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Improved Human Health Risk Characterization for Regions with Arsenic-Contaminated Groundwater

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Abstract

Widespread installation of shallow tube wells to provide microbially–safe groundwater has exposed some rural populations in Bangladesh to high arsenic concentrations in their drinking water. Arsenic concentrations in groundwater are shown to be statistically significant ($r^2 = 0.32$) at explaining arsenicosis rates in the rural populations. Comparable, and statistically significant explanations of arsenicosis rates in the populations, are also demonstrated using the ratio of arsenic concentration divided by iron concentration ($r^2 = 0.32$). While competition exists between arsenic and other chemicals including phosphate, manganese, sulfate, and silicate, issues of interference are not evident in explaining arsenicosis rates. The strength of the relationship between arsenicosis rates and the ratio of arsenic/iron concentrations has value in focussing efforts to remediate groundwater for purposes of water consumption.

1. Introduction

Contaminants in surface waters complicate the challenges in providing sustainable, safe water supplies to the rural poor in many countries. Further, in many south Asian countries, surface water is relatively abundant but is highly impacted by microbial pollution. In response, there were ten million tube wells placed in Bangladesh in the early 1980s (Sambu and Wilson, 2008), to access the shallow groundwater for water supply for the rural populations. However, the widespread implementation of tube wells was later determined to be highly problematic due to high arsenic contamination at many locations in the groundwater in Bangladesh.

Long-term exposure to inorganic arsenic in drinking water may lead to a number of serious health problems, including a long list of cancers: bladder, kidney, liver, prostate, skin, and lung cancer (BGS, 2008). It is reported that 97% of rural Bangladeshis obtain drinking water from the groundwater. Studies in 2008 found that 30% of 4.7 million tested tubewells contained arsenic above the Bangladesh standard of 50 μg/L (NAISU, 2003; UNICEF, 2008). About 46% of 3500 tested wells in another nationwide survey exceeded the World Health Organization (WHO) guideline of 10 μg/L (NAISU, 2003). Further, the British Geological Survey [2001] reported that 35% exceeded the WHO guideline in this same survey. As a result, it is estimated that between 21 and 40 million people are exposed to arsenic in drinking water at concentrations exceeding the Bangladesh standard (Safiuddin and Karim, 2001; WHO, 2001; Smedley and Kinnibiargh, 2007, Caldwell et al., 2005), although the real numbers may be as high as 77 million (WHO, 2002). Furthermore, it is estimated that 42-70 million people are exposed to drinking water with arsenic above 10 μg/L (Samba et al., 2008; Caldwell et al., 2005). Similar findings have been realized in numerous other countries including Taiwan, India (West Bengal), China, Thailand, Viet Nam, Laos, Myanmar, Nepal and Cambodia.

In parallel with the above-mentioned arsenic exposures, since the discovery of arsenic in Bangladesh's drinking water in 1993, hydrogeological investigations have been undertaken to characterize the extent of arsenic contamination (NAISU, 2003). As well, patient studies have been conducted to determine how many people are suffering from arsenicosis, the term used for arsenic poisoning. Health professionals are generally mostly concerned about areas with a high prevalence of patients, whereas hydrogeologists are concerned about areas with high arsenic concentrations in groundwater. To some extent, there is an expectation that high arsenicosis rates are associated with high arsenic concentrations. However, the situation is considerably more complicated because arsenic in ground water is not necessarily equivalent to arsenic in drinking water; aeration of water during "groundwater extraction to the point of consumption" may occur as oxidation may result in co-precipitation of iron and arsenic as a result of the aeration (see Brennan and McBean, 2011a). Further complications may arise due to interference from phosphates (see Brennan and McBean, 2011b)

Of interest is to assess the degree to which arsenicosis is related to arsenic concentrations in groundwater (and other constituents) where, the resulting information could have potential to develop improved collaboration between health professionals and hydrogeologists to focus remedial efforts where the benefits would be greatest.

2. Background on Data Assembly

In Review of Data on the Status of Arsenic Pollution and Arsenic Mitigation in Bangladesh for Revision of the Implementation Plan for Arsenic Mitigation 2009, Ahmed and Ravenscroft (2009) prepared an outline of the major activities and reported no correlation between the percentage of arsenic-contaminated wells and the number of arsenicosis patients in each upazila (sub-district) in Bangladesh. However, as described below, there are, in fact, statistically significant relationships available. To assess the degree of causal relationship, analyses were undertaken as described in the paragraphs below.

