered water would be tested for each individual filter. In this step, it was assumed that the groundwater source would not change drastically over the course of a few hours. Resulting data from each groundwater and filtered water sample would be documented in a notebook and later updated into an electronic spreadsheet. In addition, user survey results would be collected by ENPHO staff personnel in Nepali and later translated to English. Also, the stored groundwater and filtered water samples would be labeled to match the corresponding test serial number on the data sheet. The testing instruments would then be cleaned and re-supplied for the next round of testing.

Chapter 5 – Results

5.1 Analytical Results of Field Study

This section will present the results of all chemical parameters tested in the field. Filter performance was determined by the effluent filtered water arsenic concentrations relative to the Nepali standard for arsenic in drinking water (50 µg/L). The parameters measured were graphed against the effluent arsenic concentrations to observe any relationship and correlation between the two data sets. Also, the KAFs were evaluated based on the percent arsenic removal. The parameter measurements and the percent arsenic removal corresponding to each filter were graphed against each other to observe any correlation. A regression analysis was preformed to determine the significance of any perceived correlation. An R^2 value above 0.0645 for 100 samples was taken to be significant to the 0.01 (Downie and Heath, 1965). Associated errors in measured values were estimated using previous studies and calibration curves of measured parameters against standards and split sample values tested by the ENPHO Lab. Overall, 100 separate KAFs were tested, corresponding to 79 groundwater sources and 101[9] filtered water samples. Thus, the total sample size for all parameters was 101, with the exception of ferrous iron (N=100), phosphate (N=97) and hardness (N=97) readings.

5.1.1 Arsenic

Arsenic concentration measurements ranged from 0 non-detectable (ND)[10] to a maximum of 500 µg/L (upper detection limit). **Figure 5-1** displays an overview of the arsenic concentration ranges for both influent groundwater and effluent filtered water sources. Most filters were observed remove some fraction of the influent groundwater arsenic concentrations. Also, there was a 58:43 ratio between well performing and poorly performing filters. Well performing filters removed on average 91% of the inlet arsenic concentration while poorly performing filters removed on average only 50% of the inlet arsenic concentration (**Table 5-1**). However, there was no correlation (R^2 = 0.0288) between inlet groundwater arsenic concentration and arsenic

[9] Filter number 43 and 53 are the same GEM505 filter tested with the same groundwater source on two separate days.
[10] Below detection limit of the measuring instrument

removal performance (**Figure 5-2**). There was, though, an observed relationship between influent arsenic concentrations below 200µg/L and effluent arsenic concentrations below the Nepali standard (**Figure 5-3**). About 93% of the samples (N=27) with groundwater concentrations below 200µg/L correspond to a filtered water arsenic concentration below 50µg/L.

Table 5-1: Averages and standard deviations of measured arsenic concentrations in the groundwater, effluent filtered water, and the percent arsenic removal by the filters.

	# Samples	GW [As]		Filtered [As]		% [As] removal	
		Average	σ**	Average	σ**	Average	σ**
Well performing*	58	204	98	17	12	91	10
Poorly performing*	43	270	71	134	80	50	26
Total filter Samples	**101**	**232**	**93**	**67**	**79**	**73**	**27**

*Based on Nepali drinking water standard of [As]<50 µg/L.

**Values above 100 µg/L of arsenic had an error of +/- 50 µg/L so standard deviations may be higher.

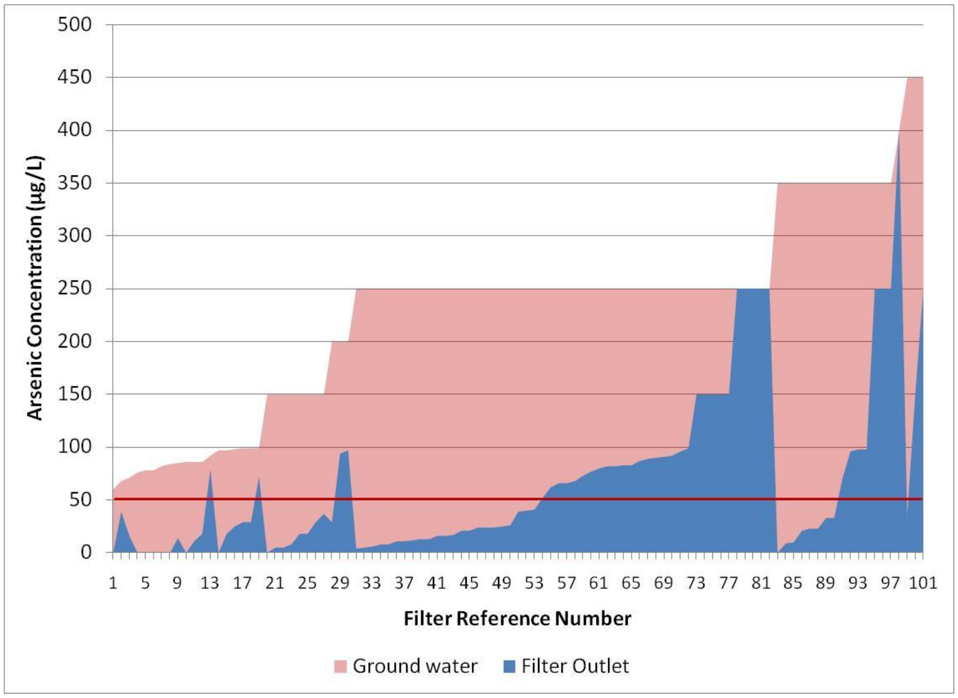

Figure 5-1: Arsenic concentrations in groundwater and filtered water samples. Error: +/- 25% (As ≤ 100 µg/L) and +/- 50 µg/L (As >100 µg/L). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

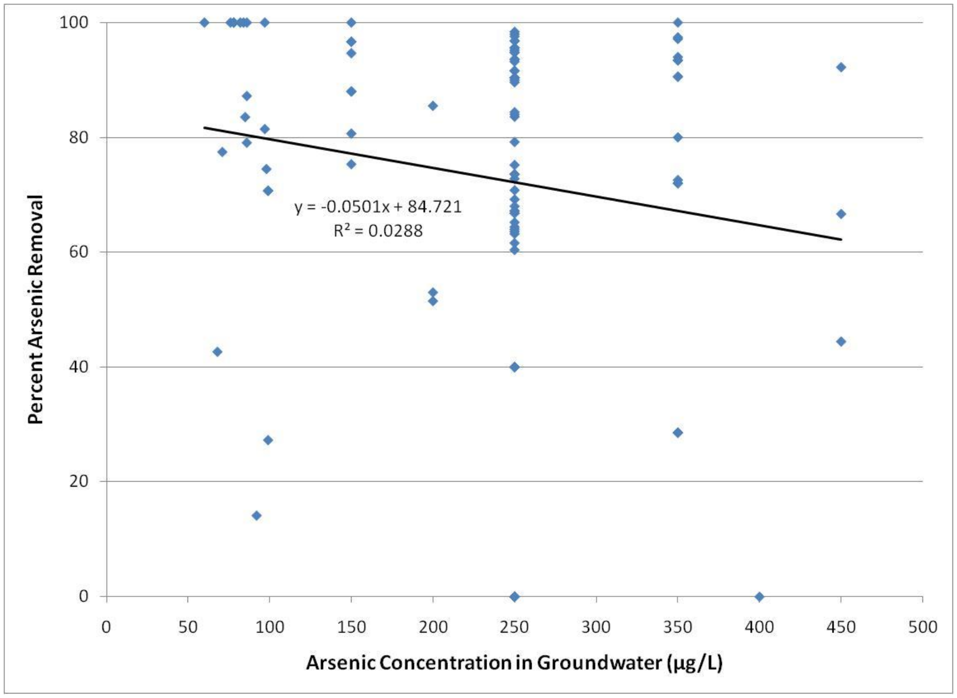

Figure 5-2: Groundwater arsenic concentrations vs. percent arsenic removal of the KAF. Error: +/- 25%

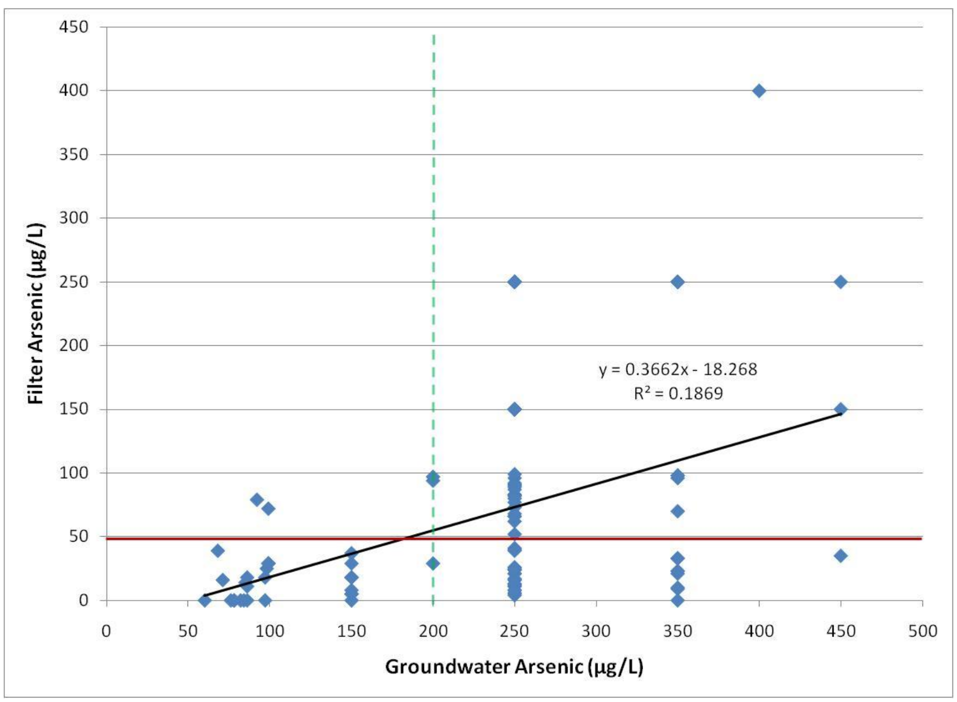

Figure 5-3: Groundwater arsenic concentrations vs. filtered water arsenic concentrations. Error: +/-25% (As ≤ 100 µg/L) and +/-50 µg/L (As >100 µg/L). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Dotted green line: Observed shift from mostly well performing filters (left) to both poor and well performing filters (right).

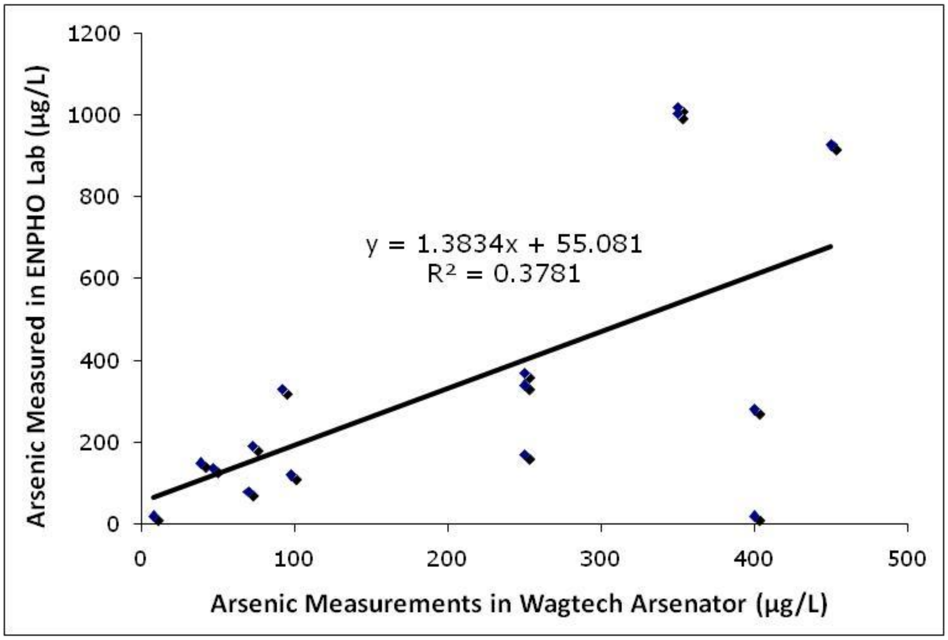

Figure 5-4: Split sample calibration between measured arsenic concentrations in an atomic absorption spectrometer (ENPHO) and the Wagtech Arsenator.

Split sample results with the ENPHO atomic adsorption spectrometer show a 0.39 correlation with the Wagtech Arsenator readings and an error of about 40% (**Figure 5-4**). This calibration was much lower than previous published errors for the Wagtech Arsenator of about 10-15% for concentrations as high as 250 µg/L (Swash, 2003; Sankararamakrishnan et al., 2008; Shukla et al., 2010). In addition, a 10% error was reported by ENPHO for the split sample readings. Therefore, an approximate error of 25% was used for arsenic values below 100 µg/L. Arsenic values from 100 µg/L to 500 µg/L were read using a color indicator table in increments of 100 µg/L, thus there is an associated error of +/- 50 µg/L (**Appendix C**, **Figure C-1**).

5.1.2 Iron

Ferrous iron (Fe(II)) concentrations ranged from 0 ND to 7.4 mg/L in groundwater, 0 ND to 1.8 mg/L in filtered water, and 0 ND to 3 mg/L in the nail water sources. Overall, Fe(II) concentrations in the groundwater and nail water were higher in the well performing filters than in the poorly performing filters (**Table 5-2**). High groundwater Fe(II) concentration s correlated significantly with low effluent arsenic concentrations (R^2=0.114) and with high percent arsenic removal (R^2=0.153) (**Figure 5-5** and **Figure 5-6**). Similarly, high nail water Fe(II) concentrations correlate significantly with low effluent arsenic concentrations (R^2=0.085) and with high percent arsenic removal (R^2=0.133) (**Figure 5-7** and **Figure 5-8**). In addition, a strong relationship between effluent arsenic concentrations below the Nepali standard and both Fe(II) concentrations >3mg/L in groundwater and >1.1 mg/L in nail water samples was observed. Also, most of the Fe(II) concentrations after the nails were due to influent groundwater Fe(II) concentrations but there was no correlation with delta Fe(II) values (groundwater minus nail water Fe(II) concentrations) and effluent arsenic concentrations (**Figure 5-9**). Furthermore, Fe(II) concentrations in the effluent filtered water of well performing filters were on average lower than the WHO standard for total iron concentrations in drinking water (0.3 mg/L), but higher for poorly performing filters, as shown in **Table 5-2 (**WHO: Guidelines for Drinking-water Quality, 2008). Regression analysis showed that Fe(II) concentrations in the filter water were not significantly correlated to effluent arsenic concentrations (R^2=0.0018) (**Figure 5-10**) or the percent arsenic removal (R^2=0.0455) (**Figure 5-11**).

Associated error in Fe(II) readings was determined by calibrating the Portable HACH spectrophotometer against a set of prepared standards. The standard concentrations were made using the HACH Ferrous Ammonium Sulfate, Hexahydrate reagent[11]. The standard calibration indicated an increased error for Fe(II) values above 1mg/L, thus measured values above this range were adjusted according to the equation (**Figure 5-12**):

$$y = 0.613x + 0.336 \tag{5}$$

Table 5-2: Averages and standard deviations of measured ferrous iron concentrations in the groundwater, effluent filtered water, and the water after passing through the nails.

	GW [Fe(II)] (mg/L)		**Filtered [Fe(II)] (mg/L)**		**Nail [Fe(II)] (mg/L)**	
	Average	σ	Average	σ	Average	σ
Well performing*	1.90	0.87	0.13	0.32	0.46	0.59
Poorly performing*	0.92	1.42	0.44	0.58	0.96	0.88
Total filters	1.48	1.31	0.31	0.51	0.75	0.81

*Based on Nepali drinking water standard of [As]<50 µg/L.

[11] Product number: 1125614. Web: http://www.hach.com/

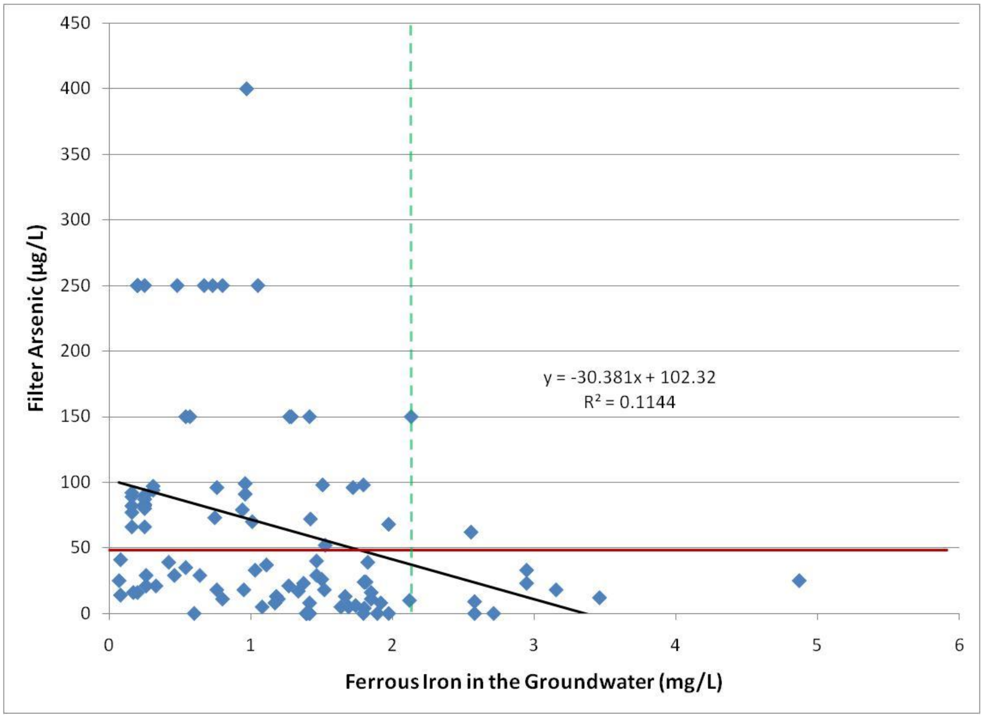

Figure 5-5: Fe(II) concentrations in groundwater vs. filtered water arsenic concentrations. Error: +/-25% (As ≤ 100 µg/L), +/- 50 µg/L (As >100 µg/L), +/- 0.03 mg/L (Fe ≤ 1mg/L), and +/- 20% (Fe > 1mg/L). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Dotted green line: observed shift from mostly well performing filters (right) to both poor and well performing filters (left).

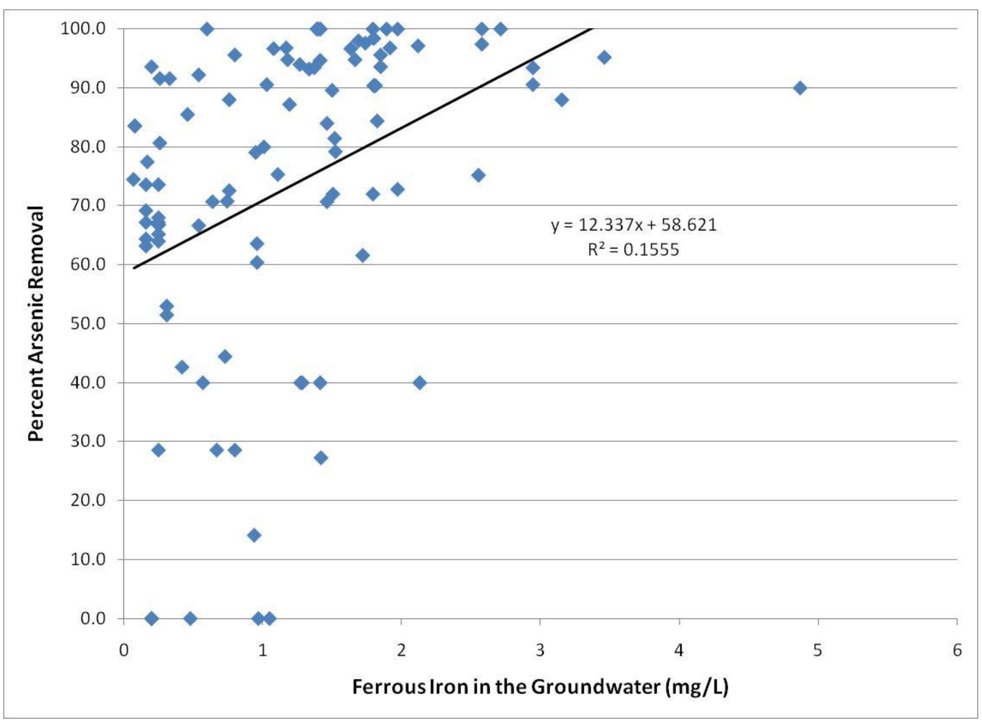

Figure 5-6: Fe(II) concentrations in groundwater vs. percent arsenic removal. Error: +/- 25% (As), +/- 0.03 mg/L (Fe ≤ 1mg/L), and +/- 20% (Fe > 1mg/L).

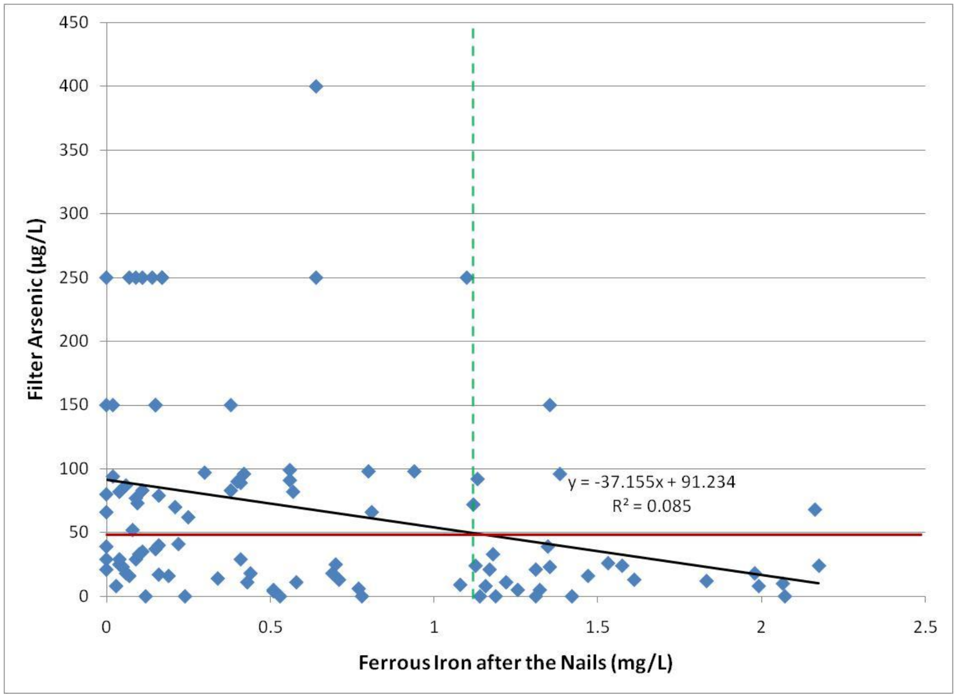

Figure 5-7: Fe(II) concentrations after the nails vs. arsenic concentrations in the effluent filtered water. Error: +/-25% (As ≤ 100 µg/L), +/- 50 µg/L (As >100 µg/L), +/- 0.03 mg/L (Fe ≤ 1mg/L), and +/- 20% (Fe > 1mg/L). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Dotted green line: shift from mostly well performing filters (right) to both poor and well performing filters (left).

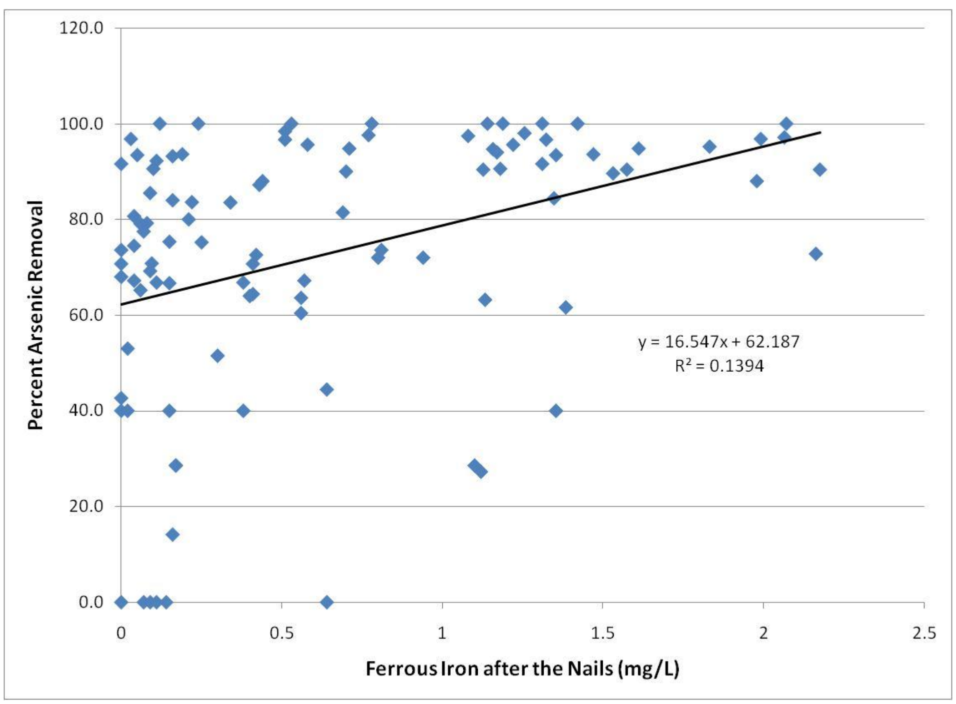

Figure 5-8: Fe(II) concentrations in the nail water vs. percent arsenic removal. Error: +/- 25% (As), +/- 0.03 mg/L (Fe ≤ 1mg/L), and +/- 20% (Fe > 1mg/L).