Bangladesh is grouped into divisions, which are subdivided into districts, which are further subdivided into upazilas. In the entire country, there are 483 upazilas, 64 districts, and 7 divisions (BBI, 2011). In Bangladesh, there is a large degree of spatial variability of arsenic contamination (Smedley and Kinniburgh, 2001), even within relatively short distances (m to km according to BGS (2000)). The spatial variability is the result of many factors including varying tubewell depths, local and regional geology, and local redox conditions (VanGeen et al., 2003). Given the large differences in arsenic concentrations that exist on a small spatial scale, for analyses of correlations, the smaller the resolution of the data the better; for the assessment described herein, upazila-level data were the smallest level for which data were available. District-level analysis would tend to obscure trends, as one upazila may have high rates of arsenicosis and a neighboring upazila may have low rates. As a result, correlations between hydrogeological data from the National Hydrochemical Survey data and arsenicosis patient data from the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) are assessed herein at the upazila level.

With data reported from 270 upazilas, patients were identified based on the manifestation of arsenicosis symptoms (Ahmed and Ravenscroft, 2009). These survey data would have identified only the skin lesions and pigmentation that can result from chronic exposure to high arsenic concentrations but not have identified internal cancers as a result of arsenic exposure. Further, the population of each upazila was used to convert patient data into patients/1000, to represent arsenicosis prevalence. The BAMWSP project also collected data on the percentage of contaminated wells for a number of upazilas, based on field test kit results (Ahmed and Ravenscroft, 2009), information which is used below.

The National Hydrochemical Survey (NHS) in 1998-1999 collected water samples from 7-8 randomly selected wells in each of 433 upazilas, totalling 3534 wells (Ahmed and Ravenscroft, 2009). Samples were collected primarily from shallow wells, although samples from deep wells were collected in the coastal areas (Ahmed and Ravenscroft, 2009). While it is recognized that there are shortfalls in using hydrogeological data with only 7 to 8 wells in each upazila, given the high spatial variability of arsenic (and other chemicals in the groundwater), the NHS data were the most extensive hydrogeologic data set available, from the British Geological Survey website (BGS, 2001).

Along with investigating hydrogeology on a national scale, three Special Study Areas from the NHS were also examined in more detail by the same investigators (the British Geological Survey, BGS, and the Department of Public Health Engineering, DPHE, of the Government of Bangladesh). More wells were tested, and more parameters were analyzed in these areas in comparison with other areas in the nationwide survey. Results of assessment of correlations between arsenicosis prevalence and hydrogeological parameters at these three Special Study Areas are also described below.

Monitoring well data were averaged ('less than' detection data for each chemical were taken as one-half the detection limit, for purposes of subsequent calculations) for each upazila for each of the parameters of arsenic, iron, phosphorus, silicate, manganese and sulfate using the Pivot Table function in Microsoft Excel. Along with averages of the above data, the percentage of contaminated wells (as characterized by concentrations in excess of [As]≥50 µg/L, the Bangladesh standard) was calculated,