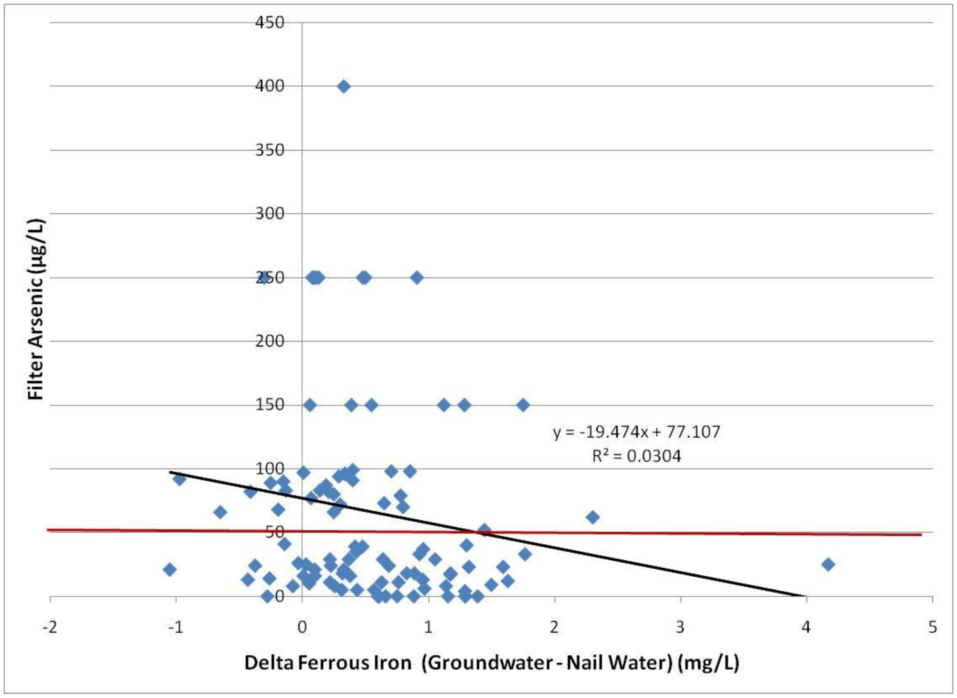

Figure 5-9: Delta Fe(II) concentrations (Groundwater minus Nail Water) vs. percent arsenic removal. Error: +/- 25% (As), +/- 0.03 mg/L (Fe ≤1mg/L), and +/- 20% (Fe >1mg/L).

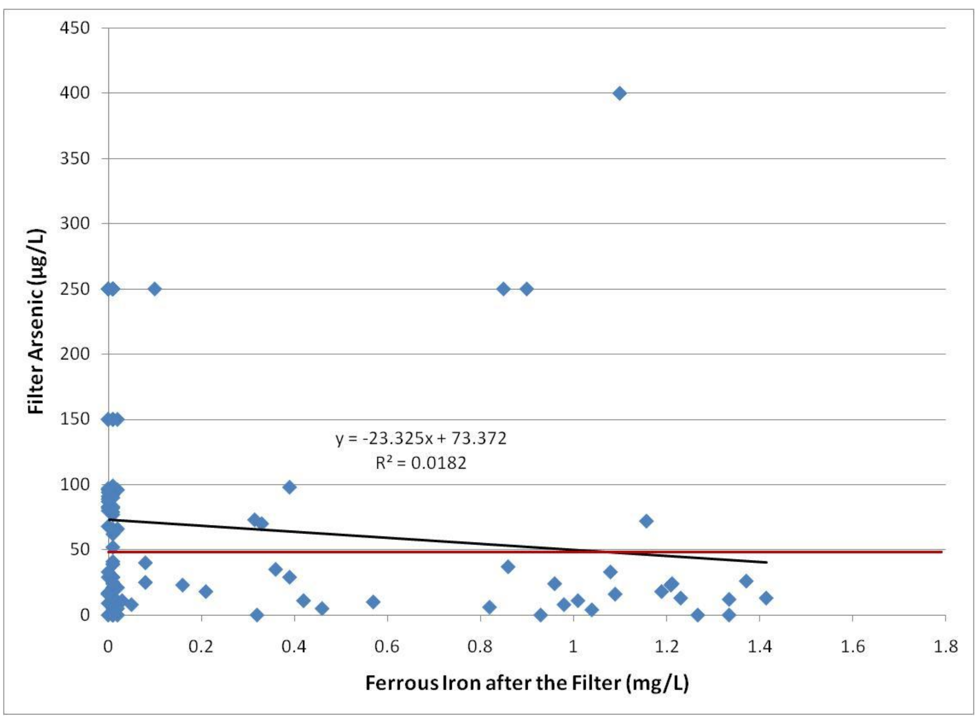

Figure 5-10: Fe(II) concentrations in effluent filtered water vs. arsenic concentrations in the effluent filtered water. Error: +/-25% (As ≤100 µg/L), +/- 50 µg/L (As >100 µg/L), +/- 0.03 mg/L (Fe ≤1mg/L), and +/- 20% (Fe >1mg/L). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

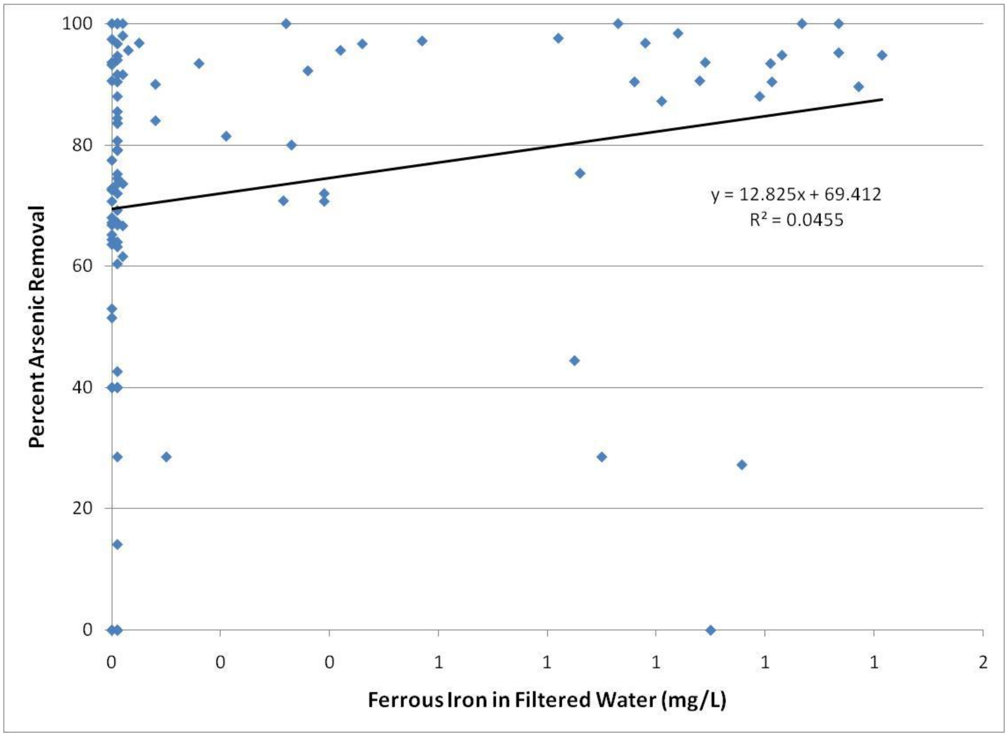

Figure 5-11: Fe(II) concentrations in the filtered water vs. percent arsenic removal. Error: +/- 25% (As), +/- 0.03 mg/L (Fe ≤1mg/L), and +/- 20% (Fe >1mg/L).

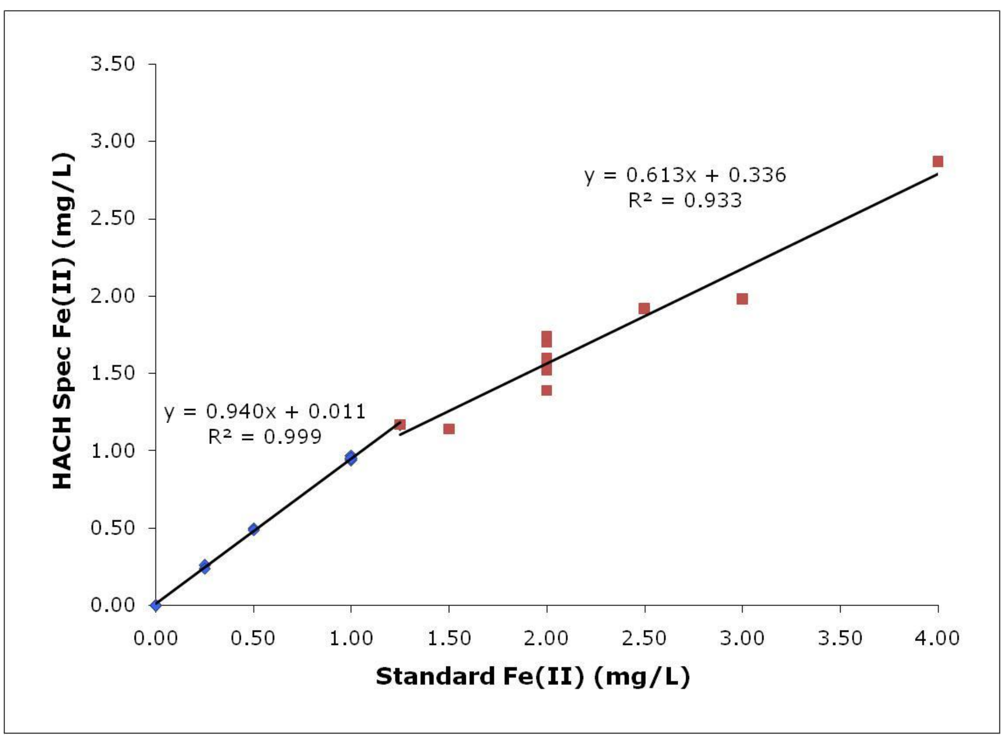

Figure 5-12: Calibration of Fe(II) readings from the portable HACH spectrometer vs. prepared Fe(II) standards.

5.1.3 Phosphorus

Measurements of phosphorus concentration in the influent groundwater sources ranged from 0 ND to 1 mg/L. Phosphorous concentrations were on average 0.2 mg/L for both well performing and poor performing filters. Stored samples were measured in the ENPHO Lab using a spectrophotometer with a reported analytical error of 10%. **Figure 5-13** shows no significant trend in phosphorous concentrations and arsenic concentrations in the filtered water (R^2=0.0233). Also, there was no correlation between phosphorous concentrations and percent arsenic removal (R^2=0.0047) (**Figure 5-14**). As previously discussed, studies indicate that phosphorus concentrations above 0.5 mg/L can negatively impact the arsenic removal mechanism of the KAF due to competition, thus the observed values of phosphorous may have been too low to have a notable impact.

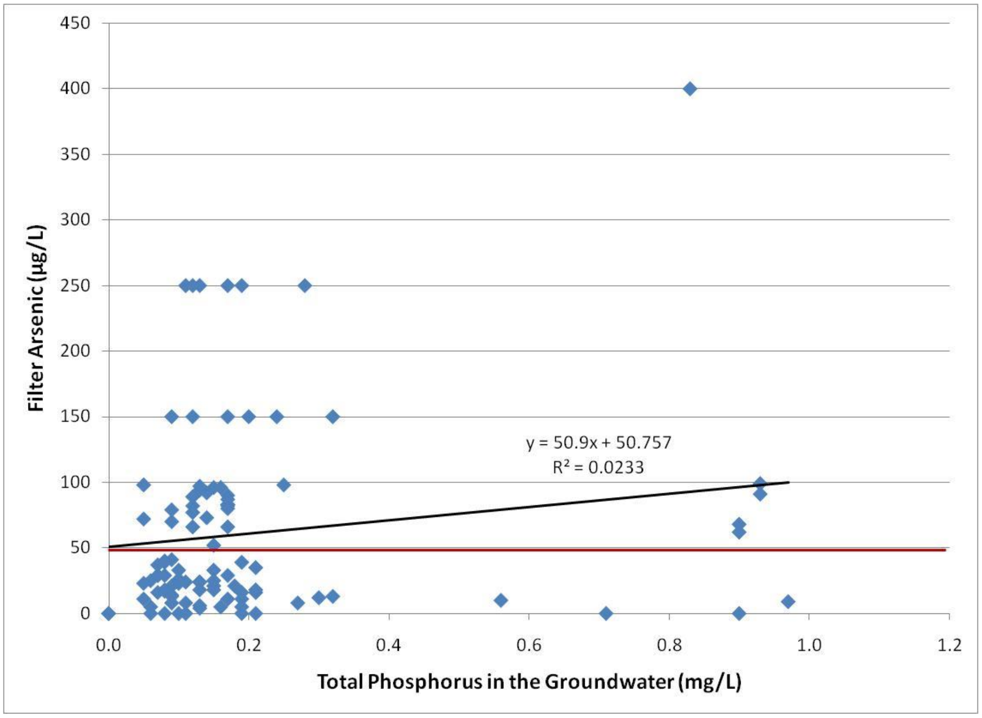

Figure 5-13: Total phosphorus concentrations in groundwater vs. arsenic concentrations in the filtered water. Error: +/-25% (As values ≤100 µg/L), +/- 50 µg/L (As values >100 µg/L), and +/- 10% (P). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

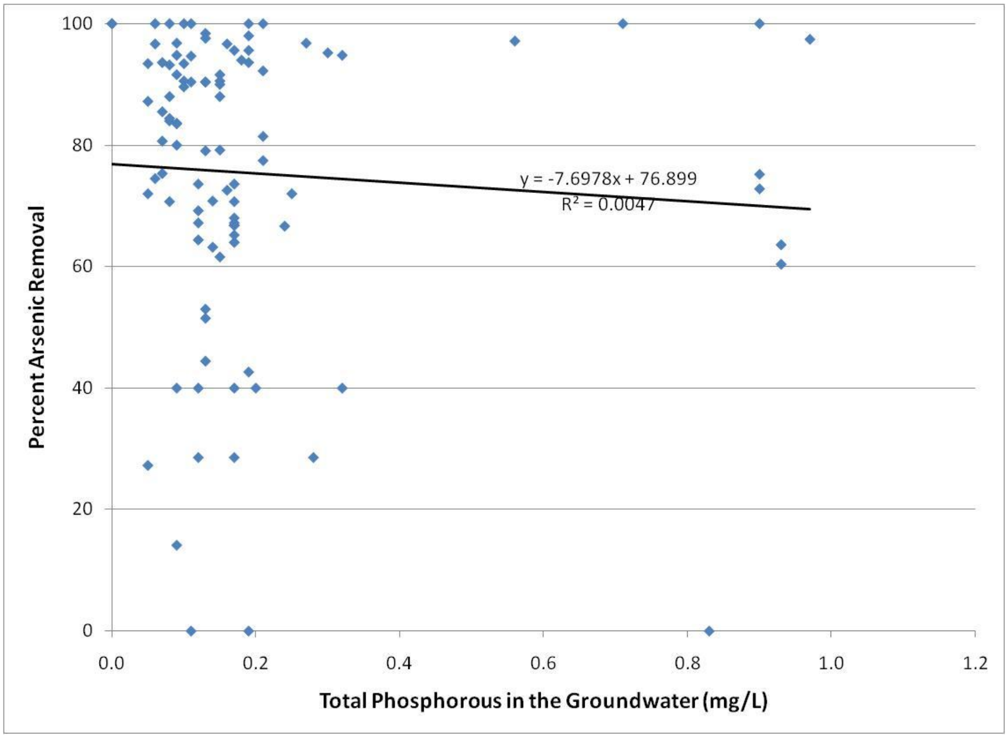

Figure 5-14: Total phosphorous concentrations in groundwater vs. percent arsenic removal. Error: +/- 25% (As), +/- 10% (P).

5.1.4 Silica

Measurements of silica concentration ranged from about 8.5 to 37 mg/L, and on average were about 22 mg/L for both well and poor performing filters. Silica concentrations showed no significant correlation with arsenic concentrations in the filtered water (R^2=0.0061) (**Figure 5-15**) or with percent arsenic removal (R^2=0.0026) (**Figure 5-16**). Split sample analysis with the ENPHO Lab indicates a poor correlation in measured values of silica with our field equipment (**Figure 5-17**). However, readings from prepared standards indicated a 10% error for silica readings in the HACH portable spectrophotometer.

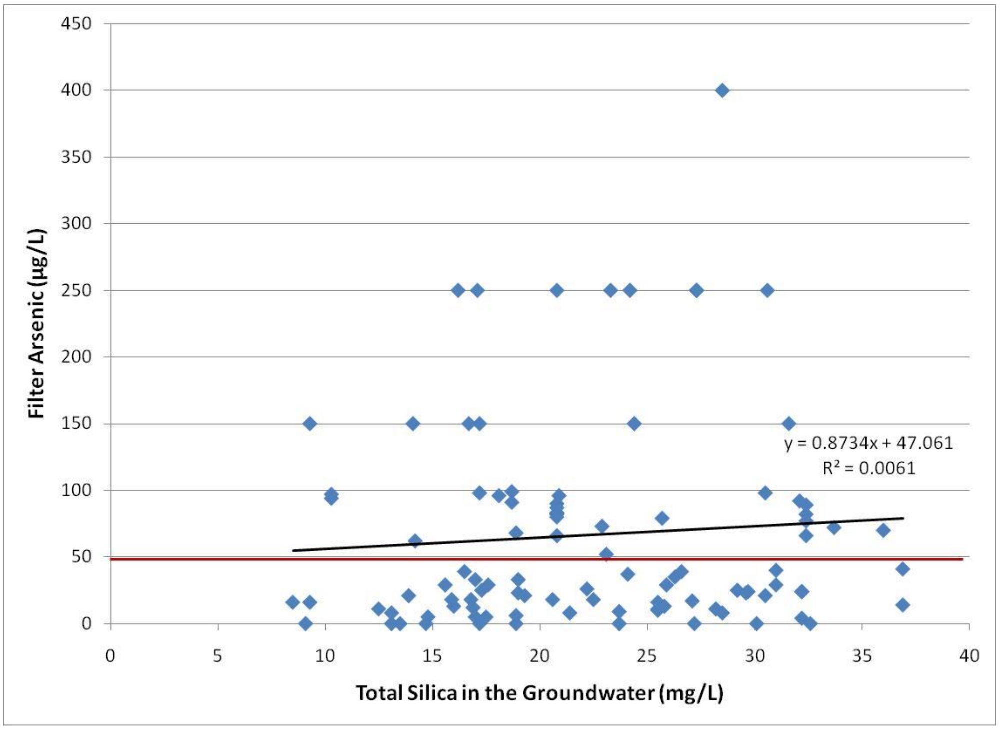

Figure 5-15: Total silica concentrations in groundwater vs. arsenic concentrations in the filtered water. Error: +/- 25% (As values ≤100 µg/L), +/-50 µg/L (As values >100 µg/L), and +/- 10% in Si. Solid red line: Nepali arsenic drinking water standard (50 µg/L).

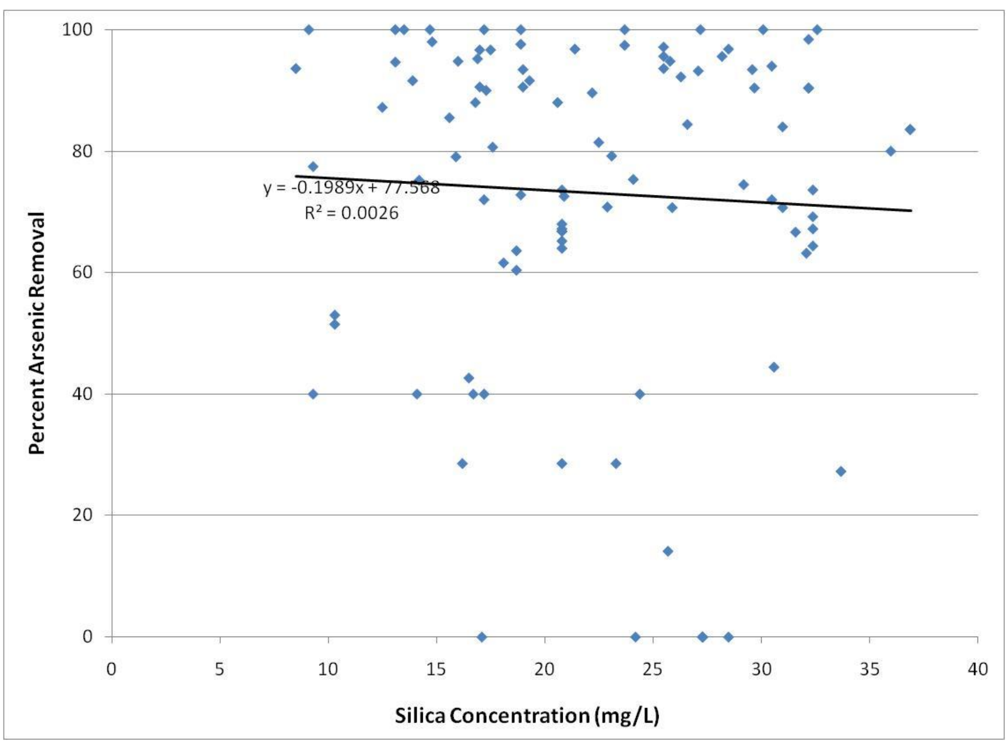

Figure 5-16: Silica concentrations in groundwater vs. percent arsenic removal. Error: +/- 25% (As), +/- 10% (Si).

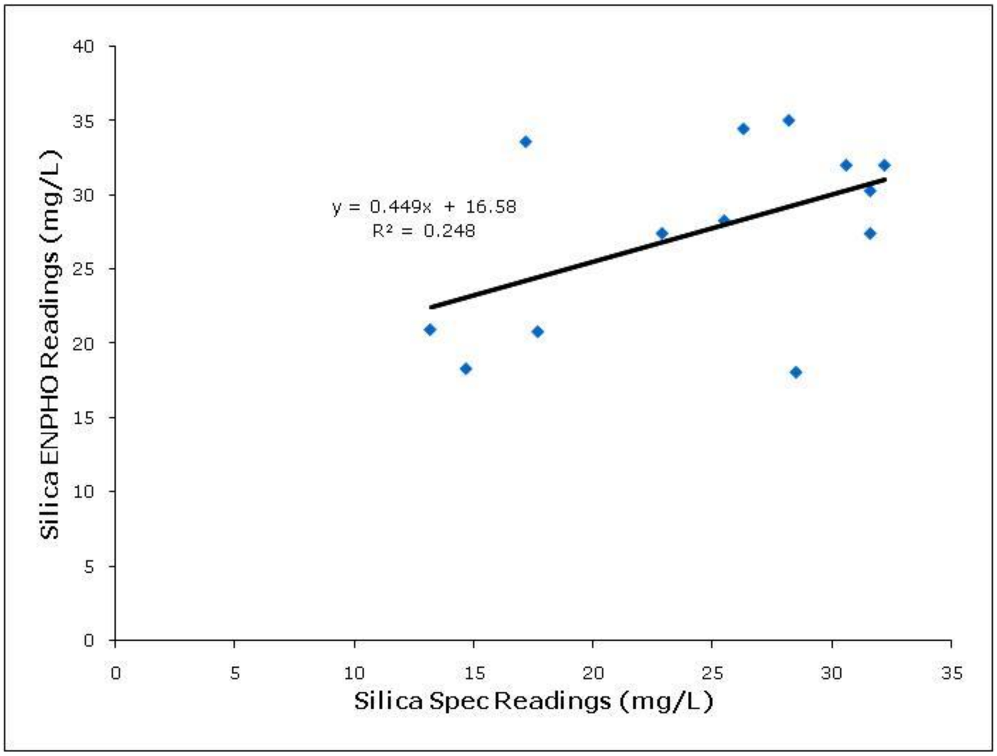

Figure 5-17: Split sample calibration with ENPHO spectrophotometer and HACH portable spectrophotometer.