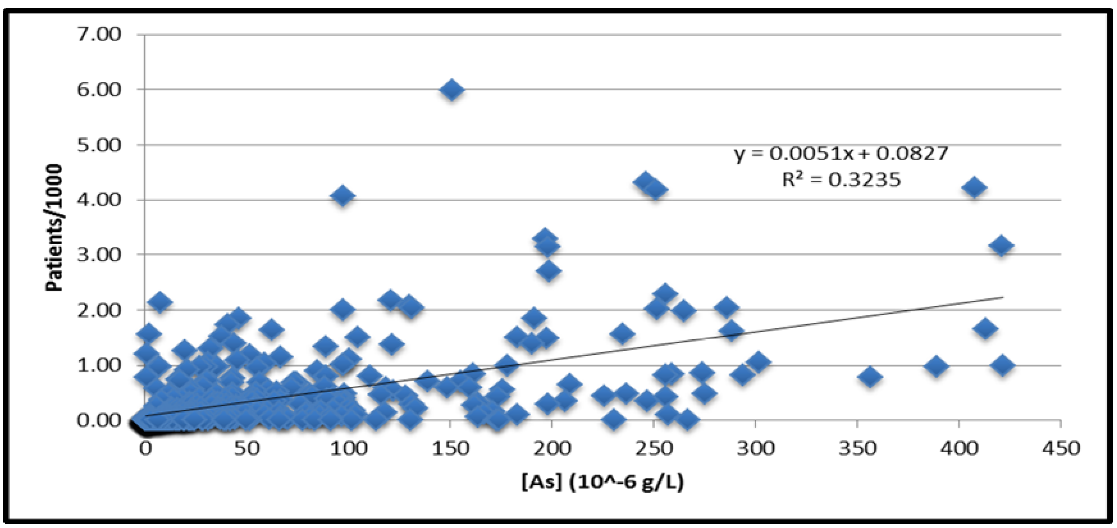

Fig.1. Arsenicosis Patient Incidence vs. Arsenic Concentration in Groundwater

As illustrated in Fig.1 where Arsenicos is Patient/1000 population within the upazila is plotted against arsenic concentrations in groundwater, there is a statistically significant correlation (r^2=0.32), indicating that, in fact, arsenic concentrations in groundwater are indeed, statistically significant in explaining rates of arsenicosis. Further, when the ratios of concentrations of arsenic/iron are plotted as in Figure 2, versus arsenicosis data, the correlation is similar (r^2=0.32).

The critical t-statistic for statistical significance of the correlation, with n- 2 degrees of freedom (McBean and Rovers, 1998), is

$$t^* = r\,\frac{\sqrt{n-2}}{\sqrt{1-r2}}$$

For $r^2 = 0.32$, $r = 0.57$, $n = 433$, the correlation is statistically significant. $t^* = 14.4$
It follows that the presence of high iron, in combination with the oxidation of the groundwater which occurs as the water is brought to the surface, is important in decreasing arsenicosis rates through co-precipitation of arsenic and iron.

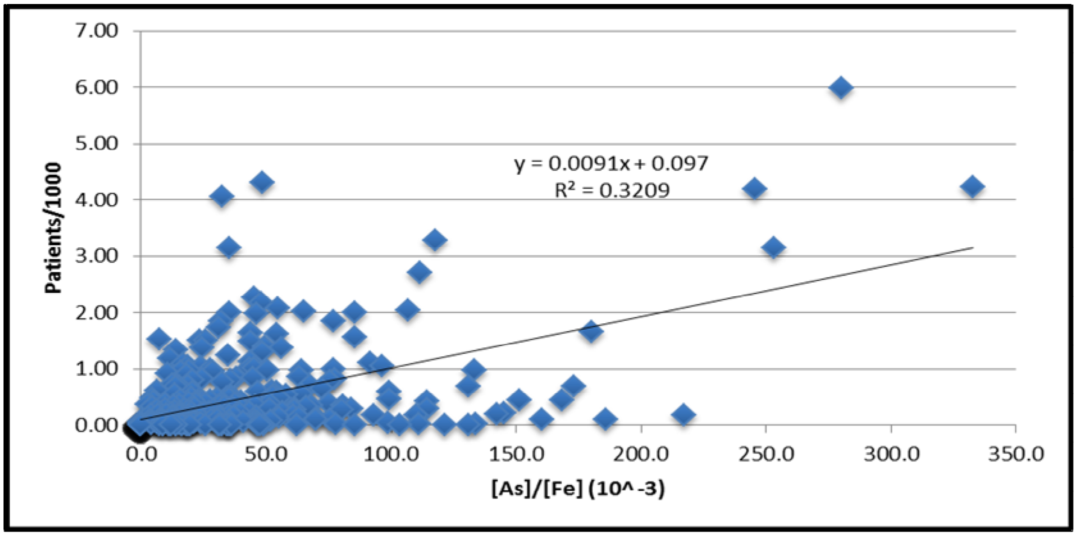

Fig.2. Arsenicosis Patient Incidence vs. Ratio of [As]/[Fe] Concentrations

Of interest is the degree to which there may exist interference with arsenic from other constituents such as phosphates, silicates, manganese and sulfate. Table 1 summarizes the R^2 – values over n = 433 upazilas for the individual constituents with arsenicosis rates of incidence. Two sets of analyses are indicated in Table 2, one including all wells (column 2) and other (column 3) only when arsenic is greater than 50ug/L. These findings indicate that only arsenic in groundwater is significant at explaining arsenicosis rates and the other constituents (phosphates, silicates, manganese and sulfate) are not demonstrating large influence (by interference in co-precipitation of iron) on observed arsenicosis rates.

Table1. R^2 Values of select Parameters as correlated to Arsenicosis Rates in 433 Upazilas.

Chemical	R2 Values	
	All Wells	Contaminated Wells
Phosphate	0.015	0.066
Silicate	0.021	0.128
Manganese	0.002	0.026
Sulfate	0.003	0.034
Arsenic	0.323	0.228
n = 433		

A scatterplot in Fig. 3, demonstrates that arsenic and phosphates in groundwater are not highly correlated, further supporting that interference between arsenic and phosphate for co-precipitation with iron doesn't appear to be occurring to a large extent.