5.1.5 pH

Measurements of pH in groundwater and filtered water samples ranged from 6 to 8.5. Average pH measurements were not significantly different between well performing and poorly performing filters or between influent and effluent sources (**Table 5-3**). However, **Figure 5-18** shows a slight relationship between low filtered water pH levels (pH<6) and filtered water arsenic concentrations below the Nepali standard, but this only accounts for 7% of the data. Furthermore, regression analysis indicates that there is no significant correlation between filtered water pH levels and effluent arsenic concentrations (R^2=0.0597) or percent arsenic removal (R^2=0.0357) (**Figure 5-19**).

Table 5-3: Averages and standard deviations of measured pH units in the groundwater, and filtered water.

	GW pH		Filtered pH	
	Average	σ	Average	σ
Well performing*	7.3	0.5	7.2	0.5
Poorly performing*	7.6	0.4	7.5	0.4
Total filters	7.4	0.4	7.3	0.5

*Based on Nepali drinking water standard of [As]<50 µg/L.

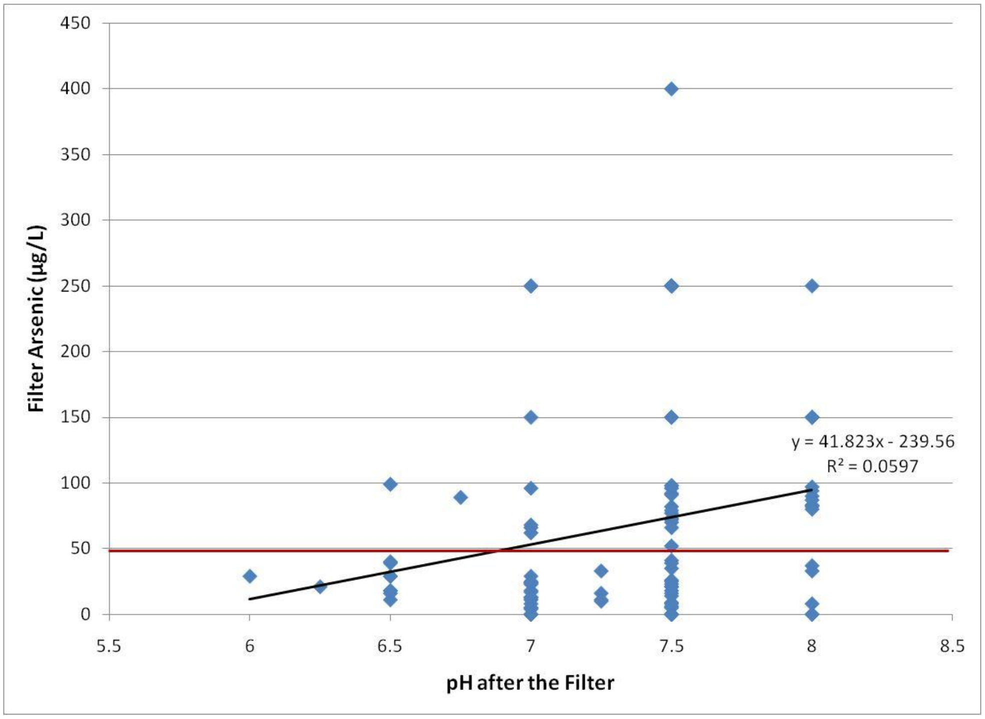

Figure 5-18: pH levels after the filter vs. filtered water arsenic concentration. Error: +/- 25% (As ≤ 100 µg/L), +/-50 µg/L (As >100 µg/L), and +/-0.5 units (pH). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

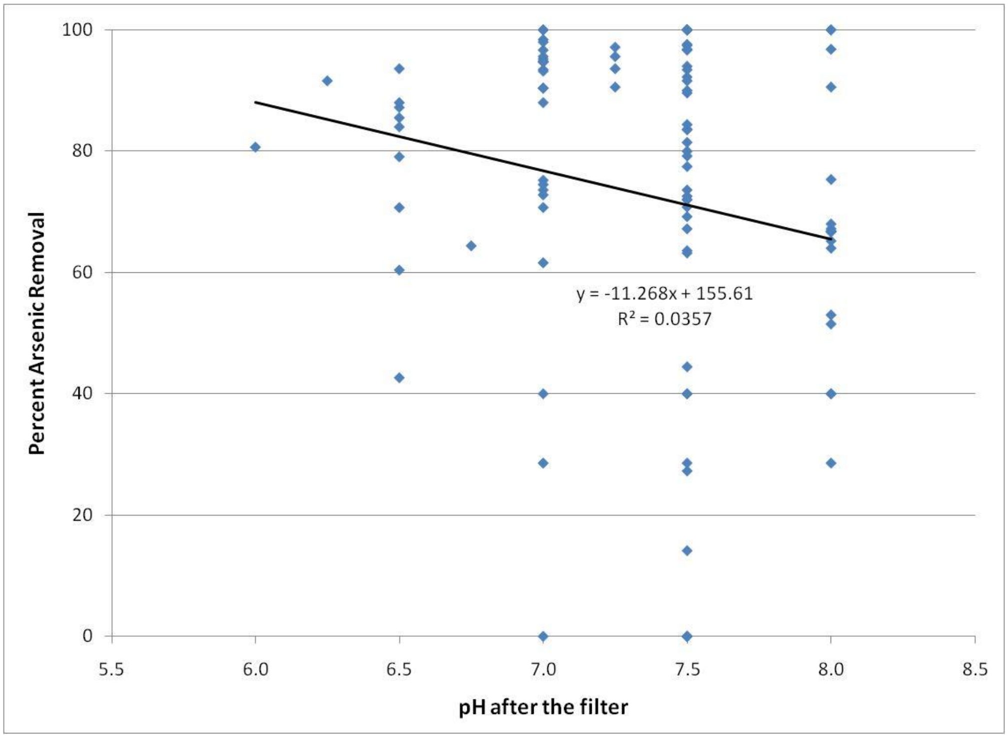

Figure 5-19: pH levels in the groundwater vs. percent arsenic removal. Error: +/- 25% (As) and +/-0.5 units (pH). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

5.1.6 Dissolved Oxygen

Measurements of dissolved oxygen in the effluent filtered water samples ranged from 0.7mg/L to 12 mg/L, and on average were about 3.6 mg/L. There was no considerable difference in dissolved oxygen concentrations in the well performing (3+/-2 mg/L) or poorly performing filters (4+/-2 mg/L). In addition, there is no correlation between dissolved oxygen concentrations and arsenic concentrations in the effluent water (R^2=0.016) (**Figure 5-20**) or percent arsenic removal (R^2=0.0214) (**Figure 5-21**). Split sample calibrations with the ENPHO Lab show a poor correlation between the HACH DO test kit and the standardized lab titration method performed at ENPHO (**Figure 5-22**). However, this large error could be due to differences in sampling batches or storage. Previous calibrations in the ENPHO lab showed about a 10% difference in measurements between the standard DO titration and the HACH kit titration.

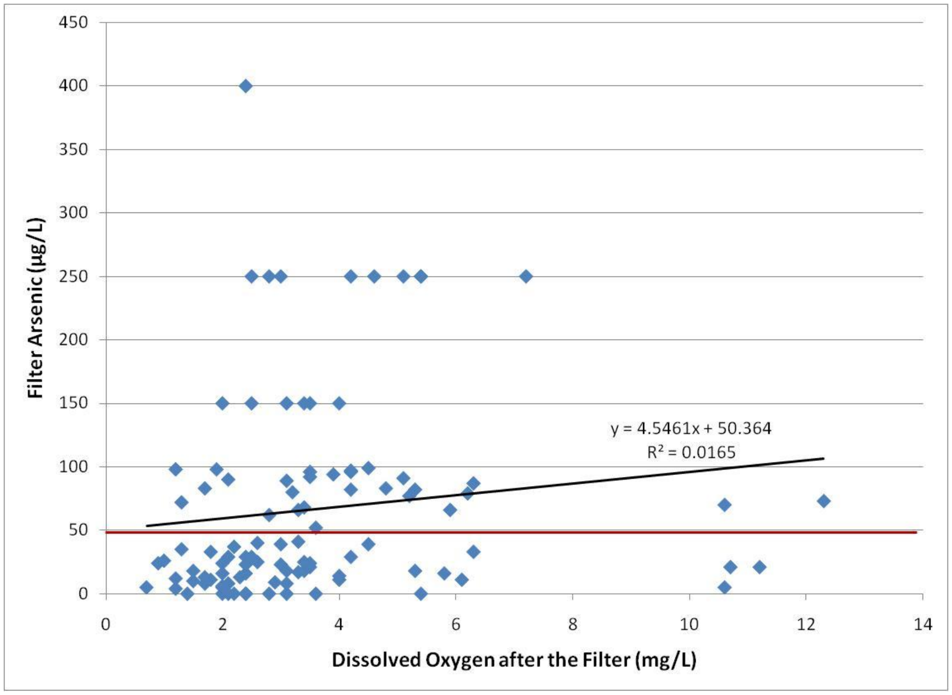

Figure 5-20: Dissolved oxygen concentration vs. effluent arsenic concentration. Error: +/- 25% (As ≤ 100 µg/L), +/-50 µg/L (As >100 µg/L), and +/- 10% mg/L (DO). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

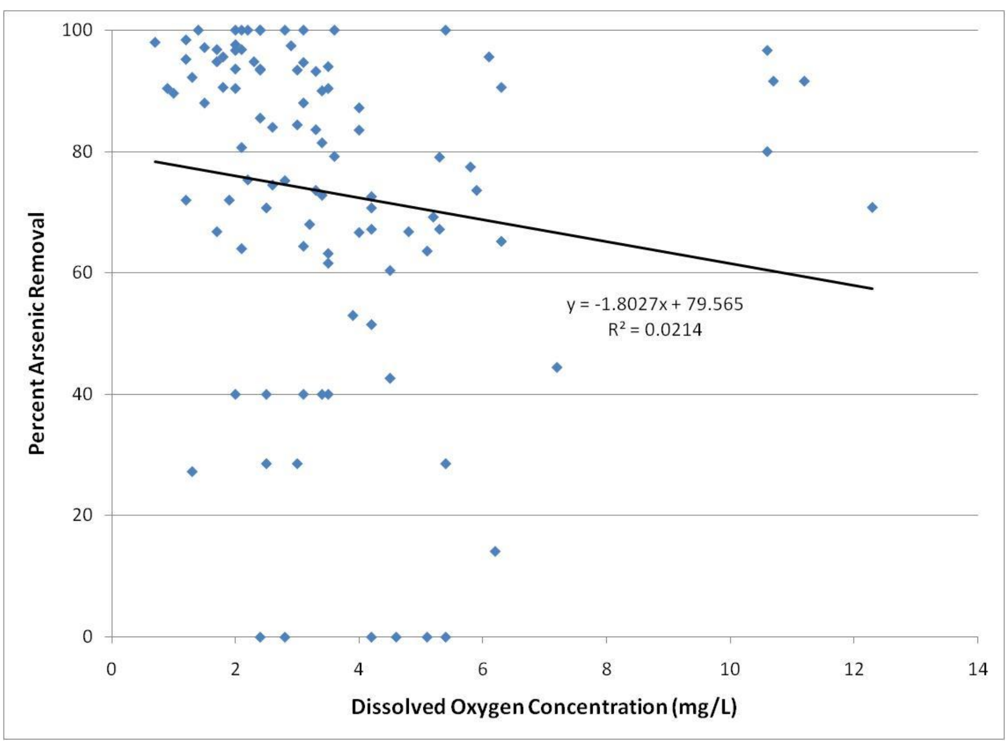

Figure 5-21: Dissolved oxygen concentration in filtered water vs. percent arsenic removal. Error: +/- 25% (As) and +/- 10% mg/L (DO).

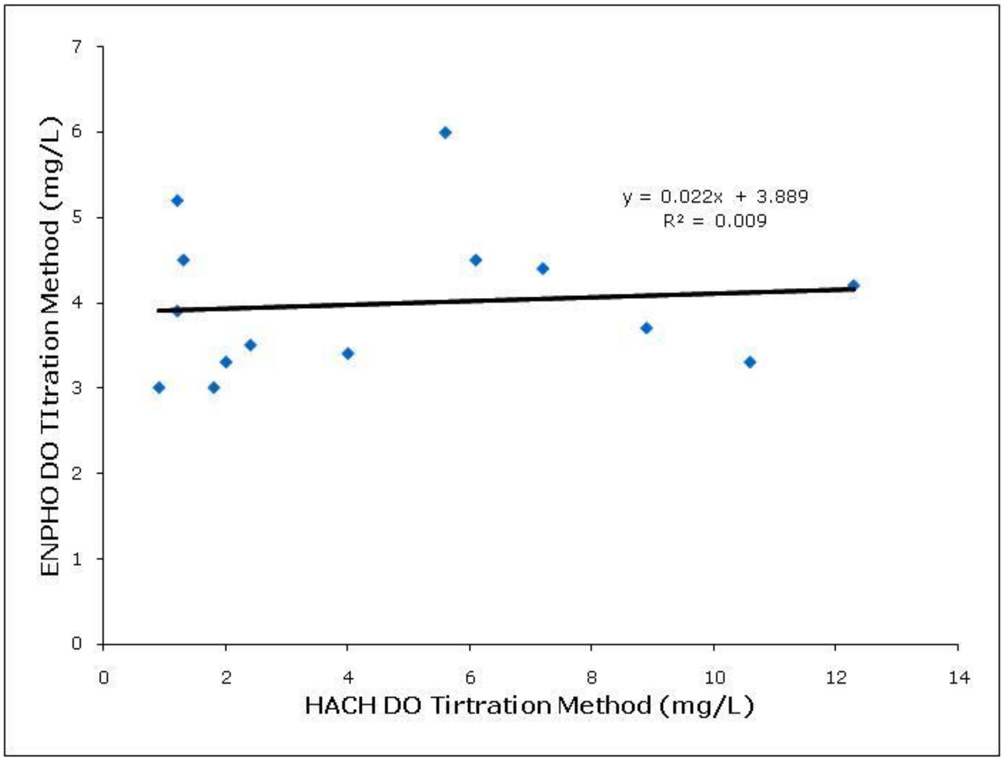

Figure 5-22: Split sample calibration between the ENPHO standard titration method and the HACH DO titration test kit.

5.1.7 Hardness

Measurements of hardness (as $CaCO_3$) ranged from 140 mg/L to 508 mg/L. Stored samples were measured in the ENPHO Lab using the EDTA titration method with a reported analytical error of 10%. Average hardness concentrations were not significantly different between the groundwater and filtered water sources or between the well performing and poorly performing filters (**Table 5-4**). Regression analysis showed that there is not a significant correlation between hardness concentrations in the groundwater and arsenic concentrations in the filtered water (R^2=0.056) (**Figure 5-23**). However, there is an observed relationship in hardness concentrations in the groundwater above 350 mg/L and arsenic concentrations in the filtered water below the Nepali standard. In addition, there was a high significant correlation between groundwater hardness concentrations and percent arsenic removal (R^2= 0.135) (**Figure 5-24**). In part, the relationships observed between hardness and arsenic could be due the high correlation (R^2=0.422) seen between groundwater hardness concentrations and Fe(II) levels after the nails (**Figure 5-25**).

Table 5-4: Averages and standard deviations of hardness concentrations (as $CaCO_3$) in groundwater, and filtered effluent water.

	GW Hardness (mg/L)		Filtered Hardness (mg/L)	
	Average	σ	Average	σ
Well performing*	325	73	316	68
Poorly performing*	278	59	260	51
Total filters	305	71	292	67

*Based on Nepali drinking water standard of [As]<50 μg/L.

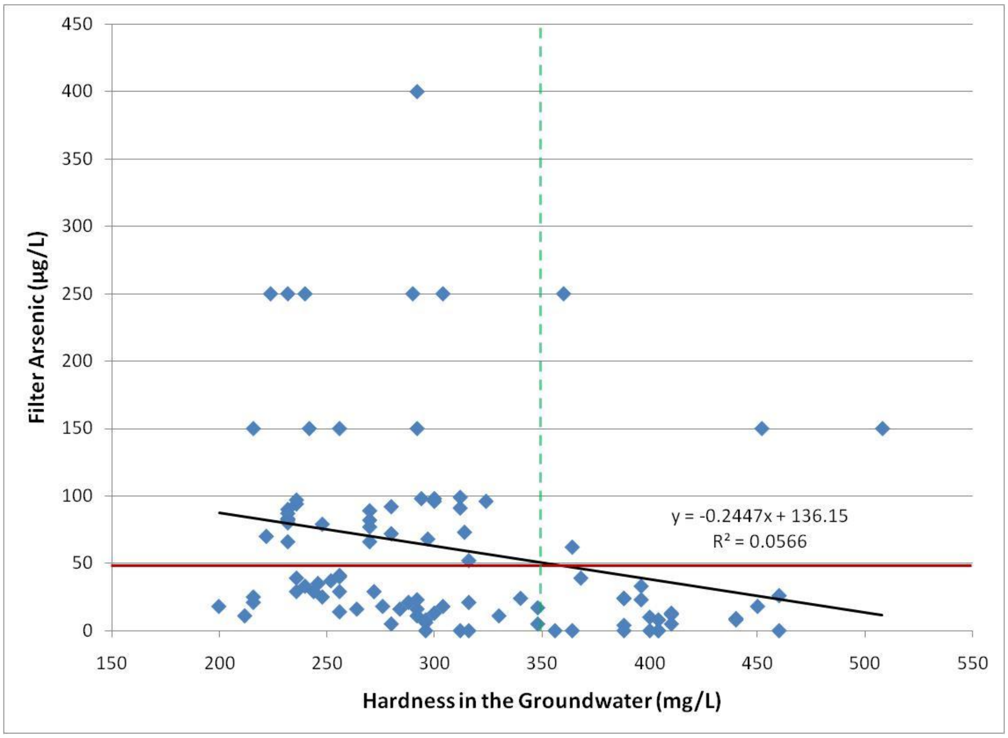

Figure 5-23: Total hardness concentration in groundwater vs. filtered water arsenic concentrations. Error: +/- 25% (As ≤ 100 μg/L), +/-50 μg/L (As >100 μg/L), and +/-10% mg/L (hardness). Solid red line: Nepali arsenic drinking water standard (50 μg/L). Dotted green line: observed shift from mostly well performing filters (right) to both poor and well performing filters (left).

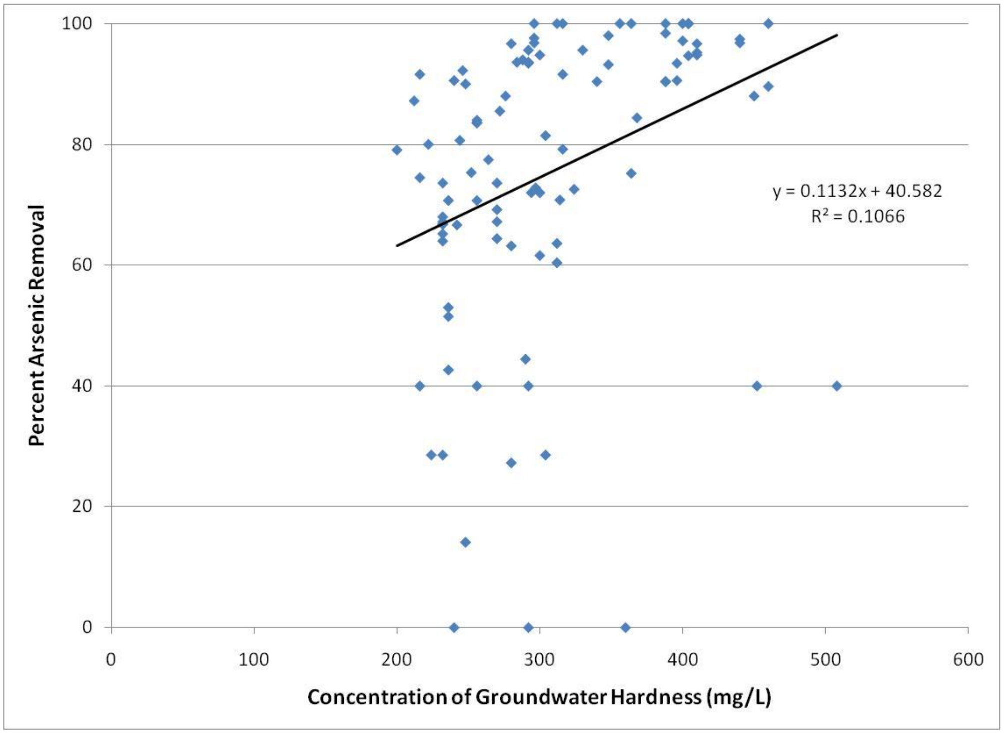

Figure 5-24: Hardness concentrations in the groundwater vs. percent arsenic removal. Error: +/- 25% (As) and +/- 10% (hardness).

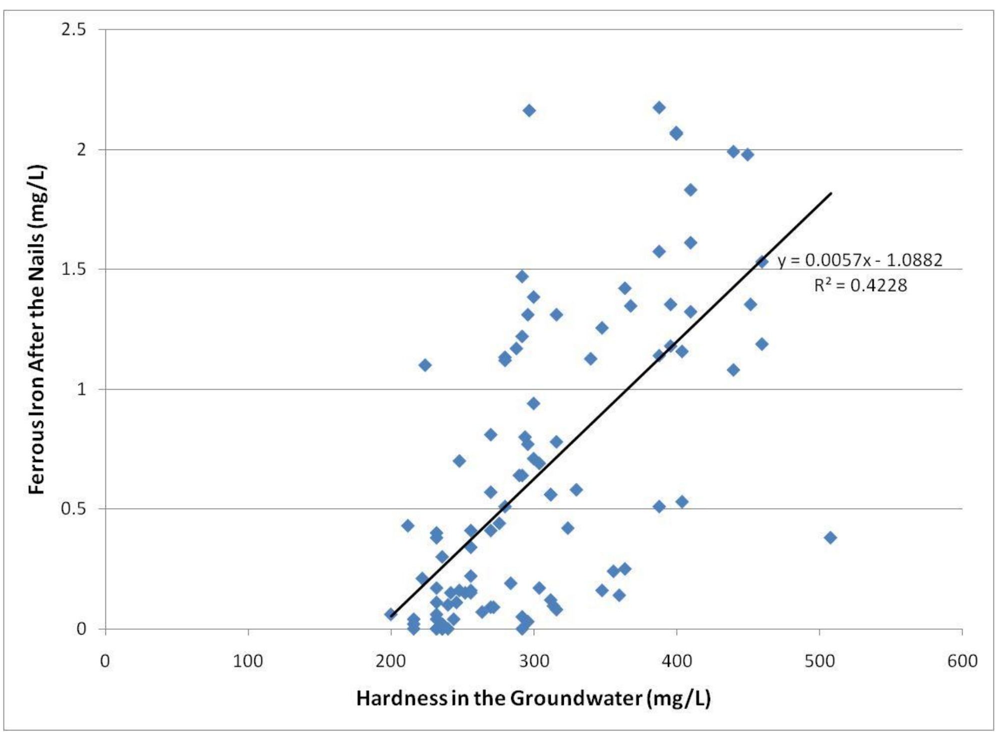

Figure 5-25: Groundwater Hardness vs. Fe(II) concentrations after the nails. Error: +/-0.03 mg/L (Fe ≤ 1mg/L), +/-10% (Fe >1mg/L), and +/-10% (hardness). There is a very good correlation between ferrous iron after the nails and groundwater hardness.

5.2 Results of Additional Measured Factors

5.2.1 Flow

Flow rate measurements averaged at 18.4 L/hour. As previously mentioned, flow rates of the tested filters were capped at about 30 L/hour so that insufficient water contact time with the nails would not interfere with the arsenic removal mechanism of the KAF. Thus, as expected, flow rate measurements did not correlate with filtered arsenic concentrations (R^2=0.005) (**Figure 5-26**). Flow rates were measured using a 500mL graduated cylinder (in increments of 10mL) and a stop watch so the measurement error is estimated to be +/-0.5 L/hour.