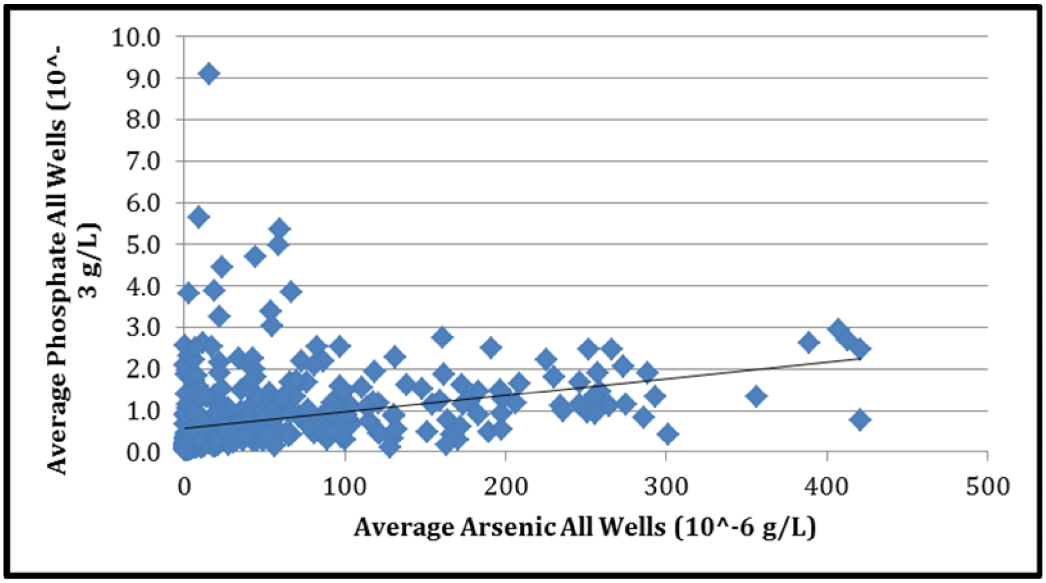

Fig.3. Average Phosphorus Concentration vs. Average Arsenic Concentration for All Wells in 433 Upazilas.

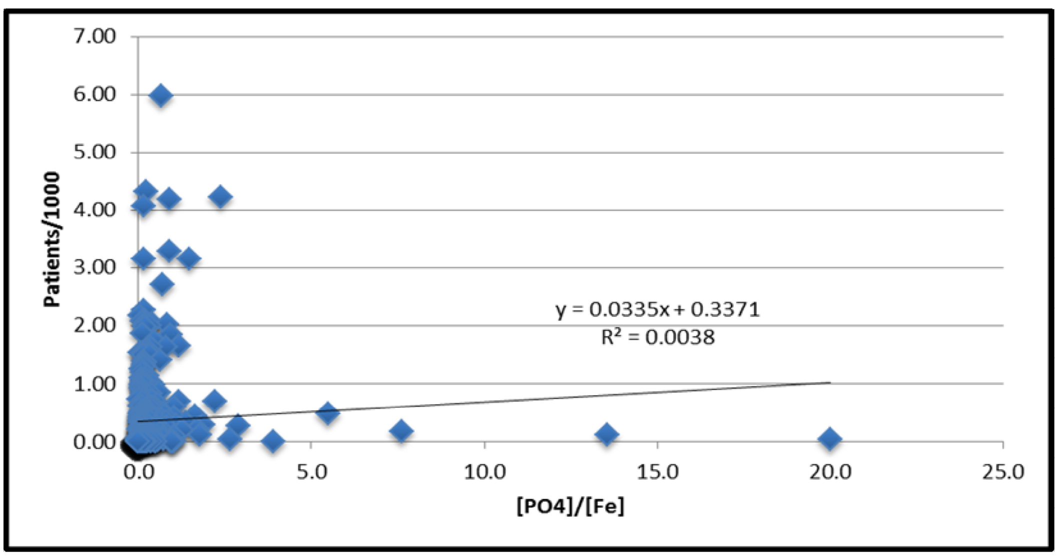

Fig.4. Arsenicosis Patient Incidence vs. Ratio of [PO4]/[Fe]

Further, as illustrated sites in Fig.4, the correlation between arsenicosis rates and rates of phosphate/iron is not statistically significant evidence that phosphates in groundwater substantially interfere with arsenic, resulting in high arsenicosis rates in rural populations.