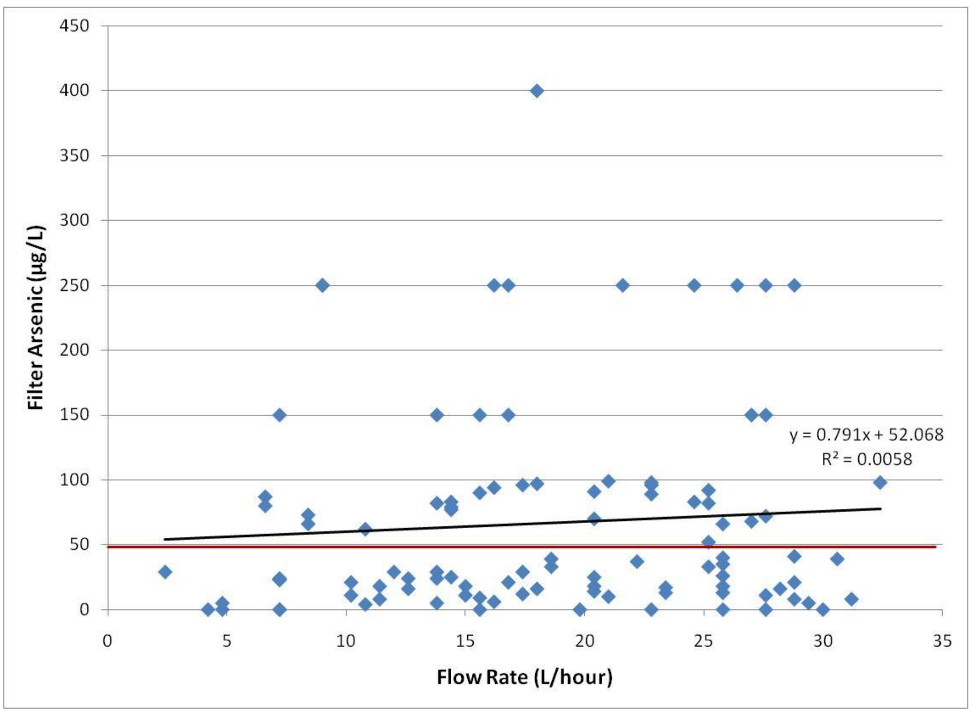

Figure 5-26: Filter flow rate vs. filtered water arsenic concentrations. Error: +/- 25% (As ≤ 100 µg/L), +/-50 µg/L (As >100 µg/L), and +/- 0.5 L/hour (flow). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

5.2.2 Installation date

The installation year of the tested KAFs ranged from 2003 through 2010 (**Figure 5-27**). The youngest filters tested were installed 3 months prior to testing and the oldest filters tested had been with the same owner for over 7 years. Filters installed in 2008 or 2009 were not found during this field study**. Figure 5-28** shows that the age of the filter did not correlate significantly with arsenic concentrations in the filtered water (R^2=0.0498).

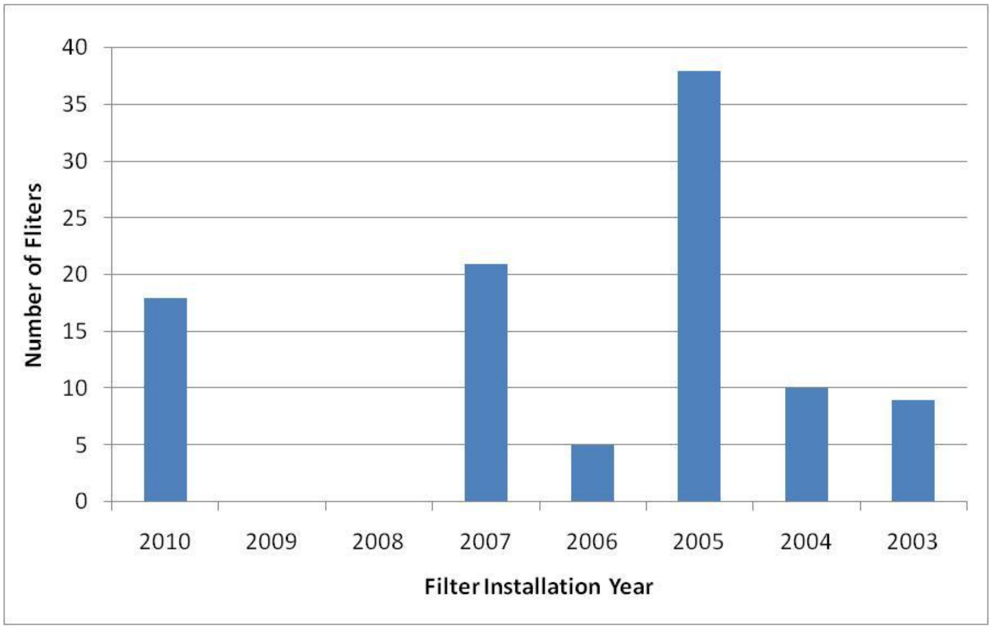

Figure 5-27: Histogram of filter age groups (years).

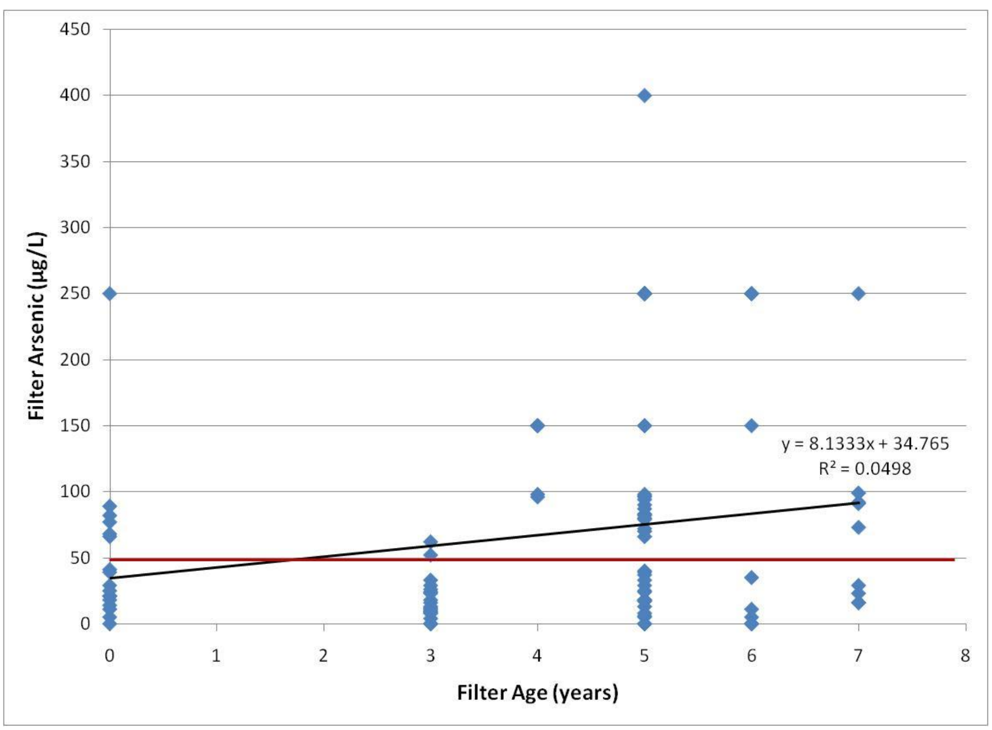

Figure 5-28: KAF age vs. arsenic concentrations in the filtered water. Error: +/- 25% (As ≤ 100 µg/L), +/-50 µg/L (As >100 µg/L), and +/- 0.5 years (age). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Note: filters of age "0" refer to filters under a year old and installed in 2010.

5.2.3 Location and user survey

The user survey was recorded to observe if there were any social, geographical or distribution factors associated with the performance of the KAF. The survey questions are located in **Appendix B**. Clusters of well performing or poor performing filters were observed in 8 out of a total of 15 villages tested (**Figure 5-29).** There were no observed relationships with the filter performance and the following documented social factors: distribution organization of the KAF (**Figure 5-30**), reported number of users (**Figure 5-31**) and the reported volume of water filtered per day (**Figures 5-32**). There was a slight relationship in the reported cleaning frequency greater than 3 months and poor filer performance (**Figures 5-33**). This relationship is better observed noting that 2 of the 3 well performing filters with low reported cleaning frequencies were 3 months old so they may have not needed cleaning.

All filters were reported to have well rusted nails by the observation of ENPHO staff. Also, each filter was observed to correspond to only one household, and all but a few households reported to use the filter each day. The households that did not use the filter each day stated that this habit was only in the winter season when the raw groundwater was much warmer (20^0 C) than the filtered water (10^0-15^0 C). Overall, it is important to note that this survey was not anonymous so the results may be biased. Moreover, the recorded findings did not lead to any strong relationships between filter performance and location or use.

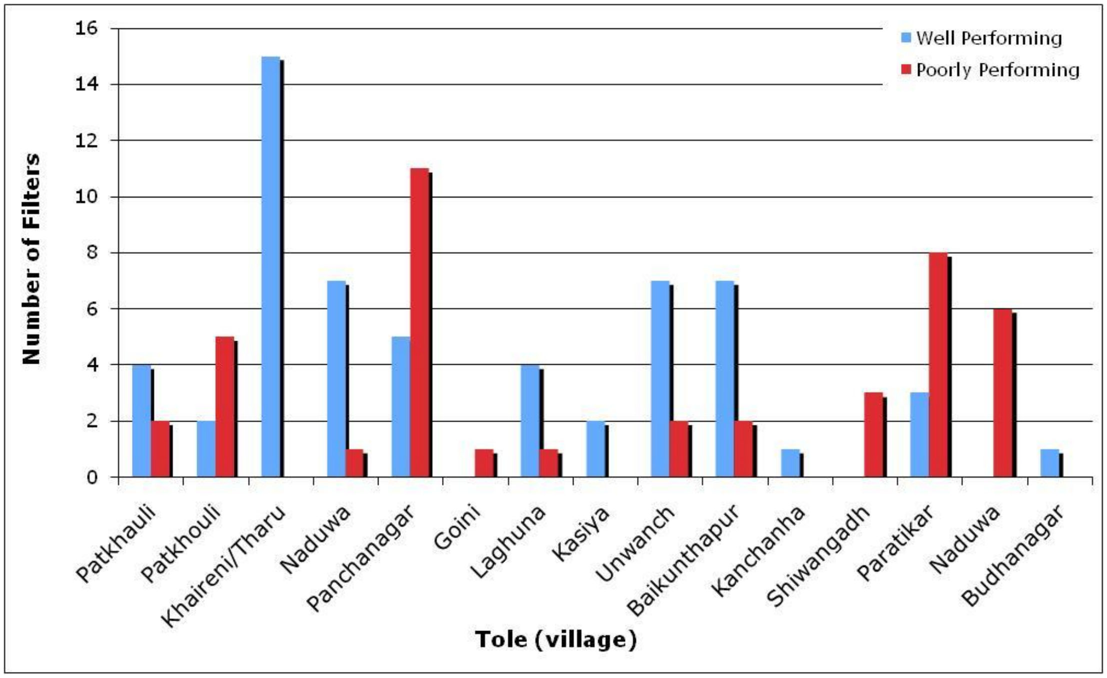

Figure 5-29: Performance of the KAF in each tested village. Performance was measured though the effluent arsenic concentrations compared to the Nepali standard of 50 µg/L.

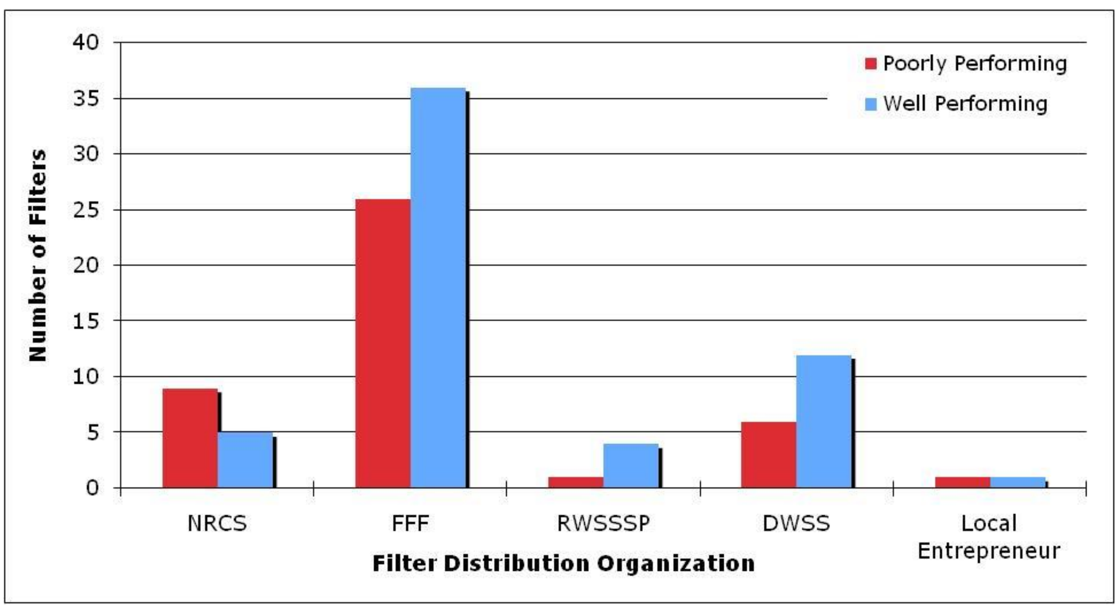

Figure 5-30: Performance of the KAF by distribution organization. Performance was measured though the effluent arsenic concentrations compared to the Nepali standard of 50 µg/L. NRCS = National Red Cross Society (Nepal); FFF = Filters for Families (Nepal); RWSSSP = Rural Water Supply and Sanitation Support Programme (Nepal); DWSS = Department of Water Supply and Swearage (Nepal).

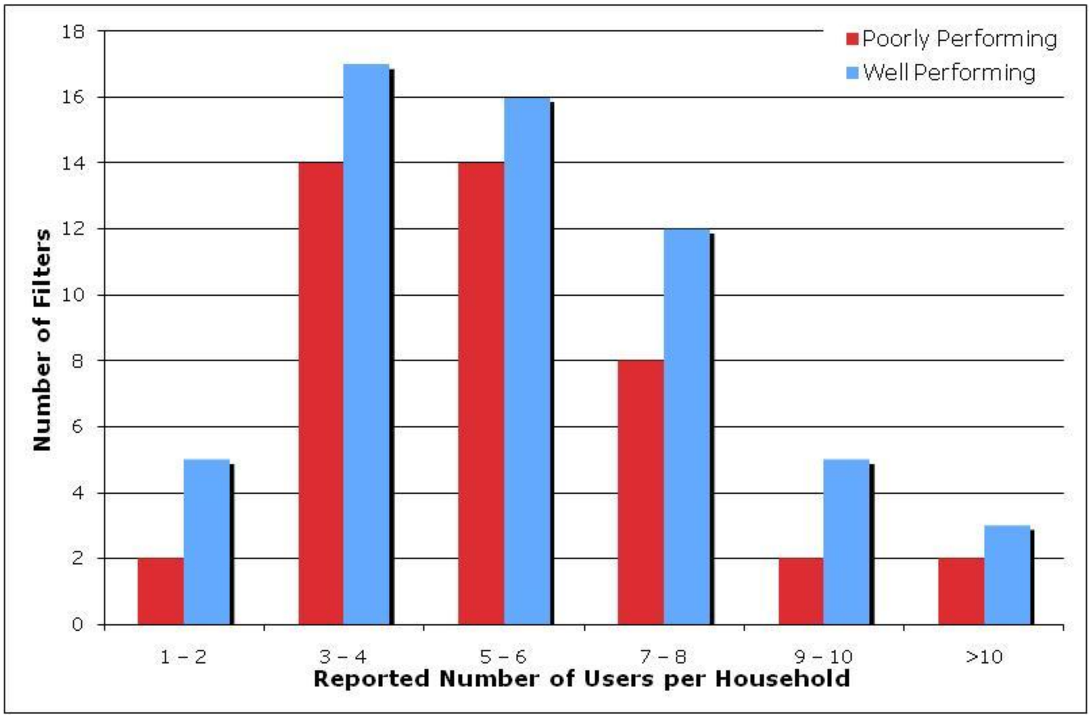

Figure 5-31: Arsenic removing performance of the KAF by reported number of users per household.

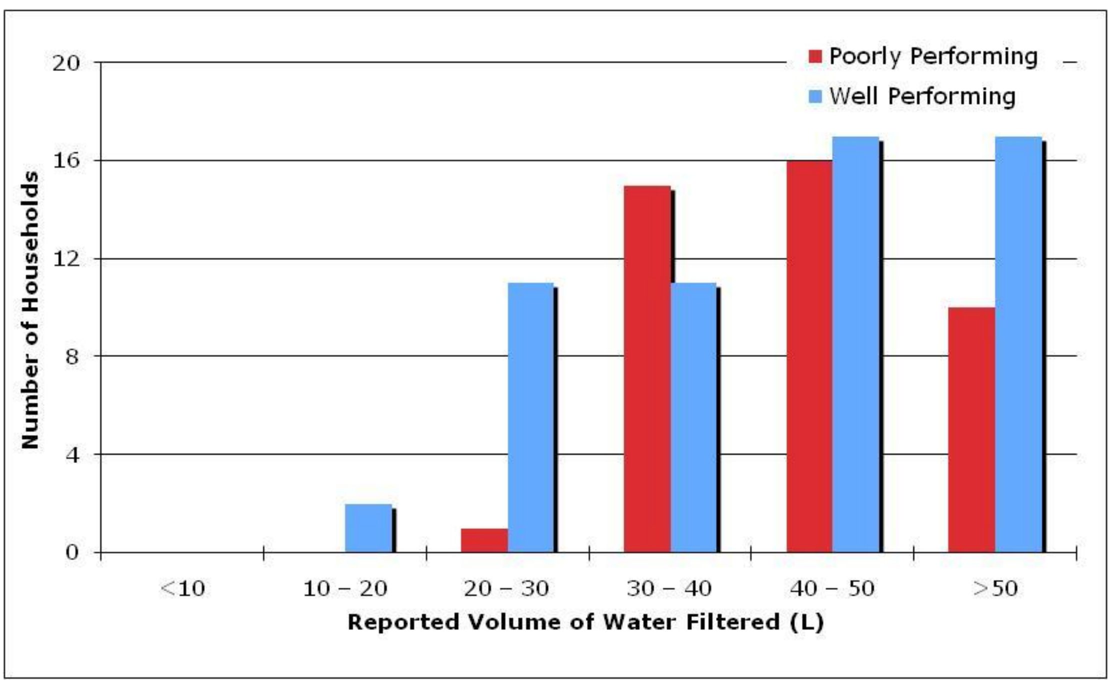

Figure 5-32: Arsenic removing performance of the KAF by reported volume of water filtered.

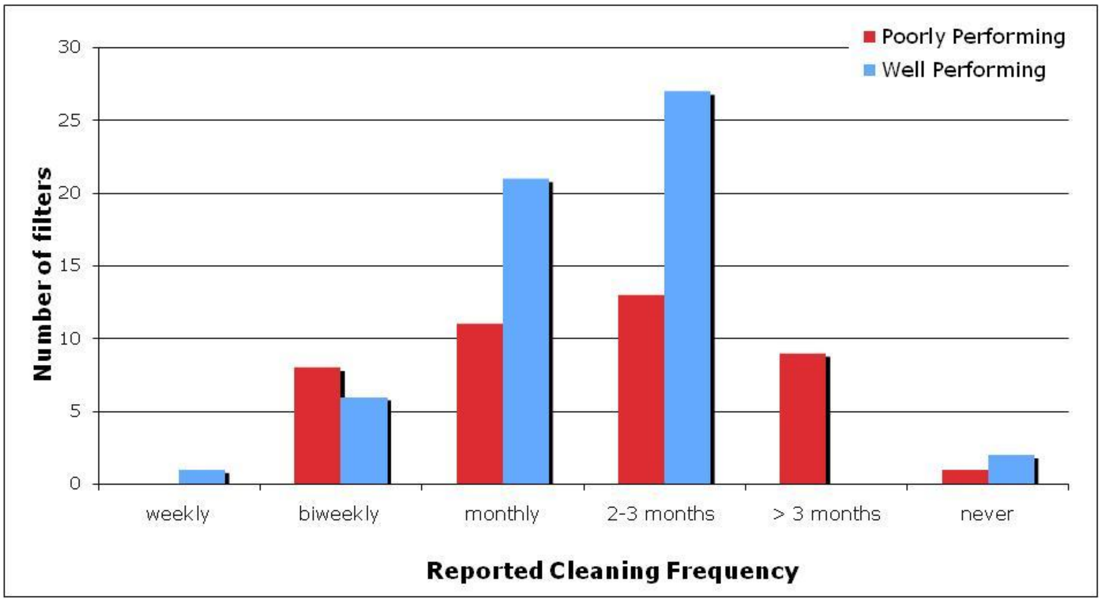

Figure 5-33: Arsenic removing performance of the KAF by reported cleaning frequency.

5.3 Discussion of Field Results

The field study results indicate that the primary parameters influencing the arsenic removal performance of the KAF were: the groundwater Fe(II) concentrations, the nail water Fe(II) concentrations, and the groundwater hardness concentrations. The competing ions of phosphate and silicate for the adsorption sites in the iron oxides did not influence the removal of arsenic concentration as seen in other studies. For phosphate, this finding may be due to the low measured concentrations in the groundwater, relative to other studies (see **Section 3.2.3**). The dissolved oxygen concentrations in the effluent water suggest ideal oxic conditions in the filter to promote the formation iron and arsenic species with low solubility. Also, there was no observed relationship between DO levels and filter performance or effluent arsenic concentrations. The pH levels in the influent and effluent waters were fairly consistent such that its effect on the filter performance was difficult to interpret. In hardness, it was expected to see high levels correlate with high arsenic concentrations in the filtered water due to calcium precipitation build up on the nails that could prevent rusting. However, the data seemed to suggest that the calcium in hardness acted more as corrosion agent for the nails, rather than a hindrance in rusting. In addition, there were observed relationships between effluent arsenic concentrations below the Nepali standard (50 µg/L) and both inlet groundwater arsenic concentrations ≤200µg/L and nail water Fe(II) concentrations >1.1 mg/L. About 88% of the tested poorly performing filters fell outside of these ranges (titled *Criteria 1*), while only 28% of the well performing filters fit outside of *Criteria 1*.

Overall, due to the importance of dissolved iron and hardness concentrations on KAF performance and effluent arsenic concentrations, further testing to understand the corrosion of the nails followed and will be discussed in **Chapter 6**. Observed KAF trouble shooting and social factors influencing the use of the KAF is also discussed in further detail in **Appendix G** and **Appendix H**.

Chapter 6 – Corrosiveness Testing

6.1 Groundwater Corrosiveness Testing

Field data analysis suggested that the performance of the KAF was related to the ferrous iron levels of the groundwater and nail water, as well as the hardness of the inlet water source. To further explore the cause of low Fe(II) levels after the nails, new parameters relating to corrosion (chloride, electrical conductivity, and manganese) were tested in the ENPHO lab from stored groundwater samples of each of the previous tested sources. In addition, pH levels were retested from the stored groundwater samples to verify the pH measurements from the pH test strips. The role each of these new parameters in the corrosiveness of the iron is explained below:

Electrical Conductivity

The electrical conductivity of water is a measure of the total ions in solution. All ions in solution can add to the corrosiveness of a water source by facilitating electron flow and the oxidation of the metal. Conductivity was measured in the ENPHO lab using a WTW® conductivity meter.

Chloride

Chloride ions are present in most groundwater sources, and due to its highly corrosive nature, concentrations of this parameter were tested for in our stored groundwater sources. The ENPHO lab used the argentometric (silver nitrate) titration method to measure chloride concentrations.

Manganese

Manganese dioxide is a catalyst in the formation of iron and arsenic complexes; therefore, it was tested in selected groundwater sources corresponding to the well performing filters that fell outside of the *Criteria 1* selection, for a total of 16 sources (sample number: 95, 71, 112, 61, 108, 7, 81, 85, 80, 47, 15, 6, 109, 94, 97, and 24 in **Appendix D**). Manganese concentrations were measured in the ENPHO lab using standard methods and an atomic absorption spectrometer.

pH

Low pH values are notorious for corroding through metals. Therefore, confirming the field measured test strip pH values with Lab measured pH values seemed practical. The pH values in the stored samples are expected to have changed from the time they were first collected; nonetheless, the accuracy and precision of the pH strips can be roughly verified with these lab results. New groundwater pH values were measured in the ENPHO lab using a WTW® pH meter.

6.2 Analysis of New Testing

Groundwater samples collected in the field for the analysis of hardness and phosphate concentrations in the ENPHO lab were used to measure the new testing parameters. These samples were stored in labeled polyethylene bottles for about 10-12 weeks prior to the new testing. One groundwater sample (corresponding to three poorly performing filters) and a couple of other parameter measurements were misplaced or undocumented so the new sample size for the following parameter analysis is 96. The estimated error reported by ENPHO for all new parameter tests is +/-10%. In addition, 14 out of 16 tested manganese concentrations were below the instrument detection limit (<0.2 mg/L) so it is not included in the proceeding test results.

6.2.1 pH

The new pH readings, shown in **Figure 6-1,** are of the same range of values as the previous field pH data, only slightly shifted to a more basic regime. Considering the few months the groundwater samples were stored, this shift is expected. Nonetheless, the new pH measurements confirm that there is not a significant correlation between pH levels in the groundwater and the effluent arsenic concentrations of the KAF (R^2= 0.002).

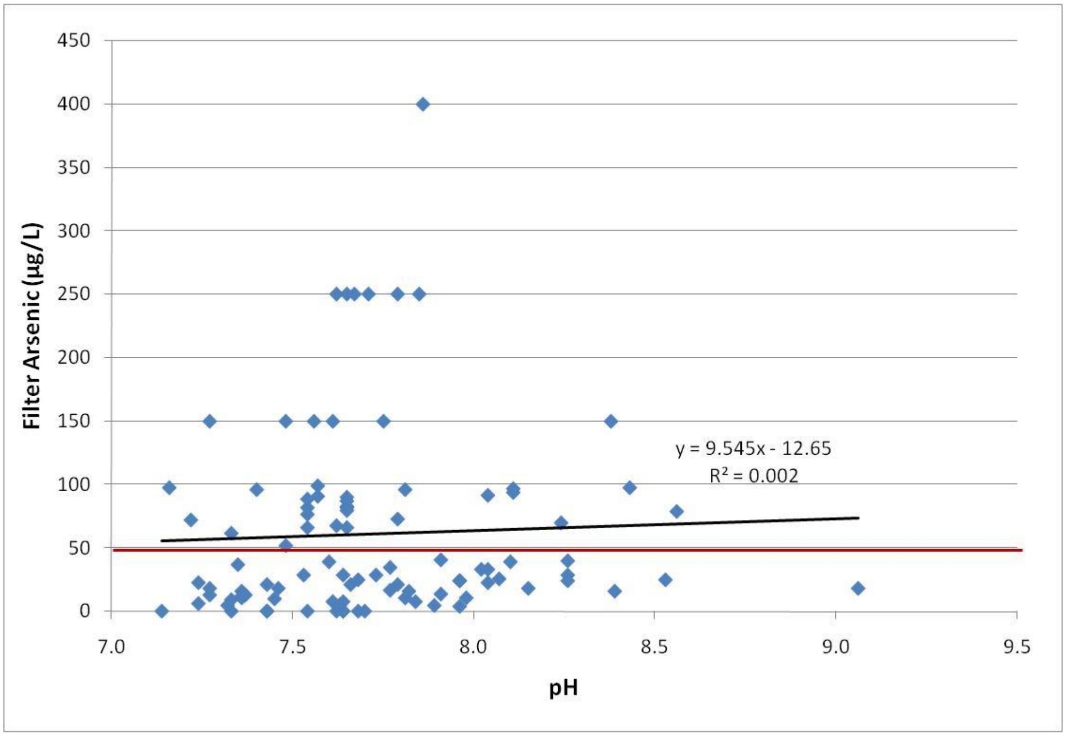

Figure 6-1: New groundwater pH concentrations vs. effluent arsenic concentrations. Error: 25% (As ≤ 100 µg/L), +/- 50 µg/L (As >100 µg/L) and +/- 10% (pH). Solid red line: Nepali arsenic drinking water standard (50 µg/L). No real correlation can be seen between these two data sets.

6.2.2 Chloride

Chloride concentrations in the water were ranged from 0 ND to 91 mg/L. **Figure 6-2** shows a strong relationship between chloride levels and effluent arsenic levels. About 94% of filters with influent chloride concentrations >7mg/L have effluent arsenic concentrations below the Nepali standard. However, there was no significant correlation (R^2=0.007) between the two parameters. In addition, **Figure 6-3** shows a small, yet significant correlation (R^2 = 0.068) between high chloride concentrations and high dissolved iron concentrations. By removing the filter data set that falls within the *Criteria 1* range, it is observed that filters with influent groundwater chloride concentrations above 7 mg/L are still very likely to have effluent arsenic concentrations below the Nepali standard, despite having low nail water Fe(II) concentrations (<1.1mg/L) and high influent groundwater arsenic levels (>200µg/L) (**Figure 6-4**). Thus, chloride may still have an effect on the KAF arsenic removing mechanism that is independent of other groundwater parameters.

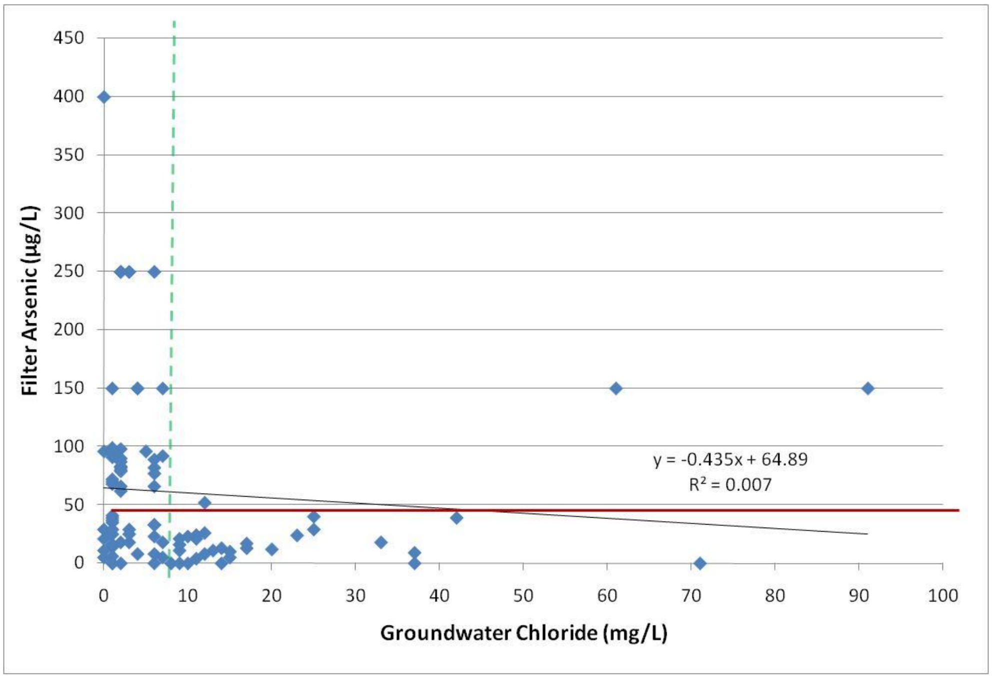

Figure 6-2: Groundwater chloride concentrations vs. effluent arsenic concentrations. Error: 25% (As ≤ 100 µg/L), +/- 50 µg/L (As >100 µg/L) and +/- 10% (chloride). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Dotted green line: observed shift from mostly well performing filters (right) to both poor and well performing filters (left).

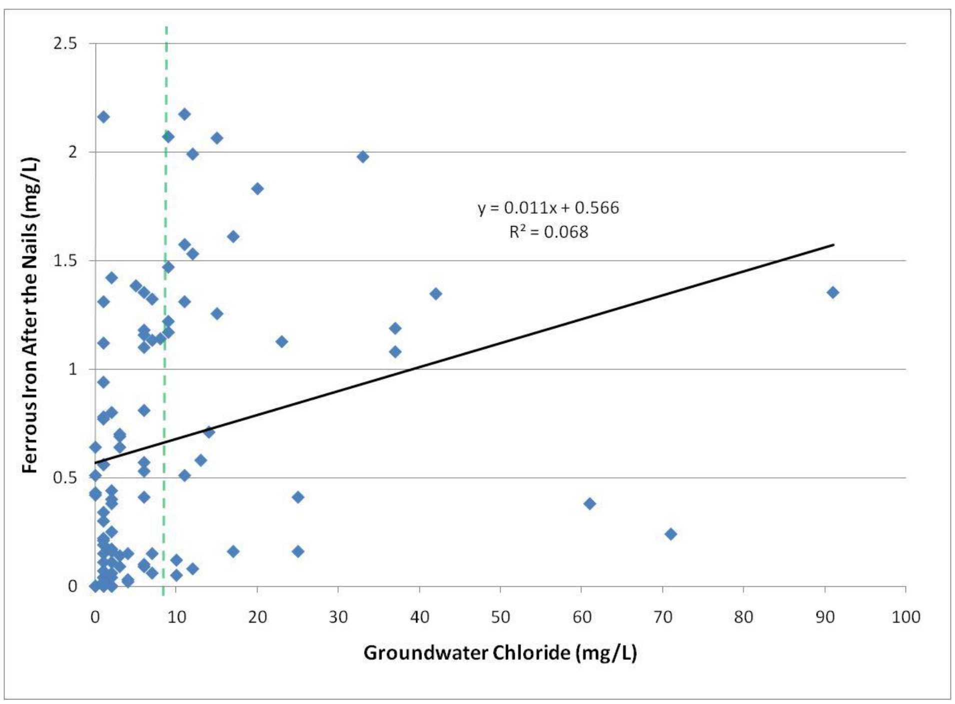

Figure 6-3: Groundwater chloride concentrations vs. Fe(II) concentrations after the nails. Error: +/- 0.03 mg/L (Fe ≤ 1mg/L), +/- 10% (Fe > 1mg/L) and +/- 10% (chloride). Dotted green line: observed shift from mostly well performing filters (right) to both poor and well performing filters (left) from the previous graph.

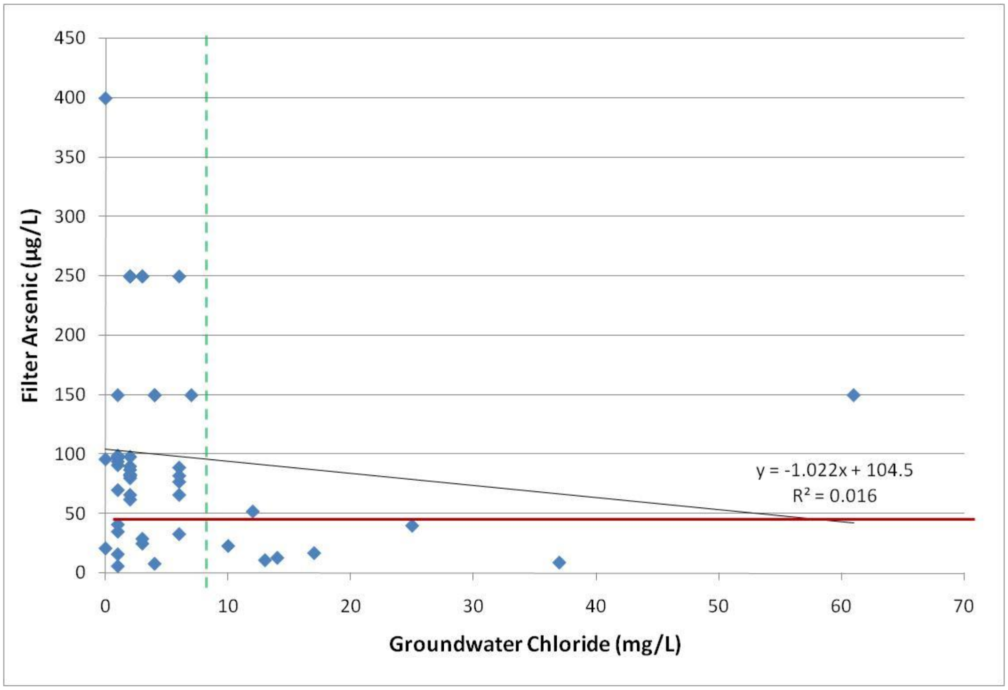

Figure 6-4: Sorted groundwater chloride concentrations vs. effluent arsenic concentrations. Error: 25% (As ≤ 100 µg/L), +/- 50 µg/L (As >100 µg/L), and +/- 10% (chloride). Solid red line: Nepali arsenic drinking water standard (50 µg/L). Dotted green line: observed shift from mostly well performing filters (right) to both poor and well performing filters (left). This data is sorted to remove all filters with receiving groundwater arsenic levels <200 µg/L, and Fe(II) levels after the nails >1.1mg/L.

6.2.3 Electrical Conductivity

Electrical conductivity in the groundwater samples ranged from 419 µS/cm to 1323µS/cm. Conductivity showed no correlation (R^2= 0.025) with effluent filtered arsenic levels (**Figure 6-5**). This is surprising considering the strong correlation conductivity levels have with chloride concentrations (R^2=0.132) (**Figure 6-6**), and also the previously observed relationship between groundwater chloride concentrations and effluent arsenic concentrations. Yet, chloride only accounts for a small portion of electrical conductivity. Other ions such as calcium (from hardness) account for a greater fraction of electrical conductivity, yet, there is no observed correlation (R^2=0.0369) (**Figure 6-7**).

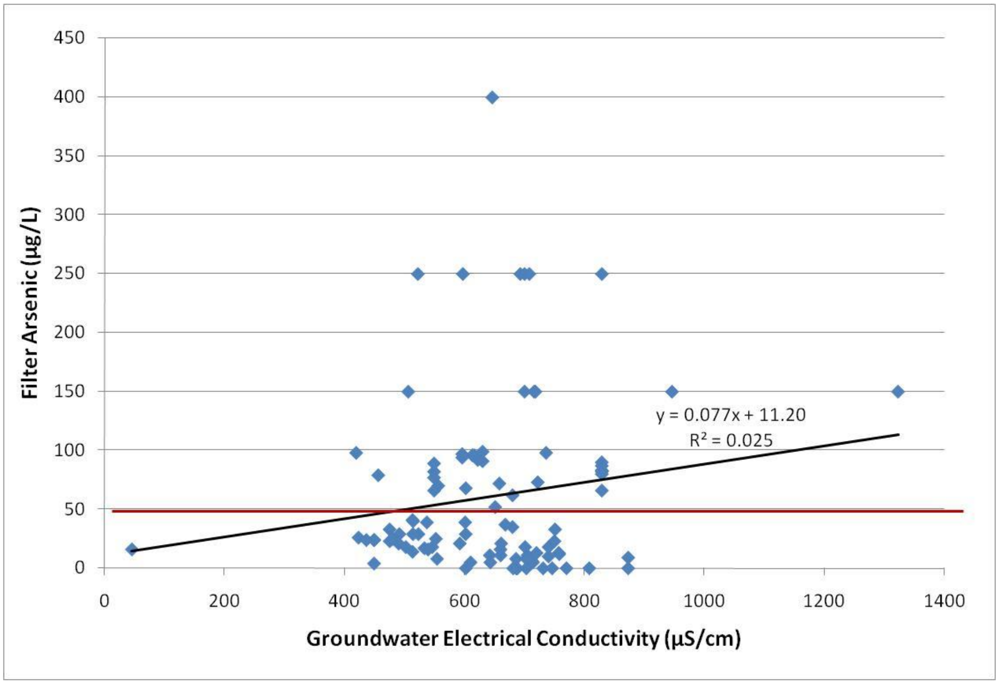

Figure 6-5: Groundwater electrical conductivity vs. effluent arsenic concentrations. Error: 25% (As ≤ 100 µg/L), +/- 50 µg/L (As>100 µg/L), and +/- 10% (conductivity). Solid red line: Nepali arsenic drinking water standard (50 µg/L).

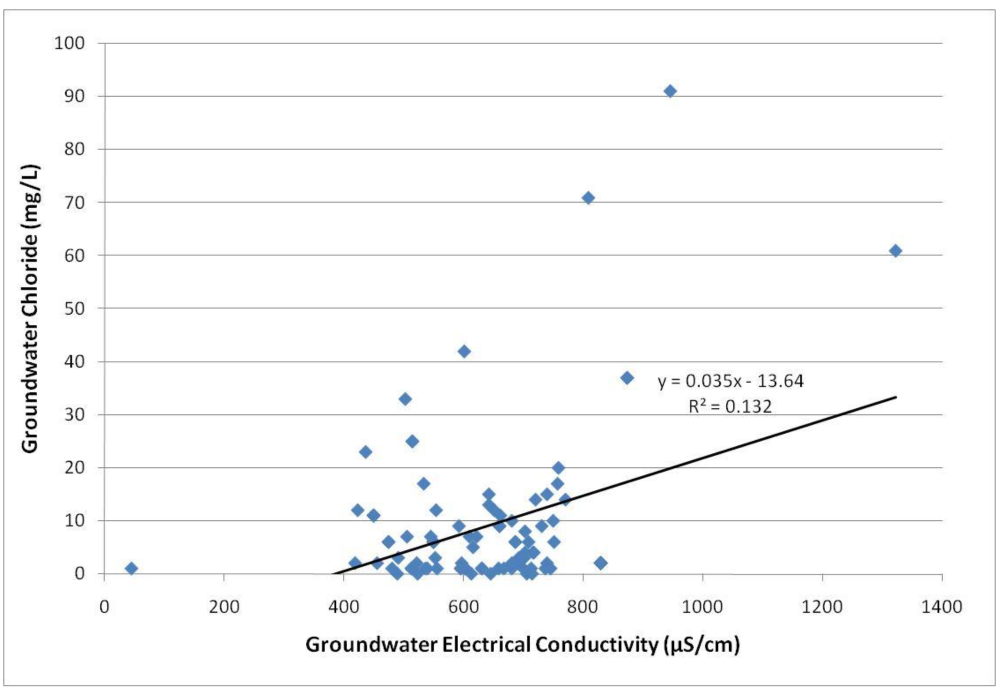

Figure 6-6: Groundwater electrical conductivity vs. groundwater chloride concentration. Error: +/- 10% (chloride) and +/- 10% (conductivity).

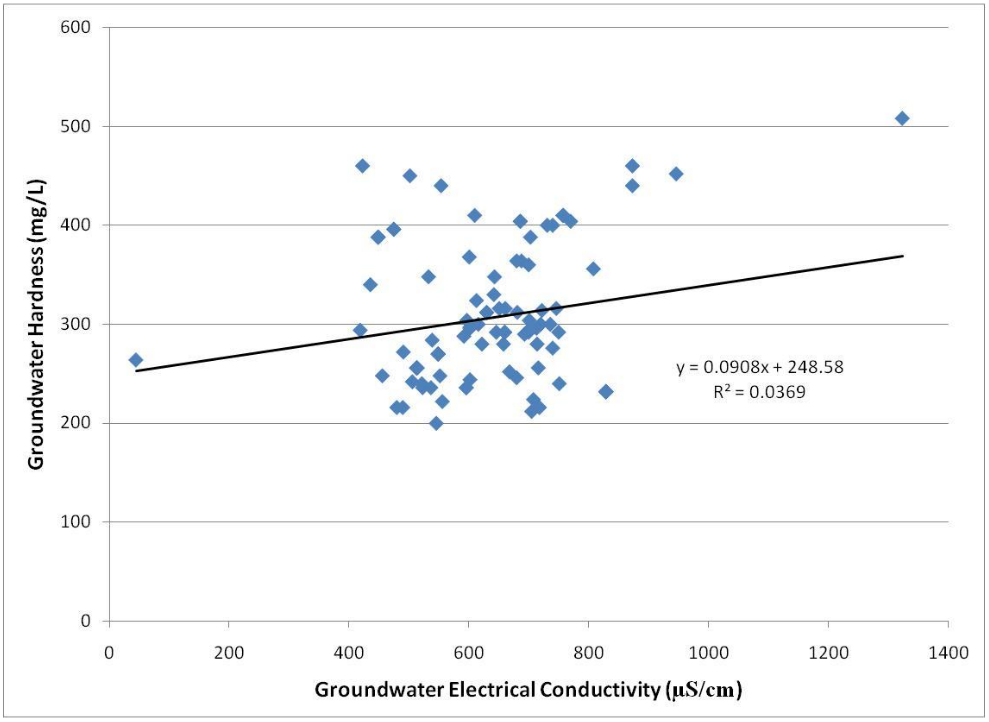

Figure 6-7: Groundwater hardness concentrations (as $CaCO_3$) vs. electrical conductivity. Error: +/- 10% (hardness) and +/-10% (conductivity).

6.3 Statistical Analyses

Factor analysis is a statistical method used to describe the variability among a large set of observed parameters to identify the number and loadings of unobserved variables referred to as factors. For this data, a factor of one was assumed in order to calculate the factor loading matrix of the model to observe any joint variations among our parameter outputs that would identify interdependencies between the measured parameters and the arsenic removal performance. The *factoran* syntax in MATLAB was used to calculate the maximum likelihood estimate of the factor loading matrix in the factor analysis model. The computed factor loading and variance values are shown in **Table 6-1**. This analysis shows a notable interdependence relationship between Fe(II) (groundwater, filtered water and nail water), hardness (groundwater and filtered water), groundwater chloride and percent arsenic removal. This further confirms our graphical findings that identified Fe(II), hardness and chloride to be major factors impacting the arsenic removing performance of the KAF.

Table 6-1: Factor loading and variance for each parameter using one common factor.

Parameter	Factor Loading	Variance
% Arsenic Removal	0.4613	0.7872
GW Arsenic	0.0007	0.9999
FW Arsenic	-0.3762	0.8584
GW Fe(II)	0.6894	0.5247
FW Fe(II)	0.5185	0.7312
Nail Fe(II)	0.7144	0.4896
GW Hardness	0.8859	0.2151
FW Hardness	0.8815	0.2229
GW Silica	0.0563	0.9968
GW Phosphate	0.0981	0.9904
FW Dissolved Oxygen	-0.3906	0.8474
GW pH	-0.1718	0.9705
FW pH	-0.0934	0.9913
Flow	-0.1563	0.9756
Age	-0.0017	0.9999
GW Electrical Conductivity	0.0855	0.9927
GW Chloride	0.5207	0.7289

GW = groundwater; FW = filtered water; Shaded parameters are shown to be related.

In addition, the Generalized Linear Model (GLM) was used to find the linear relationship between a dependent (or response) variable *Y*, and a set of predictor variables, the *X*'s, such that:

$$Y = b_0 + b_1X_1 + b_2X_2 + ... + b_nX_n$$

In this equation b_0 is the intercept coefficient and the b_i values are the regression coefficients (for variables 1 through n). The MATLAB syntax *glmfit* was used to compute the *bo* and *bi* values with a Y vector of the arsenic removal performance of each filter and the X matrix as the measured groundwater parameters (**Table 6-2**).

Table 6-2: Regression coefficients for the groundwater parameters using the GLM model.

Parameter	b (regression coefficient)
(bo) coefficient	98.72
Arsenic	-0.0424
Fe	4.4456
Fe (nail)	4.9664
Hardness	0.0466
Silica	0.2168
Phosphorous	-12.2943
pH	-4.8597
conductivity	-0.0058
chloride	-0.1325

GW = groundwater

This analysis shows that the groundwater arsenic, phosphorus, pH, conductivity and chloride concentrations negatively affect the percent arsenic removal performance of the KAF with an increase in concentration. Similarly, groundwater iron, nail water iron, groundwater hardness and silica all contribute positively to the arsenic removal performance of the filter with an increase in concentration. Though these models present more sophisticated analysis of a large data set, it should be looked at with consideration of the sample size and the variability of other factors not accounted for, such as the social and filter specific characteristics (i.e. flow rate, age, use), in non-controlled testing environment.

Chapter 7 – Conclusions & Recommendations

7.1 Conclusions

In the present study, a total of 100 KAFs were evaluated in the Nawalparasi and Rupandehi Districts of Nepal; of the 100 filters, 42 were labeled as poorly performing. Filter performance was determined using the Nepali standard for acceptable arsenic concentrations in drinking water (50 µg/L). Filters with effluent water arsenic concentrations above this standard were labeled as poorly performing or “failing.”

Collected data points to three major groundwater parameters that affect the arsenic removal performance of the KAF: (1) the influent groundwater ferrous iron concentration, (2) the ferrous iron concentration present after contact with the nails, and (3) the inlet groundwater hardness concentration. In addition, it was observed that the KAF typically fails when the groundwater arsenic concentration is ≥ 200µg/L, the ferrous iron concentration of the nails is < 1.1mg/L, and the groundwater chloride concentration is < 7mg/L. Approximately 82% of the studied poorly performing filters (N=39), as opposed to only 15% of the tested well performing filters (N=58), fell into this range of parameters. Thus, these findings suggest that groundwater conditions that promote the corrosion of the iron nails and have low inlet arsenic concentrations may result in a well performing KAF.

The groundwater corrosiveness was observed though the measured hardness (Ca^+ ions) and chloride concentrations. There was a significant correlation (R^2=0.422) between high ferrous iron concentrations after contact with the nails and high hardness concentrations in the groundwater. There was also a significant correlation (R^2=0.068) between high ferrous iron concentrations after contact with the nails and high chloride groundwater concentrations. In addition, it was observed from **Figure 6-2** and **Figure 6-4** that the filters were likely to perform well when chloride levels in the groundwater were higher than 7 mg/L.

As can be seen in **Figure 5-3**, there exists a relationship between high influent arsenic concentrations (≥200µg/L) and effluent arsenic concentrations above the Nepali drinking water standard of 50 μg/L. For influent groundwater arsenic concentrations ≥200μg/L, the minimum percent arsenic removal required to meet the Nepali standard is 75%. The average percent arsenic removal of the poorly performing filters in this study (N=42) was 50+/-26 % (with a range of 0-80 % removal); therefore, some of the labeled "poorly performing" filters could meet the Nepali standard in conditions of inlet arsenic concentrations <200μg/L. Since the average groundwater arsenic concentration from the samples observed in this study (N=79) was >200μg/L, filter performance should be evaluated at and above 200μg/L to enhance arsenic removal efficacy and prepare the KAF for dissemination in locations outside of Nepal under differing groundwater conditions.

7.2 Recommendations

7.2.1 KAF Improvements

Due to the observed correlation between high groundwater and nail water ferrous iron concentrations and the high levels of arsenic removal, it is recommended that future studies focus on the use of new, local components in the KAF system to increase iron corrosion. Due to the observed correlations between high dissolved iron and high hardness or high chloride concentrations, researching the possible incorporation and effect of adding local hardness or chloride sources (i.e. limestone or rock salt) to the filter is advised. Prior to distribution, it will be important to study how much of each component should be incorporated into the KAF system, and how frequently the component should be added to the filter. The new components must not only be effective in the removal of arsenic from raw groundwater, but they must be safe for KAF users to consume, in the short and long term, and they must be socially and economically desirable.

7.2.2 Future Studies

Groundwater pH concentrations observed in this study did not have a significant correlation with arsenic concentrations in the effluent water, but it is important to note that low groundwater pH levels (pH<6) were related to arsenic effluent concentrations below the Nepali drinking water standard of 50 μg/L. However, low groundwater pH levels accounted for only 7%

of the total measured groundwater pH data. Further studies are recommended to confirm this observation and to determine the effect of pH on KAF performance. Other studies are also necessary to pin-point the exact locations of the different iron oxidations reactions within the KAF mechanism. Particularly, it is not known if low ferrous iron concentrations after contact with the nails correspond to low production of ferrous iron by the nails or the fast oxidation of ferrous iron to ferric iron. Considering that the corrosion rate of the nails was seen to be a controlling factor in the filter's performance, resolving this ambiguity will help to identify the critical parameters that may drive the KAF's arsenic removal mechanism.

Additionally, further studies are necessary to see how the KAF performs in groundwater conditions with high levels of competing ions, such as phosphate. The observed groundwater in Nepal typically had very low concentrations of phosphorous (0.2 mg/L) when compared to groundwater phosphorous concentrations in other South Asian countries (>1mg/L). Thus, the present study does not provide significant insight into how the presence of phosphorous may reduce the KAF's arsenic removal capacity. Since high concentrations of phosphate or silicate have been previously observed to impede the absorption of arsenic onto ferric oxides, more research should be done on how to improve the filter under groundwater conditions that simultaneously do not promote iron corrosion and have high concentrations of competing ions like phosphate and silicate. This research is especially recommended for the safe dissemination of the KAF in other South Asian countries with more complicated groundwater conditions.

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Evaluation of the Kanchan^{TM} Arsenic Filter Under Various Water Quality Conditions of the Nawalparasi District, Nepal

APPENDICES

Appendix A : National Drinking Water Quality Steering Committee data

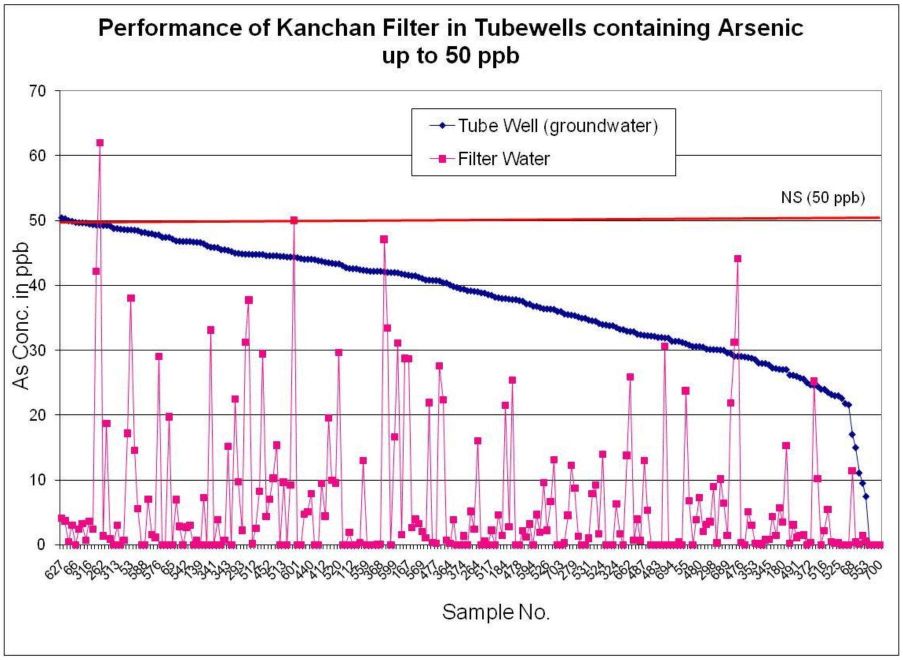

Figure A-1: Third party evaluation of KAF with influent water concentrations greater or less than 50 µg/L. Arsenic concentrations in µg/L (vertical-axis) are plotted against the filter sample number (horizontal-axis). Source: NDWQSC, 2009.

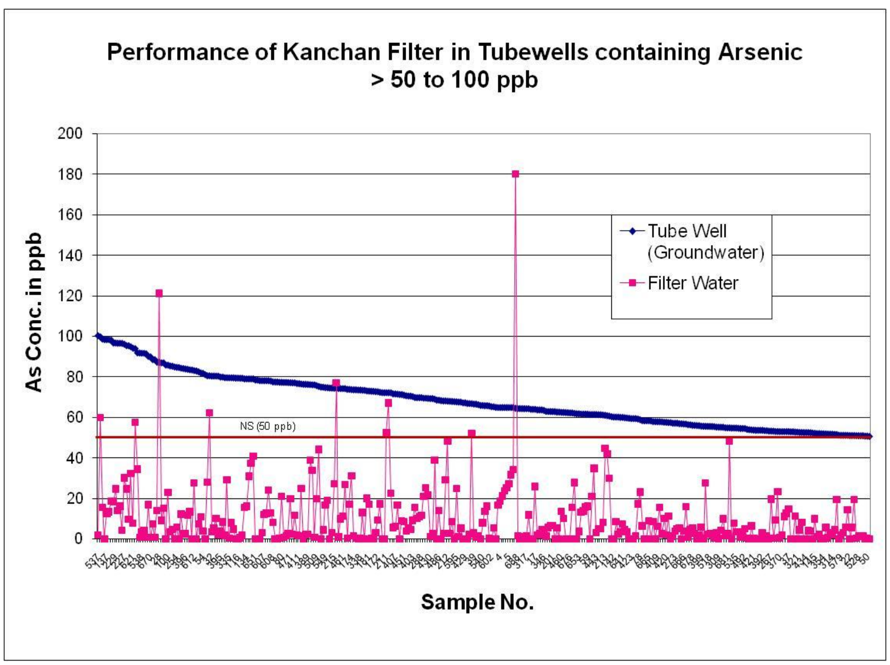

Figure A-2: Third party evaluation of the KAF with influent water concentrations between 50 µg/L and 100 µg/L. Arsenic concentrations in µg/L (vertical-axis) are plotted against the filter sample number (horizontal-axis). Source: NDWQSC, 2009.

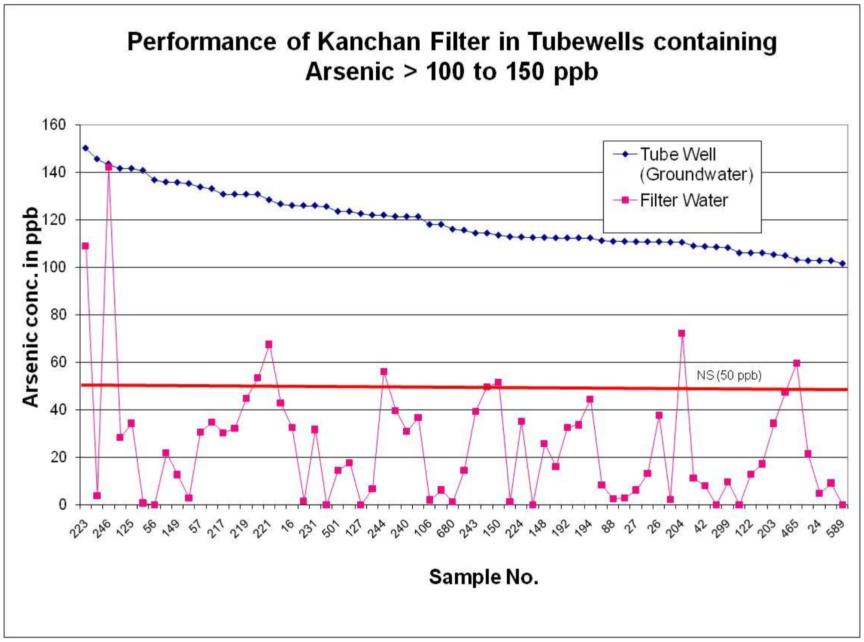

Figure A-3: Third party evaluation of the KAF with influent water concentrations between 100 µg/L and 150 µg/L. Arsenic concentrations in µg/L (vertical-axis) are plotted against the filter sample number (horizontal-axis). Source: NDWQSC, 2009.

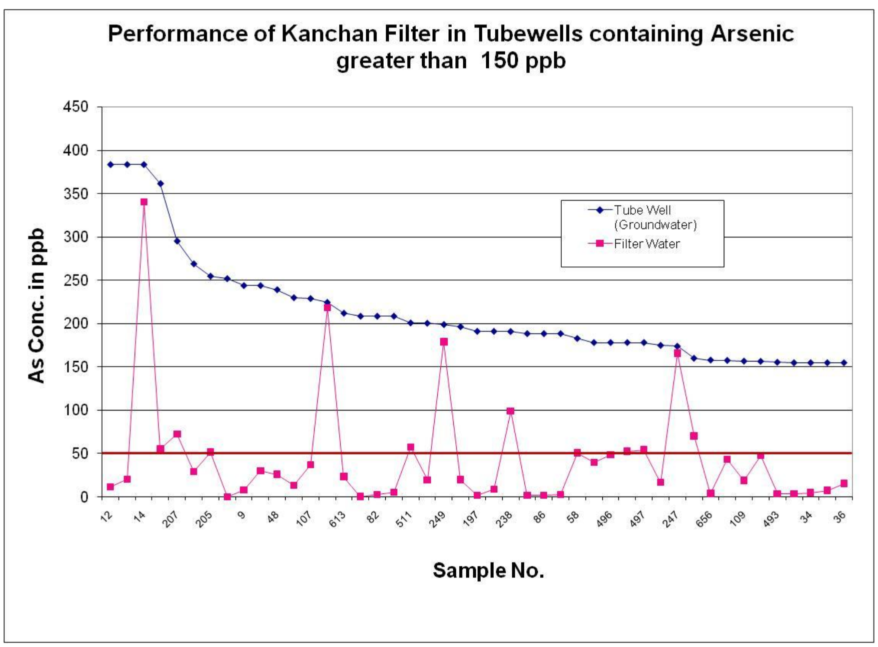

Figure A-4: Third party evaluation of the KAF with influent water concentrations above 150 µg/L. Arsenic concentration in µg/L (vertical-axis) is plotted against the filter sample number (horizontal-axis). Source: NDWQSC, 2009.

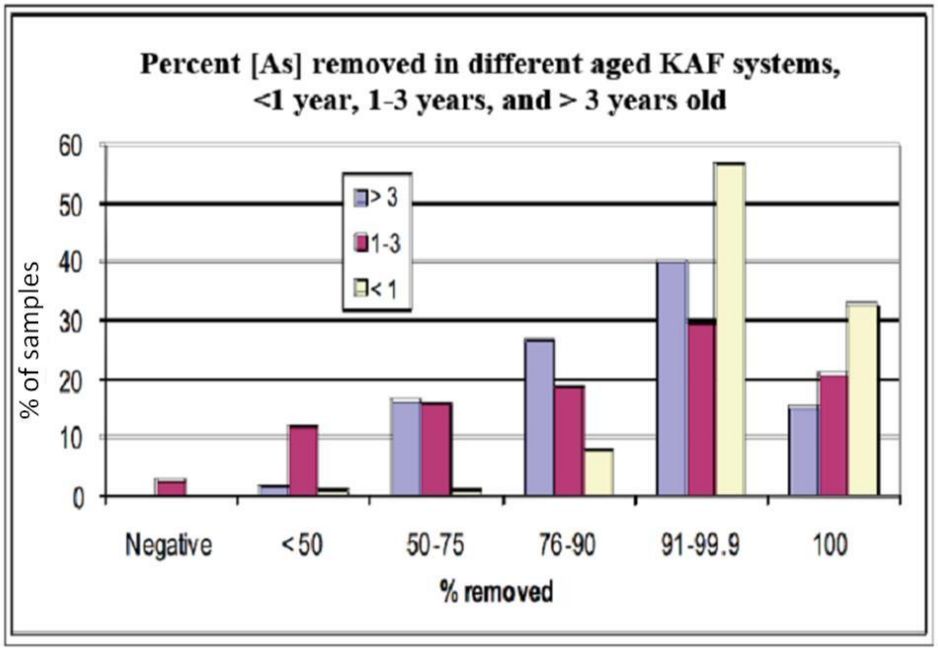

Figure A-5: Third party evaluation of the KAF at different ages (in calendar years). The cream, maroon and blue colored bars are filters aged <1 years, 1-3 years and > 3 years old, respectively. Percent of samples (vertical-axis) is plotted against the % arsenic concentration removed (horizontal-axis) Source: NDWQSC, 2009.

Appendix B : User Survey

The following survey was used to document the user and location of each studied KAF. In addition, other details related to the type of KAF and reported or observed maintenance was recorded.

Date and Time			
District			
VDC			
Ward No.			
Tole			
KANCHAN ARSENIC FILTER INFORMATION			
Type of KAF	(1) Concrete, round		(4) Plastic, square
	(2) Concrete square		(5) Gem505
	(3) Plastic, round		(6) Fiberglass
KAF Provided by	(1) NRCS		(4) Others, specify:
	(2) RWSSSP		
	(3) RWSSFDB		
KAF Installation Date			
qality of iron nails	(1) not rusted	(2) moderatly rusted	(3) well rusted
Number of KAF Housholds			
Number of KAF Users			
How many liters of water do you filter each day?	(1) less than 10 L		(4) 30 to 40 L
	(2) 10 to 20 L		(5) 40 to 50 L
	(3) 20 to 30 L		(6) over 50 L
Filter current in use?	(1) Yes, everyday		
	(2) Yes, sometimes		
	(3) No. I drinking unfiltered water.		
	(4) No. I use another arsenic-free water source, specify:		
Filter Cleaning Frequency	(1) once every week		(4) once every 2-4 months
	(2) once every two weeks		(5) never
	(3) once a month		
Date of Last Cleaning			

Appendix C : Wagtech Arsenator® Digital Arsenic Test Kit Operation Manual

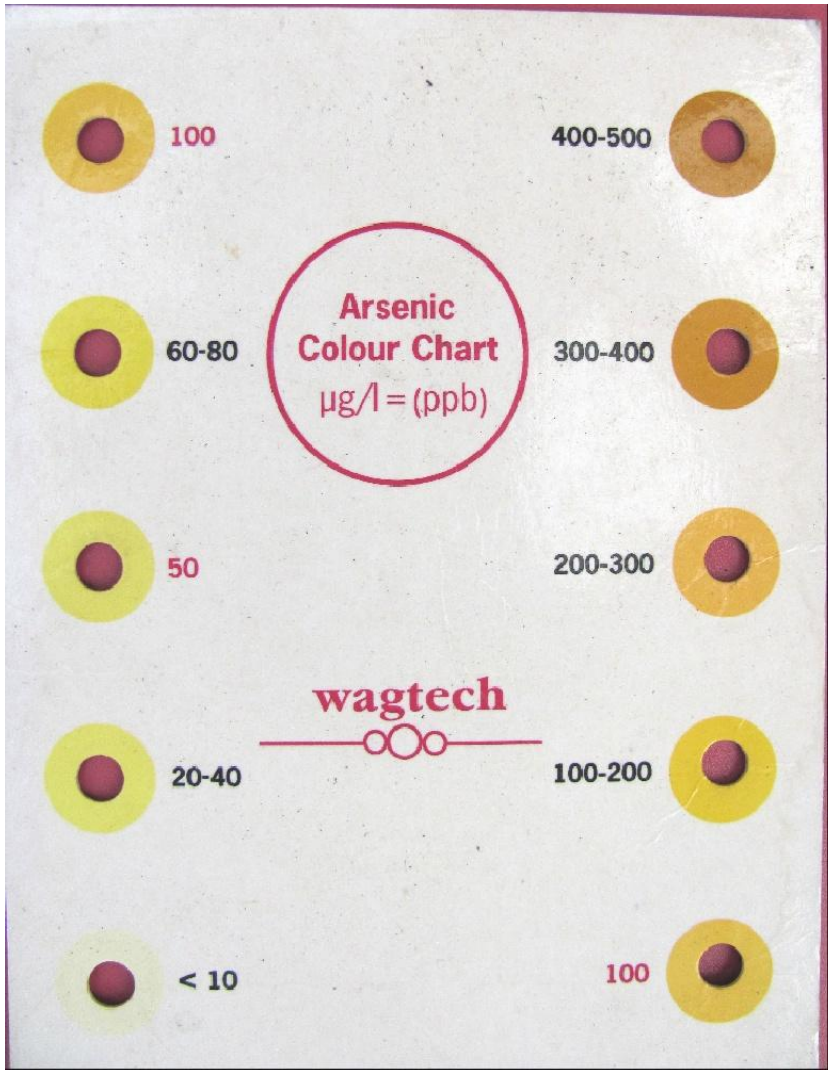

Figure C-1: Arsenic color chart for concentrations above 100µg/L.

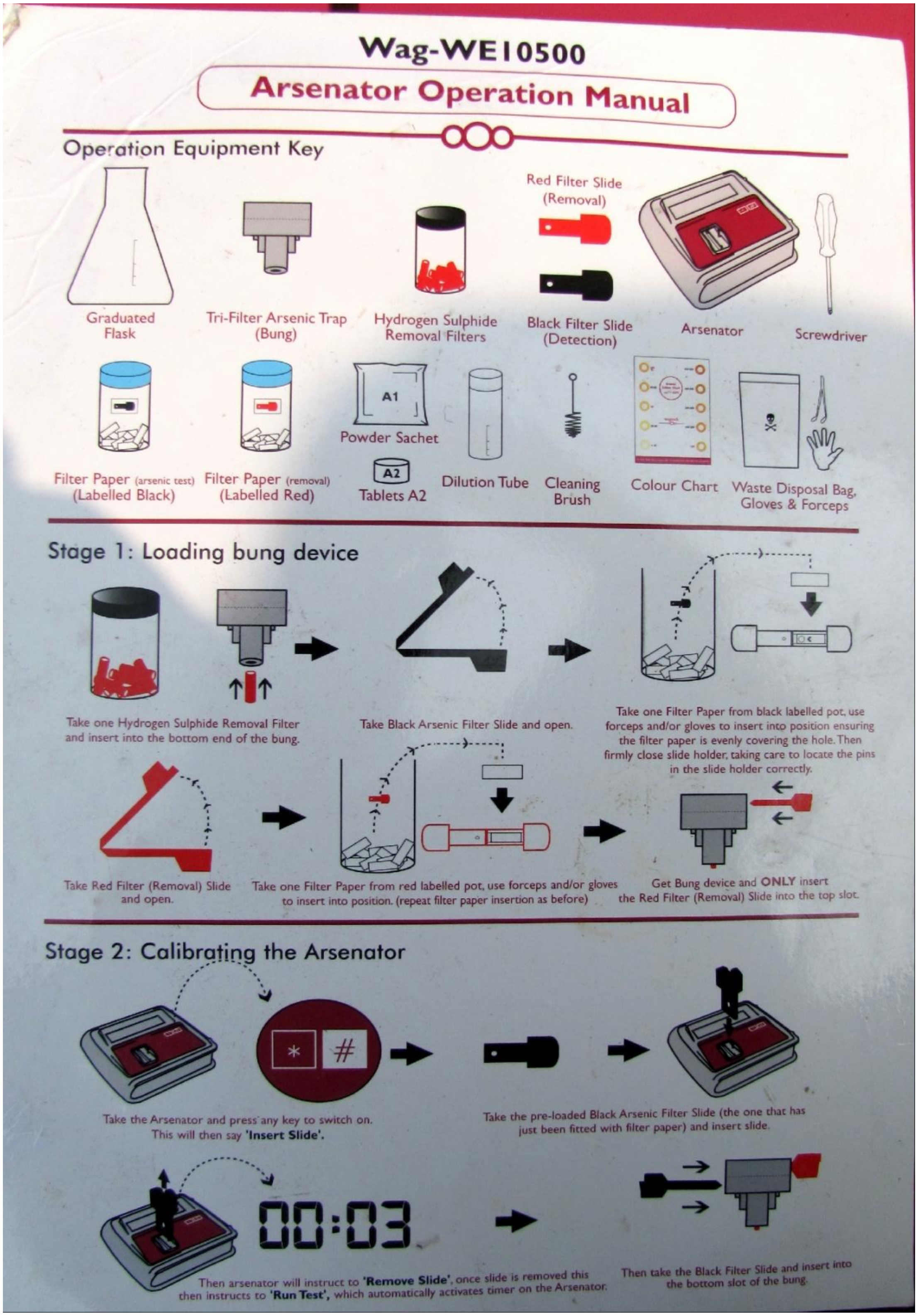

Figure C-2: Scanned copy of the Wagtech Arsenator operation manual, part 1

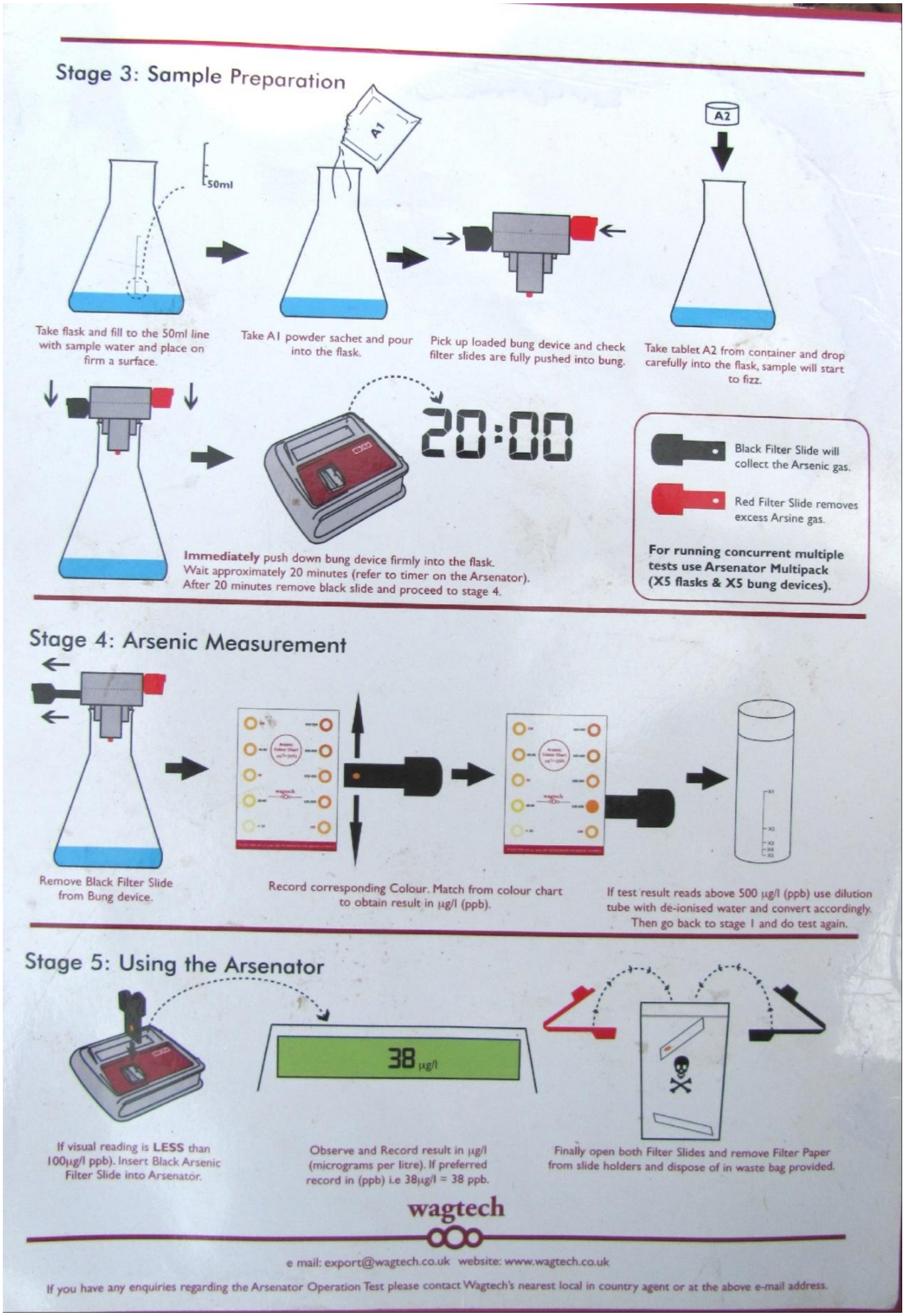

Figure C-3: Scanned copy of the Wagtech Arsenator operation manual, part 2

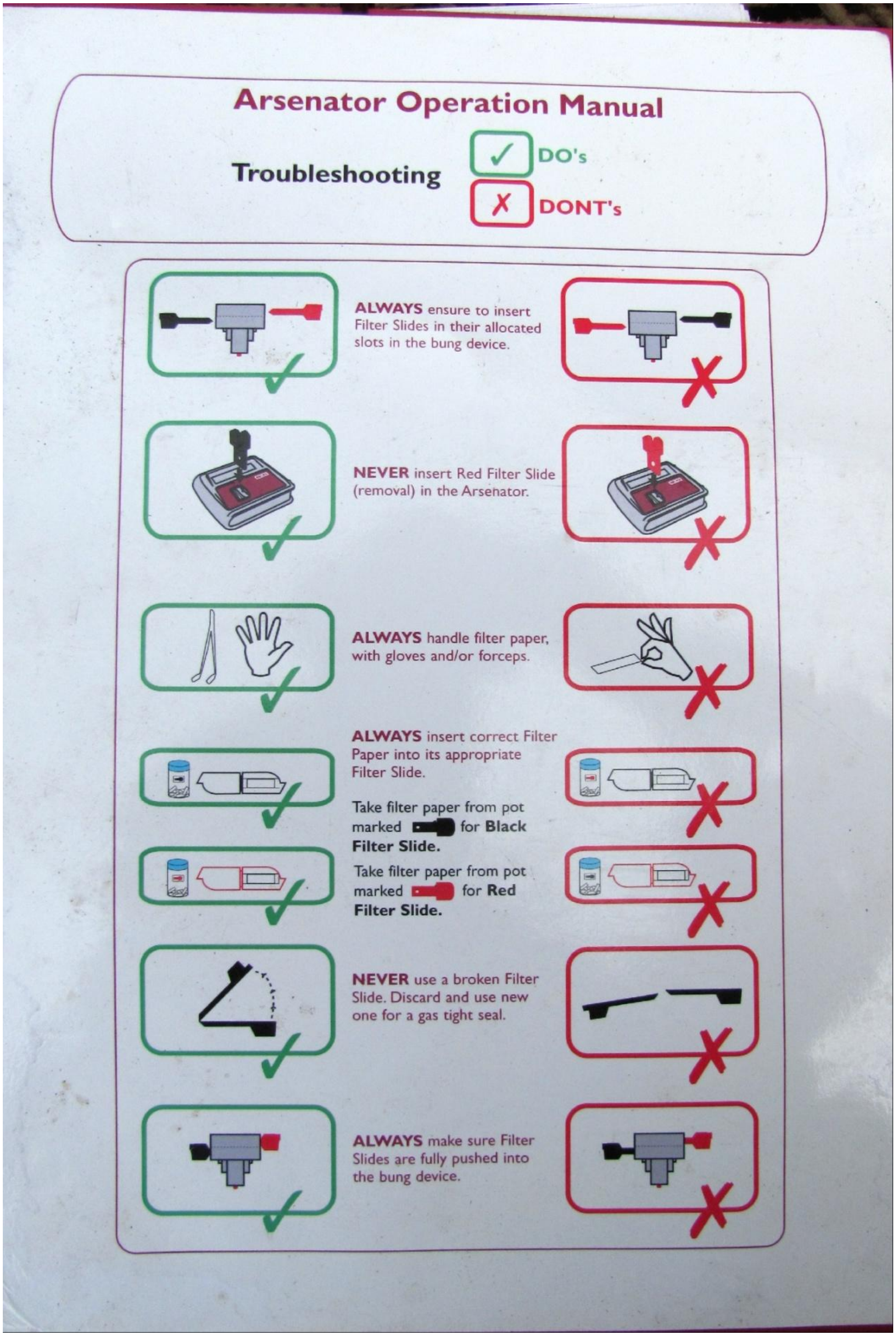

Figure C-4: Scanned copy of the Wagtech Arsenator operation manual, part 3

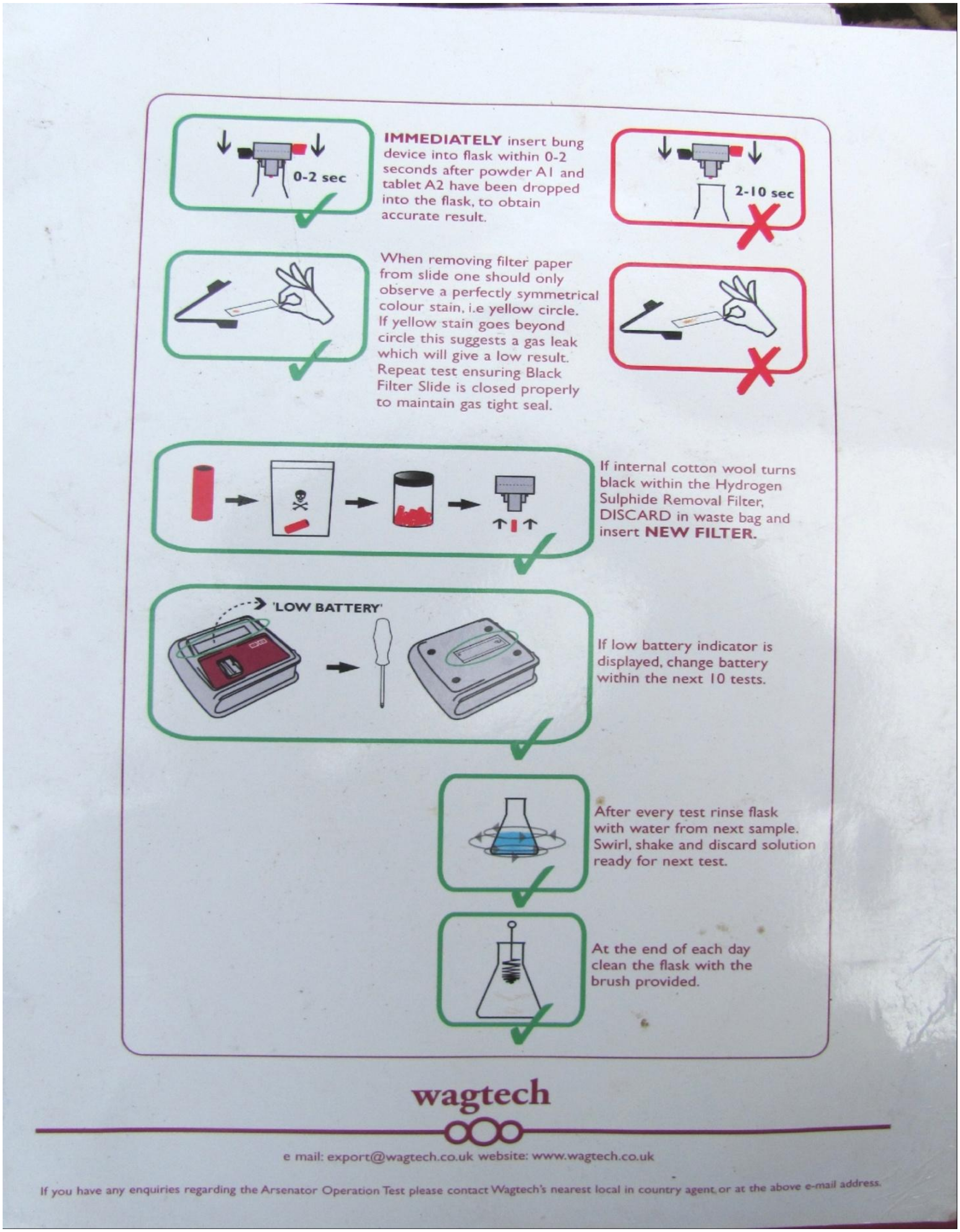

Figure C-5: Scanned copy of the Wagtech Arsenator operation manual, part 4

Appendix D : Raw Data Used in Filter Analysis

The following data in pages 91-94 includes the 101 filtered water (FW) samples and 79 groundwater (GW) samples corresponding to the 100 different KAF tested on the field. Filters that were not included in the analysis due to low influent arsenic concentrations, high flow rate, or mechanical malfunctions are not included in this data sheet.

Filter Number	FW Arsenic	GW Arsenic	Ferrous Iron After Nails	GW Ferrous Iron	FW Ferrous Iron	GW Total Phosporus	GW Silica	FW pH (field)
	(µg/L)	(µg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	-
4	73	250	0.10	0.75	0.32	0.1	22.9	7.5
5	250	450	0.64	0.73	0.85	0.1	30.6	7.5
6	11	250	0.58	0.80	0.03	0.2	28.2	7.25
7	35	450	0.11	0.54	0.36	0.2	26.3	7.5
8	70	350	0.21	1.01	0.33	0.1	36	7.5
9	98	350	0.80	1.51	0.01	0.3	17.2	7.5
10	400	400	0.64	0.97	1.10	0.8	28.5	7.5
11	150	450	0.15	0.54	0.02	0.2	31.6	8
13	24	250	2.18	1.80	1.21	0.1	32.2	7
14	24	250	1.57	1.80	0.96	0.1	32.2	7
15	4	250	0.51	1.80	1.04	0.1	32.2	7
17	11	250	1.22	1.85	0.42	0.2	25.5	7
18	16	250	1.47	1.85	1.09	0.2	25.5	7.25
19	10	350	2.06	2.12	0.57	0.6	25.5	7.25
21	18	150	1.98	3.16	1.19	0.2	20.6	7
22	33	350	1.18	2.95	1.08	0.1	19	7.25
23	23	350	1.35	2.95	1.21	0.1	19	7
24	9	350	1.08	2.58	0.00	1.0	23.7	7.5
25	13	250	1.61	1.18	1.23	0.3	16	7
26	8	250	1.99	1.92	0.98	0.3	28.5	8
27	26	250	1.53	1.50	1.37	0.1	22.2	7.5
28	0	350	1.19	2.58	1.27	0.1	23.7	7.5
29	12	250	1.83	3.46	1.34	0.3	16.9	7
31	5	150	1.32	1.64	0.01	0.2	17.5	7
32	0	84	1.14	1.89	0.01	0.1	9.1	8
33	0	150	0.53	1.41	0.01	0.1	13.1	7.5
34	8	150	1.16	1.41	0.01	0.1	13.1	7
35	0	76	unknown	0.60	0.01	0	17.2	7.5
36	0	86	2.07	1.79	0.02	0.1	14.7	7.5
37	0	82	1.42	2.71	0.32	0	13.5	7
41	21	250	1.31	0.26	0.02	0.2	19.3	7.5
42	66	250	0.81	0.16	0.02	0.1	32.4	7
43	82	250	0.57	0.16	0.01	0.1	32.4	7.5
44	77	250	0.09	0.16	0.01	0.1	32.4	7.5
45	89	250	0.41	0.16	0.00	0.1	32.4	6.75
46	5	250	1.26	1.69	0.02	0.2	14.8	7
47	41	250	0.22	0.08	0.01	0.1	36.9	7.5
48	14	85	0.34	0.08	0.01	0.1	36.9	7.5
49	21	350	1.17	1.27	0.01	0.2	30.5	7.5
50	96	250	1.38	1.72	0.02	0.2	18.1	7
51	52	250	0.08	1.53	0.01	0.2	23.1	7.5
52	150	250	0.00	1.29	0.00	0.3	17.2	7
53	92	250	1.13	0.16	0.01	0.1	32.1	7.5
54	99	250	0.56	0.96	0.01	0.9	18.7	6.5
55	91	250	0.56	0.96	0.00	0.9	18.7	7.5
56	96	350	0.42	0.76	0.00	0.2	20.9	7.5
58	250	250	0.14	1.05	0.01	0.1	24.2	7.5
60	250	350	0.17	0.67	0.90	0.1	23.3	7
61	29	200	0.09	0.46	0.01	0.1	15.6	6.5
62	18	86	0.06	0.95	0.01	0.1	15.9	6.5

Filter Number	FW Arsenic	GW Arsenic	Ferrous Iron After Nails	GW Ferrous Iron	FW Ferrous Iron	GW Total Phosporus	GW Silica	FW pH (field)
	(μg/L)	(μg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	-
63	11	86	0.43	1.19	1.01	0.1	12.5	6.5
65	0	78	1.31	1.97	0.00	0.9	18.9	7
66	68	250	2.16	1.97	0.00	0.9	18.9	7
70	62	250	0.25	2.56	0.01	0.9	14.2	7
71	21	250	0.00	0.33	0.01	0.1	13.9	6.25
72	39	68	0.00	0.42	0.01	0.2	16.5	6.5
73	29	99	0.00	0.64	0.00	0.2	25.9	7
74	25	98	0.04	0.07	0.01	0.1	29.2	7
76	250	250	0.00	0.48	0.00	0.2	17.1	7
79	29	150	0.04	0.26	0.01	0.1	17.6	6
80	16	250	0.19	0.20	0.00	0.1	8.5	6.5
81	40	250	0.16	1.46	0.08	0.1	31	6.5
82	29	99	0.41	1.46	0.39	0.1	31	6.5
83	18	150	0.44	0.76	0.01	0.1	16.8	6.5
84	0	60	0.12	1.41	0.01	0.2	27.2	7
85	17	250	0.16	1.34	0.00	0.1	27.1	7
86	150	250	0.38	2.13	0.00	0.2	24.4	7.5
87	150	250	1.35	1.41	0.01	0.2	16.7	7.5
91	16	71	0.07	0.17	0.00	0.2	9.3	7.5
92	24	250	1.13	1.81	0.01	0.1	29.7	7
93	39	250	1.35	1.83	0.01	0.1	26.6	7.5
94	13	250	0.71	1.67	1.41	0.1	25.8	7
95	23	350	0.05	1.37	0.16	0.1	29.6	7.5
96	5	150	0.51	1.08	0.46	0.1	17	7.5
97	6	250	0.77	1.74	0.82	0.1	18.9	7.5
98	72	99	1.12	1.42	1.16	0.1	33.7	7.5
99	98	350	0.94	1.79	0.39	0.1	30.5	7.5
100	18	97	0.69	1.52	0.21	0.2	22.5	7.5
101	0	97	0.78	1.39	1.34	0.2	32.6	7.5
102	0	78	0.24	1.40	0.93	0.7	30.1	8
103	37	150	0.15	1.11	0.86	0.1	24.1	8
105	250	350	1.10	0.80	0.10	0.3	16.2	8
106	150	250	0.15	1.27	0.01	0.1	14.1	8
107	150	250	0.02	0.57	0.01	0.1	9.3	8
108	33	350	0.10	1.03	0.00	0.2	17	8
109	25	250	0.70	4.87	0.08	0.2	17.3	7.5
112	8	250	0.03	1.17	0.05	0.1	21.4	7.5
113	250	350	0.17	0.25	0.01	0.2	20.8	7.5
114	66	250	0.00	0.25	0.01	0.2	20.8	7.5
115	83	250	0.38	0.25	0.00	0.2	20.8	8
116	83	250	0.11	0.25	0.01	0.2	20.8	8
117	90	250	0.40	0.25	0.01	0.2	20.8	8
118	82	250	0.04	0.25	0.00	0.2	20.8	8
119	87	250	0.06	0.25	0.00	0.2	20.8	8
120	80	250	0.00	0.25	0.00	0.2	20.8	8
121	250	250	0.07	0.20	0.00	unknown	27.3	7.5
122	250	250	0.09	0.20	0.01	unknown	27.3	7.5
123	250	250	0.11	0.20	0.01	unknown	27.3	7.5
124	94	200	0.02	0.31	0.00	0.1	10.3	8
125	97	200	0.30	0.31	0.00	0.1	10.3	8
126	79	92	0.16	0.94	0.01	0.1	25.7	7.5

Filter Number	GW Hardness	FW Hardness	FW Dissolved Oxygen	Flow Rate	GW pH (Lab)	GW Electrical Conductivity	GW Chloride
	(mg/L)	(mg/L)	(mg/L)	(L/hour)	-	(µS/cm)	(mg/L)
4	314	304	12.3	8.4	7.79	722	unknown
5	290	304	7.2	9.0	7.79	693	3
6	330	360	6.1	15.0	7.98	642	13
7	246	272	1.3	25.8	7.77	680	1
8	222	308	10.6	20.4	8.24	556	1
9	294	244	1.2	32.4	8.43	419	2
10	292	240	2.4	18.0	7.86	646	0
11	242	280	4.0	7.2	8.38	506	7
13	388	372	2.0	13.8	7.96	449	11
14	388	364	0.9	12.6	7.96	449	11
15	388	388	1.2	10.8	7.96	449	11
17	292	396	1.8	10.2	7.36	660	9
18	292	324	2.0	18.0	7.36	660	9
19	400	344	1.5	21.0	7.45	740	15
21	450	396	1.5	20.4	8.15	502	33
22	396	372	1.8	18.6	8.04	475	6
23	396	360	3.0	7.2	8.04	475	6
24	440	328	2.9	15.6	7.33	873	37
25	410	380	2.3	23.4	7.37	757	17
26	440	376	2.1	31.2	7.84	554	12
27	460	496	1.0	25.8	8.07	423	12
28	460	388	1.4	7.2	7.33	873	37
29	410	388	1.2	17.4	7.36	758	20
31	410	372	10.6	29.4	7.89	610	7
32	388	384	3.6	15.6	7.64	703	8
33	404	332	3.1	4.2	7.64	686	6
34	404	392	3.1	11.4	7.64	686	6
35	404	348	2.0	4.8	7.54	770	14
36	400	400	2.8	7.2	7.70	731	9
37	364	356	2.2	19.8	7.43	688	2
41	316	332	11.2	16.8	7.79	661	11
42	270	260	3.3	8.4	7.54	549	6
43	270	272	5.3	25.2	7.54	549	6
44	270	280	5.2	14.4	7.54	549	6
45	270	260	3.1	22.8	7.54	549	6
46	348	332	0.7	13.8	7.63	643	15
47	256	260	3.3	28.8	7.91	513	1
48	256	212	4.0	20.4	7.91	513	1
49	288	240	3.5	10.2	7.43	592	9
50	300	272	3.5	17.4	7.40	616	5
51	316	332	3.6	25.2	7.48	651	12
52	292	244	3.5	13.8	7.75	700	1
53	280	240	3.5	25.2	8.04	622	7
54	312	280	4.5	21.0	7.57	630	1
55	312	272	5.1	20.4	7.57	630	1
56	324	304	4.2	22.8	7.81	613	0
58	360	312	4.2	9.0	7.67	700	3
60	304	272	2.5	16.2	7.85	597	2
61	272	252	2.4	2.4	7.73	491	3
62	200	224	5.3	25.8	**9.06**	546	7

Filter Number	GW Hardness	FW Hardness	FW Dissolved Oxygen	Flow Rate	GW pH (Lab)	GW Electrical Conductivity	GW Chloride
	(mg/L)	(mg/L)	(mg/L)	(L/hour)	-	(µS/cm)	(mg/L)
63	212	204	4.0	27.6	7.81	705	0
65	296	268	5.4	30.0	7.62	602	1
66	297	268	3.4	27.0	7.62	602	1
70	364	336	2.8	10.8	7.33	680	2
71	216	192	10.7	28.8	7.66	490	0
72	236	216	4.5	30.6	7.60	537	1
73	236	224	4.2	13.8	7.64	523	0
74	216	200	2.6	20.4	7.68	480	1
76	240	212	4.6	16.8	7.71	522	2
79	244	252	2.1	12.0	7.53	602	1
80	284	228	2.4	12.6	7.82	539	1
81	256	332	2.6	25.8	8.26	514	25
82	256	320	2.5	17.4	8.26	514	25
83	276	296	3.1	15.0	7.46	740	2
84	312	296	2.4	25.8	7.43	681	10
85	348	300	3.3	23.4	7.77	533	17
86	508	280	2.0	15.6	7.27	1323	61
87	452	420	2.5	16.8	7.48	946	91
91	264	220	5.8	28.2	8.39	45	1
92	340	312	3.5	7.2	8.26	436	23
93	368	332	3.0	18.6	8.10	601	42
94	300	304	1.7	25.8	7.27	720	14
95	292	348	2.4	7.2	7.24	750	10
96	280	324	2.0	4.8	7.32	714	0
97	296	380	2.0	16.2	7.24	713	1
98	280	300	1.3	27.6	7.22	658	1
99	300	340	1.9	22.8	7.16	736	1
100	304	320	3.4	11.4	7.27	701	3
101	316	352	2.1	27.6	7.14	746	1
102	356	404	2.4	22.8	7.68	808	71
103	252	252	2.2	22.2	7.35	668	1
105	224	240	3.0	27.6	7.62	708	6
106	256	248	3.1	27.6	7.61	716	4
107	216	240	3.4	27.0	7.56	718	4
108	240	200	6.3	25.2	8.02	751	6
109	248	240	3.4	14.4	8.53	552	3
112	296	280	1.7	28.8	7.61	703	4
113	232	140	5.4	26.4	7.65	829	2
114	232	160	5.9	25.8	7.65	829	2
115	232	208	4.8	24.6	7.65	829	2
116	232	236	1.7	14.4	7.65	829	2
117	232	240	2.1	15.6	7.65	829	2
118	232	188	4.2	13.8	7.65	829	2
119	232	168	6.3	6.6	7.65	829	2
120	232	200	3.2	6.6	7.65	829	2
121	unknown	256	5.1	24.6	unknown	unknown	unknown
122	unknown	226	5.4	21.6	unknown	unknown	unknown
123	unknown	260	2.8	28.8	unknown	unknown	unknown
124	236	240	3.9	16.2	8.11	596	1
125	236	248	4.2	18.0	8.11	596	1
126	248	260	6.2	14.4	8.56	456	2

Appendix E : User Survey Raw Data

The following data in pages 96-103 includes the survey data for the 100 households corresponding to the 100 different filters. Sample number 53 corresponding to the same filter as sample number 43 was not included. Also, filters that were not included in the analysis due to low influent arsenic concentrations, high flow rate, or mechanical malfunctions are not included in this data sheet.

Filter Number	Age (Years)	Date	District	VDC	Ward No.	Tole	Type of KAF	Name of the Household owner
4	7	Jan. 9, 2011	Nawalparasi	Tilakpur	7	Patkhauli	Gem 505	Thagey Prasad Chaudhary
5	6	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Kamalesh Chaudhary
6	6	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Narsingh Kurmi
7	6	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Nagendra Kurmi
8	5	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Hem Narayan Chaudhary
9	4	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Bharat Thatel
10	5	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Santosh Jaiswal
11	4	Jan. 10, 2011	Nawalparasi	Devgaun	1	Patkhouli	Gem 505	Amar singh kurmi
13	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Tika Prasad Chaudhary
14	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Chatraman Chaudhary
15	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Birendra Chaudhary
17	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Bahadur Tharu
18	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Chet Narayan Tharu
19	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Govinda Chaudhary
21	3	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Ramhari Bidari
22	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Bal Bahadur Chaudhary
23	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Om Narayan Chaudhary
24	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Bishu Prasad Upadhaya
25	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Madan Chaudhary
26	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Madari Prasad Chaudhary
27	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Tularam Chaudhary
28	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Ashok Kashodhan
29	3	Jan. 12, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Tek Narayan Chaudhary
31	6	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Concrete square	Sanju Thapa
32	6	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Concrete round	Jay Budhathoki
33	3	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Khim Raj Rana
34	3	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Khalzir Budhathoki
35	6	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Concrete square	Baliram Thapa
36	6	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Concrete round	Ganesh Budhathoki
37	3	jan. 13,2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Laxmi Bhusal
41	0	Jan. 14, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Lila Chaudhary
42	0	Jan. 14, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Birendra Chaudhary
43	0	Jan. 14, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Fanendra Chaudhary
44	0	Jan. 14, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Top Narayan Chaudhary
45	0	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Shivanath Chaudhary
46	0	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Mohalla Chaudhary
47	0	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Dhirendra Chaudhary
48	0	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Ramesh Chaudhary
49	0	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Naresh Chaudhary
50	4	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Ayodhya Chaudhary
51	3	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Chedi Chaudhary
52	4	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Man Bahadur Chaudhary
53	7	Jan. 15, 2011	Nawalparasi	Bhutaha	9	Panchanagar	Gem 505	Farendra Chaudhary
54	7	Jan. 16, 2011	Nawalparasi	Bhutaha	6	Panchanagar	Gem 505	Yam Bahadur Chaudhary
55	7	Jan. 16, 2011	Nawalparasi	Bhutaha	6	Panchanagar	Gem 505	Rita Chaudhary
56	5	Jan. 16, 2011	Nawalparasi	Bhutaha	6	Panchanagar	Gem 505	Tara Prasad Chaudhary
58	6	Jan. 16, 2011	Nawalparasi	Bhutaha	6	Panchanagar	Concrete square	Sushila Faudhar
60	7	Jan. 16, 2011	Nawalparasi	Sarawal	1	Goini	Concrete square	Hari Narayan Chaudhary
61	0	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Uday raj Tharu
62	0	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Bhud narayan Tharu

Filter Number	Age (Years)	Date	District	VDC	Ward No.	Tole	Type of KAF	Name of the Household owner
63	0	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Khel ram kanta Chaudhary
65	0	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Dhani ram Chaudhary
66	0	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Ram chandra Chaudhary
70	3	Jan. 18, 2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Chitra Bahadur Faudar
71	0	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Tikaram Bashyal
72	0	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Humanath Bashyal
73	3	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Balaram Pandey
74	0	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Mira lal Bashyal
76	0	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Yadav Aryal
79	7	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	12	Kasiya	Gem 505	Madhav lal Shrestha
80	7	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	12	Kasiya	Gem 505	Fagu Yadav
81	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Rishi raj Chaudhary
82	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Gobinda Chaudhary
83	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Om Prakash Chaudhary
84	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Kailash Chaudhary
85	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Padam Narayan Chaudhary
86	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Ganesh Kewat
87	5	Jan. 19, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Ramzya Kewat
91	7	Jan. 20, 2011	Rupandehi	Dudharakshya	3	Budhanagar	Concrete square	Kul Bahadur Tandon
92	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Kailash Sahani
93	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Unwanch	Gem 505	Ramdas Gupta
94	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Ramchandra Bhar
95	7	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Rabindra Pd. Bhar
96	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Madan Kurmi
97	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Sanu Pd. Bhar
98	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Kedarnath Gupta
99	5	Jan. 21, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Tribhuvan Gupta
100	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Ram Harijan
101	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Ram Kewal Harijan
102	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	8	Baikunthapur	Gem 505	Jayram Gupta
103	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Kanchanha	Gem 505	Mustakim Ansari
105	6	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Shiwangadh	Gem 505	Shivalal Aryal
106	6	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Shiwangadh	Gem 505	Sabitri Aryal
107	4	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Shiwangadh	Gem 505	Parag Gupta
108	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Babu lal Harijan
109	5	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Ram abadh Gupta
112	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Radhika Chaudhary
113	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Mohan Chaudhary
114	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Some Tharu
115	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Ash Narayan Chaudhary
116	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Praladh Badhai
117	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Algu Badhai
118	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Ganesh Bahadur Chaudhary
119	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Laxman Sharma
120	5	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Goli Gupta
121	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Gobardhan Chaudhary
122	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Man Bahdaur Chaudhary
123	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Ani Rudra Tharu
124	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Mahabir Bi. Ka.
125	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Shree ram Bi. Ka.
126	5	Jan.24, 2011	Nawalparasi	Sukrauli	9	Naduwa	Gem 505	Shiva Kumar Sahani

Filter Number	KAF provided by	KAF Installed Date	Quality of Iron nails	No. of KAF Households	Number of KAF Users
4	NRCS	2003	Well rusted	1	7
5	NRCS	2004	Well rusted	1	9
6	NRCS	2004	Well rusted	1	3
7	Filters for families	2004	Well rusted	1	2
8	Filters for families	2005	Well rusted	1	5
9	Filters for families	2006	Well rusted	1	5
10	Filters for families	2005	Well rusted	1	4
11	Filters for families	2006	Well rusted	1	5
13	Filters for families	2007	Well rusted	1	2
14	Filters for families	2007	Well rusted	1	4
15	Filters for families	2007	Well rusted	1	3
17	Filters for families	2007	Well rusted	1	7
18	Filters for families	2007	Well rusted	1	2
19	Filters for families	2007	Well rusted	1	4
21	Filters for families	2007	Well rusted	1	5
22	Filters for families	2007	Well rusted	1	5
23	Filters for families	2007	Well rusted	1	4
24	Filters for families	2007	Well rusted	1	5
25	Filters for families	2007	Well rusted	1	7
26	Filters for families	2007	Well rusted	1	10
27	Filters for families	2007	Well rusted	1	7
28	Filters for families	2007	Well rusted	1	4
29	Filters for families	2007	Well rusted	1	4
31	RWSSSP	2004	Well rusted	1	4
32	RWSSSP	2004	Well rusted	1	7
33	Filters for families	2007	Well rusted	1	2
34	Filters for families	2007	Well rusted	1	3
35	RWSSSP	2004	Well rusted	1	3
36	RWSSSP	2004	Well rusted	1	7
37	Filters for families	2007	Well rusted	1	3
41	DWSS	2010	Well rusted	1	4
42	DWSS	2010	Well rusted	1	5
43	DWSS	2010	Well rusted	1	4
44	DWSS	2010	Well rusted	1	7
45	DWSS	2010	Well rusted	1	4
46	DWSS	2010	Well rusted	1	4
47	DWSS	2010	Well rusted	1	4
48	DWSS	2010	Well rusted	1	10
49	DWSS	2010	Well rusted	1	8
50	NRCS	2006	Well rusted	1	7
51	NRCS	2007	Well rusted	1	2
52	NRCS	2006	Well rusted	1	7
53	NRCS	2003	Well rusted		
54	NRCS	2003	Well rusted	1	6
55	NRCS	2003	Well rusted	1	4
56	NRCS	2005	Well rusted	1	4
58	Local entrepreneur (Raju Bishwo)	2004	Well rusted	1	5
60	RWSSSP	2003	Well rusted	1	27
61	DWSS	2010	Well rusted	1	7
62	DWSS	2010	Well rusted	1	6

Filter Number	KAF provided by	KAF Installed Date	Quality of Iron nails	No. of KAF Households	Number of KAF Users
63	DWSS	2010	Well rusted	1	4
65	DWSS	2010	Well rusted	1	2
66	DWSS	2010	Well rusted	1	9
70	Filters for families	2007	Well rusted	1	4
71	DWSS	2010	Well rusted	1	5
72	DWSS	2010	Well rusted	1	8
73	NRCS	2007	Well rusted	1	5
74	DWSS	2010	Well rusted	1	6
76	DWSS	2010	Well rusted	1	4
79	NRCS	2003	Well rusted	1	6
80	NRCS	2003	Well rusted	1	8
81	Filters for families	2005	Well rusted	1	11
82	Filters for families	2005	Well rusted	1	11
83	Filters for families	2005	Well rusted	1	5
84	Filters for families	2005	Well rusted	1	9
85	Filters for families	2005	Well rusted	1	6
86	Filters for families	2005	Well rusted	1	4
87	Filters for families	2005	Well rusted	1	5
91	Local Entrepreneur (Narayan Pandey)	2003	Well rusted	1	8
92	Filters for families	2005	Well rusted	1	5
93	Filters for families	2005	Well rusted	1	11
94	Filters for families	2005	Well rusted	1	6
95	NRCS	2003	Well rusted	1	6
96	Filters for families	2005	Well rusted	1	8
97	Filters for families	2005	Well rusted	1	5
98	Filters for families	2005	Well rusted	1	4
99	Filters for families	2005	Well rusted	1	6
100	Filters for families	2005	Well rusted	1	9
101	Filters for families	2005	Well rusted	1	4
102	Filters for families	2005	Well rusted	1	5
103	Filters for families	2005	Well rusted	1	8
105	Filters for families	2004	Well rusted	1	8
106	Filters for families	2004	Well rusted	1	3
107	Filters for families	2006	Well rusted	1	12
108	Filters for families	2005	Well rusted	1	5
109	Filters for families	2005	Well rusted	1	10
112	Filters for families	2005	Well rusted	1	4
113	Filters for families	2005	Well rusted	1	6
114	Filters for families	2005	Well rusted	1	3
115	Filters for families	2005	Well rusted	1	6
116	Filters for families	2005	Well rusted	1	5
117	Filters for families	2005	Well rusted	1	6
118	Filters for families	2005	Well rusted	1	8
119	Filters for families	2005	Well rusted	1	4
120	Filters for families	2005	Well rusted	1	6
121	Filters for families	2005	Well rusted	1	5
122	Filters for families	2005	Well rusted	1	2
123	Filters for families	2005	Well rusted	1	8
124	Filters for families	2005	Well rusted	1	7
125	Filters for families	2005	Well rusted	1	4
126	Filters for families	2005	Well rusted	1	4

Filter Number	Filter Water Per Day (L)	Filte use	Filter cleaning Frequency	Date of last cleaning
4	45	everyday	When water is insuffient/once in every 2-3 months	20 days back
5	30	everyday	once in every two weeks	5 days back
6	20	everyday	once in a month	a month back
7	25	everyday	once in every two weeks	two week back
8	30	everyday	when water is insufficient/once in every 2-3 months	two months back
9	40	everyday	once in every two weeks	3 days back
10	30	everyday	once in a month	20 days back
11	30	everyday	once in a month	a month back
13	25	everyday	once in month	25 days back
14	over 50 litre	everyday	once in a month	a month back
15	30	everyday	once in a month	a month back
17	40	everyday	once in a month	23 days back
18	10	everyday	once in a month	more than a month
19	30	everyday	once in a two weeks	10 days back
21	over 50 litre	everyday	once in every 2-3 months	two months back
22	30	everyday	once in a month	a month back
23	30	everyday	once in every three month	two months back
24	50	everyday	once in two week	two weeks back
25	over 50 litre	everyday	once in a month	two weeks back
26	over 50 litre	everyday	once in a month	yesterday
27	40	everyday	once in a month	yesterday
28	50	everyday	once in a week	a week back
29	20	everyday	once in a month	yesterday
31	20	everyday	When water is insufficient/ 1-3 month	a month back
32	30	everyday	once in a month	15 days back
33	20	everyday	When water is insufficient/once in every 2-3 months	three months back
34	20	everyday	once in every two month	a month back
35	20	everyday	when water is insufficient/once in every 2-3 months	two months back
36	40	everyday	once in two month	No idea
37	20	everyday	when water is insufficent	two months back
41	20	everyday	once in every 2-3 months	25 days back
42	25	everyday	once in every 2-3 months	3 months back
43	35	everyday	once in every two weeks	10 days back
44	30	everyday	once in every 2-3 months	2 months back
45	25	everyday	once a month	a month back
46	30	everyday	once in every 2-3 months	45 days back
47	10	everyday	once in every 2-3 months	3 months back
48	over 50 litre		No idea	No idea
49	50	everyday	once in every 2-3 months	3 months back
50	35	everyday	Never	Never
51	25	everyday	once in every two weeks	12 days back
52	50	everyday	once in every 2-3 months	1 day back
53				
54	40	everyday	once in every 6 months	6 months back
55	35	everyday	once in every 2-3 months	two months back
56	40	everyday	once in every two weeks	7 days back
58	25	everyday	once in every 2-3 months	two months back
60	over 50 litre	everyday	once in a month	15 days back
61	20	everyday	once in every 2-3 months	two months back
62	30	everyday	once in every 2-3 months	two months back

Filter Number	Filter Water Per Day (L)	Filte use	Filter cleaning Frequency	Date of last cleaning
63	40	everyday	once in every 2-3 months	3 months back
65	12	everyday	Never	Never
66	over 50 litre	everyday	once in a month	a month back
70	25	everyday	once in every 4 month	two months back
71	35	everyday	Never	Never
72	over 50 litre	everyday	once in every 2-3 months	20 days back
73	40	everyday	once in every 2-3 months	a month back
74	40	everyday	once in every 2-3 months	a month back
76	40	everyday	once in every 2-3 months	15 days back
79	50	everyday	once in a month	12 days back
80	40	everyday	once in a month	a month back
81	over 50 litre	everyday	once in every 2-3 months	20 days back
82	over 50 litre	everyday	once in every 2-3 months	a month back
83	40	everyday	once in every 2-3 months	40 days back
84	over 50 litre	everyday	once in every 2-3 months	20 days back
85	40	everyday	once in every 2-3 months	2 months back
86	30	everyday	once in every two weeks	15 days back
87	40	everyday	once in a month	15 days back
91	over 50 litre	everyday	once in a month	15 days back
92	40	everyday	once in every 2-3 months	a month back
93	over 50 litre	everyday	once in a month	5 days back
94	50	everyday	once in a month	10 days back
95	40	everyday	once in a month	25 days back
96	50	everyday	once in every 2-3 months	a month back
97	30	everyday	once in a month	10 days back
98	30	everyday	once in a month	10 days back
99	50	everyday	once in a month	20 days back
100	40	everyday	once in every two weeks	8 days back
101	40	everyday	once in every two weeks	7 days back
102	35	everyday	once in every 2-3 months	45 days back
103	40	everyday	once in a month	one month ago
105	40	everyday	once in every two weeks	a months back
106	30	everyday	once in a month	15 days back
107	over 50 litre	everyday	once in every two weeks	12 days back
108	35	everyday	once in a month	a month back
109	30	don't uses during cold season	once in every two weeks	2 months back
112	20	everyday	once in every 2-3 months	a month back
113	32	everyday	once in every 7-8 months	5 months back
114	20	everyday	once in every 2-3 months	45 days back
115	over 50 litre	don't uses during cold season	once in every 2-3 months	2 months back
116	40	everyday	once in every 2-3 months	45 days back
117	50	everyday	once in every 4 month	4 months back
118	over 50 litre	don't uses during cold season	once in every 4 month	3 months back
119	40	don't uses during cold season	once in every 4 month	4 months back
120	30	everyday	once in every 4 month	4 months back
121	40	everyday	once in every 2-3 months	a month back
122	30	everyday	once in a month	a month back
123	40	everyday	once in every 2-3 months	a month back
124	over 50 litre	everyday	once in every 4 month	4 months back
125	40	everyday	once in every 4 month	a day back
126	36	everyday	once in a month	a month back

Filter Number	Remarks
4	
5	Some floating materials above sand layer
6	
7	
8	
9	
10	
11	Filter was not in use from 10 days becoz filter water is cold.
13	
14	
15	
17	
18	Filter was not in use from past 15 days due to cold water from KAF
19	
21	
22	
23	
24	
25	Low sand level (~1 inch less)
26	
27	Low sand level (~1 inch less)
28	Using tubewell of filter no. 24
29	
31	
32	
33	Low sand level (~1 inch less)
34	
35	
36	
37	
41	Low sand level (~1/2 inch less)
42	Arsenicosis symptom seen in HH member
43	Low sand level (~1/2 inch less)
44	Low sand level (~1/2 inch less)
45	Low sand level (~1/2 inch less)
46	Low sand level (~1/2 inch less)
47	Low sand level (~1/2 inch less)
48	Not in use since a month
49	
50	
51	
52	
53	Retest of filter no. 43
54	
55	
56	
58	
60	Nails more than 5 kg
61	Large nail size
62	

Filter Number	Remarks
63	Large nail size
65	Large nail size
66	
70	
71	
72	
73	absence of resting water level
74	
76	
79	
80	
81	
82	
83	
84	
85	
86	
87	
91	
92	
93	
94	
95	
96	Fine sand mixed with coarse sand
97	Filter was not in use from past 15 days due to cold water from KAF
98	
99	
100	
101	
102	
103	
105	
106	
107	
108	
109	Filter was not in use from past 2 months due to cold water from KAF
112	
113	
114	filter was not in use from past 1 months due to cold water from KAF
115	
116	
117	
118	Filter was not in use from past 2 months due to cold water from KAF
119	
120	Filter was not in use from past 4 months due to cold water from KAF
121	
122	
123	
124	
125	
126	

Appendix F : Data of Samples Not Used in the Present Study

Filter #	H20 sourse	As (ppb)	Fe(II) (ppm)	Sil (ppm)	pH (1)	pH (2)	Hard (2) ppm	Alk (ppm)	Cl (ppm)	Flow (L/min)	Notes (1):
1	GW	47	2.33	13.2	8	7.8	425	240+	0	0.91	too low GW [As], <50ppb
2	GW	39	2.98	17.7	8	7.2	425	240+	0		too low GW [As], <50ppb
3	GW	92	0.47	14.7	8	7.8	250	180	0		Filter type 4 discarted
	filter	8	0	11.9	7.5	7.2-7.8	120	120	0		
	after nails		0.84								
16	GW	200-300	3.75 OR	30.9	7.5	7.2	250-425	180	0	>0.5	flow too fast
20	GW	100			7	7.2	425	180	0	>0.5	flow too fast
30	GW	<10	2.04	9.5	7	7.2	425	240	0		too low GW [As], <50ppb
38	GW	0 UR	1.28	16	7	6.8	425	290	0	0.14	too low GW [As], <50ppb
39	GW	0 UR	1.78	13.5	7.5	6.8	425	280	0	0.30	too low GW [As], <50ppb
40	GW	13	4.24	18.5	7	6.8	425	280	0		too low GW [As], <50ppb
57	GW	200-300	1.2	14.4	7.5	7.2-7.8	425	280	0	0.08	flow too fast
59	GW	41	1.28	12.3	7.5	7.2-7.8	425	280	0	0.30	too low GW [As], <50ppb
64	GW	56	2.92	14.1	6.5	6.8	425	240	0	0.48	too low GW [As], <50ppb
67	GW	39	3.66	22.5	7	7.2	425	240	0	0.48	too low GW [As], <50ppb
68	GW	48	4.04	15.1	7	7.2	425	240	0	0.30	too low GW [As], <50ppb
69	GW	42	5.32	17.4						0.38	too low GW [As], <50ppb
75	GW	12			6.5	7.2	425	240	0	0.31	too low GW [As], <50ppb
77	GW	2	4.5 OR	12.3	6.5	6.8	425	240	0	0.28	too low GW [As], <50ppb
78	GW	37		14.6	7	7.2	250	240	0		too low GW [As], <50ppb
88	GW	0									too low GW [As], <50ppb
89	GW	0									too low GW [As], <50ppb
90	GW	47									too low GW [As], <50ppb
104	GW	28	2.67	15.5	7.5	7.2-7.8	425	240	0	0.13	too low GW [As], <50ppb
110	GW	41			7.5	7.8-8.4	425	240	0		too low GW [As], <50ppb
111	GW	19	3.56 OR	25.2	7.5	7.8-8.4	425	240	0	0.23	too low GW [As], <50ppb

Filter No.	Date	District	VDC	Ward No.	Tole	Type of KAF	Name of the Household owner
1	Jan. 9, 2011	Nawalparasi	Tilakpur	7	Patkhauli	Concrete square	Netra Narayan Chaudhary
2	Jan. 9, 2011	Nawalparasi	Tilakpur	7	Patkhauli	Concrete square	Amar Narayan Chaudhary
3	Jan. 9, 2011	Nawalparasi	Tilakpur	7	Patkhauli	Plastic square	Baliram Chaudhary
16	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Plastic square	Bishwonath Chaudhary
19	Jan.11, 2011	Nawalparasi	Pratappur	1	Khaireni/Tharu	Gem 505	Govinda Chaudhary
30	Low Arsenic						
38	Jan. 14, 2011	Nawalparasi	Swathi	8	Swathi	Gem 505	Sima Chaudhary
39	Jan. 14, 2011	Nawalparasi	Swathi	8	Swathi	Gem 505	
40	Jan. 14, 2011	Nawalparasi	Swathi	8	Swathi	Gem 505	
57	Jan. 16, 2011	Nawalparasi	Bhutaha				
59	Jan. 16, 2011	Nawalparasi	Bhutaha				
64	Jan. 17, 2011	Nawalparasi	Tilakpur	7	Pathkhouli	Gem 505	Dinesh Chaudhary
67	Jan. 17, 2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Nawodurga Primary School
68	Jan. 17, 2011	Nawalparasi	Sunwal	3	Naduwa	Gem 505	Nawodurga Primary School
69	Jan. 17, 2011						
75	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Krishna Pageni
77	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Ram Prasad Mishra
78	Jan. 18, 2011	Nawalparasi	Makar	8	Laghuna	Gem 505	Uday Bdr. Lamichane
88	Jan. 20, 2011	Rupandehi	Rudrapur	4	Gargare	Concrete square	Buddhadeep English Boarding School
89	Jan. 20, 2011	Rupandehi	Rudrapur	4	Gargare	Concrete square	Buddhadeep English Boarding School
90	Jan. 20, 2011	Rupandehi	Rudrapur	4	Bargadhawa	Concrete square	Dinanath Acharya
104	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Shiwangadh	Gem 505	Sukhed Ansari
110	Jan. 22, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Hari Harijan
111	Jan. 23, 2011	Nawalparasi	Ramgram Municipality	13	Paratikar	Gem 505	Laxman Harijan

Filter No.	KAF provided by	Installed Date	Quality of Iron nails	No. of Households	Number of Users
1	Local entrepreneur (Raju Bishwo)	2007	Well rusted	1	6
2	Local entrepreneur (Raju Bishwo)	2007	Well rusted	1	2
3	NRCS	2003	Well rusted	1	6
16	Filters for families	2003	Well rusted	1	7
19	Filters for families	2007	Well rusted	1	4
30					
38	DWSS	2010	Well rusted	1	4
39	DWSS	2010	Well rusted	1	
40	DWSS	2010	Well rusted	1	
57					
59				1	
64	DWSS	2010	Well rusted	1	2
67	Filters for families	2007	Well rusted	1	120 students
68	Filters for families	2007	Well rusted	1	120 students
69	No arsenic		Well rusted		
75	DWSS	2010	Well rusted	1	4
77	DWSS	2010	Well rusted	1	3
78	DWSS	2010	Well rusted	1	8
88	Local Entrepreneur (Narayan Pandey)	2007	Well rusted	1	total 42 teachers and 900 student
89	Local Entrepreneur (Narayan Pandey)	2007	Well rusted	1	total 42 teachers and 900 student
90	Local Entrepreneur (Narayan Pandey)	2003	Well rusted	1	5
104	Filters for families	2005	Well rusted	1	6
110	Filters for families	2005	Well rusted	1	5
111	Filters for families	2005	Well rusted	1	4

Filter No.	filter water per day(in. lit)	Filte use	Filter cleaning Frequency	Date of last cleaning
1	30	everyday	When water is insufficient once in every 2-3 months	a month back
2	10	everyday	when flow rate drops/once in every 2-3 months	15 days back
3	45	everyday	once in a month	a month back
16	40	everyday	once in every 4 month	2 months back
19	30	everyday	once in a two weeks	10 days back
30				
38	20	everyday	once in every two weeks	10 days back
39				
40				
57				
59				
64	40	everyday	Never	Never
67	over 50 litre	not use during vacation	once in every 2-3 months	45 days back
68	over 50 litre	not use during vacation	once in every 2-3 months	45 days back
69				
75	30	everyday	once in every 2-3 months	20 days back
77	30	everyday	once in every 2-3 months	10 days back
78	over 50 litre	everyday	once in every 2-3 months	a month back
88	over 50 litre	everyday	once in every 2-3 months	20 days back
89	over 50 litre	everyday	once in every 2-3 months	20 days back
90	40	everyday	once in every 2-3 months	45 days back
104	30	everyday	once in every 2-3 months	3 months back
110	20	everyday	once in a month	15 days back
111	20	everyday	once in every 2-3 months	2 months back

Filter No.	Remarks
1	Arsenic concentration below 50 ppb
2	Arsenic concentration below 50 ppb
3	
16	
19	
30	Low arsenic
38	Low As concentration in GW
39	Low As concentration in GW
40	Low As concentration in GW
57	
59	Low Arsenic in GW
64	
67	
68	
69	Low Arsenic in GW
75	
77	
78	
88	
89	
90	
104	
110	
111	

Appendix G : KAF Trouble Shooting

The focus of the present study was to evaluate the performance of the KAF though various groundwater quality conditions, yet many poorly performing filters were excluded from this study due to mechanical and social modifications, roughly encompassing 30% of the total observed filters in the field. Many of the structural failures are presented in the pictorial diary below:

Cracks

A number of KAFs had physical defects so they were excluded from this study. This refers to cracks in the filter body or in the components. In addition, some pieces were broken off, like the spout on the GEM 505 model.

Figure G-1: Crack across the external structure of the concrete round KAF model, and across the diffuser lid, holding the nails, of the GEM 505 KAF model (to the right of the dotted line).

Taps

There were also modifications made to the KAF models, such as adding a tap into the filter effluent spout such that the filtered water will flow as needed without adding in more source water. This addition was most common in the concrete KAF models.

Figure G-2: Copper tap and plastic tap installed into the concrete square KAF model.

Sand

In other cases it was observed that the sand layer inside the KAF was not sufficient. This may be due to the user removal of the sand to increase flow rate or not enough sand was provided by the distributer, as was in one occasion. Also, the sand layers were not always stacked correctly and we observed a mixture of fine and course sand at the top layer.

Nails

It is common for the nails to solidify after rusting but this will not affect the mechanism of the KAF so long as the nails remain evenly spread out and allowing water to flow through the diffuser basin. In some cases, we observed that the nails solidified with large gaps such that the influent water could flow into the sand layers without having contact with the nails. This was caused by the repeated poring of influent water without the presence of large bricks (also evenly spread out) to break the incoming force of the water. In this case, it is advised to remove the nails, break them off and spread them out evenly throughout the basin. Other times, we observed the absence of nails altogether.

Figure G-3: Solidified nails with a gap in diffuser or the absence of nails.

Appendix H : Social Issues Observed

In addition to structural or mechanical failures in several of the observed KAFs in the field, many social habits added to the effectiveness of the KAF. Several of the modifications made to the filter were clear misunderstandings on how the filter worked. For example, locals would remove nails or sand in the filter to speed up the filtered water flow rate without knowing that these actions would affect the filter's performance. This lack of knowledge and care for the filter was observed more predominantly with locals who had received the KAF for free or though subsidy programs, and with those who in villages without an obvious cases of arsenicosis. On the contrary, locals who purchased their own filter or were suffering from arsenicosis did value the filter and tried to keep it well maintained. Another surprising issue encountered was the notion of not using the KAF during the winter season. Since the groundwater temperature remained a steady 20^{0} C even during the cold ambient temperatures, this warm water was more desirable than cold filtered water. Overall, a lack of education on the importance of groundwater filtration and also in the function of an arsenic removing filter, was observed.