To further explore possibilities to explain the relative magnitudes of arsenicosis, reflecting the importance of high iron, a histogram of iron concentrations across all upazilas is depicted in Fig.5.

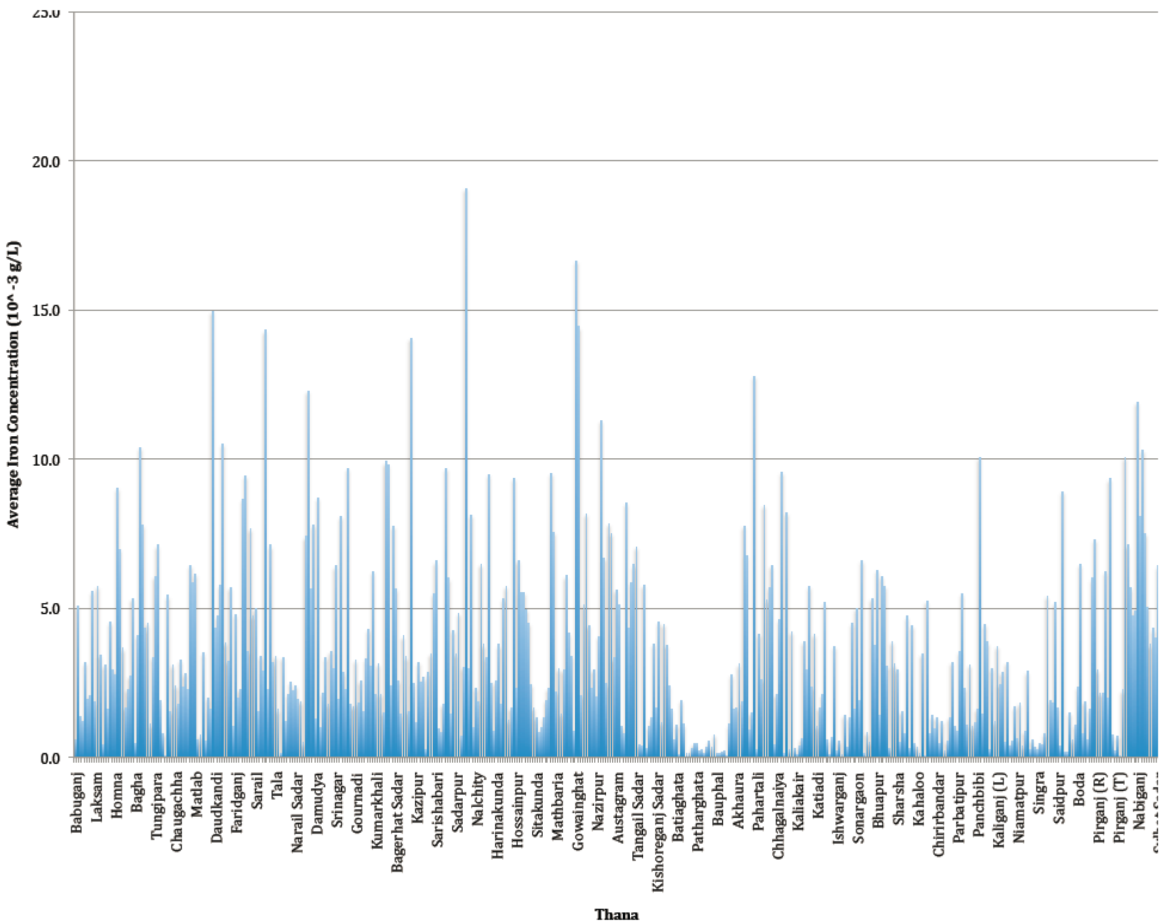

Fig.5. Histogram of Iron Concentrations for Various Upazilas

The variations of iron concentrations across Bangladesh are shown to be high, with significant numbers of upazilas with low iron. Given the statistical significance of the inverse of iron concentrations in explaining arsenicosis rates, the utility of iron as an explanatory variable is evident and hence, should be included as contributory evidence where efforts at removal of arsenic in groundwater by Arsenic-Iron Removal Plants would be best focused.

3 Conclusions

In assessing whether high incidence of arsenicosis is likely, high concentrations of arsenic in groundwater are shown to be strongly linked with high rates of arsenicosis (statistically significant). As well, a statistically significant indicator of arsenicosis rates is the ratio of arsenic/iron Patterns observed in correlations between arsenic and iron (inversely) and the prevalence of arsenicosis patients indicates that iron concentrations, along with arsenic concentrations in the groundwater, are useful measures, for determining the prevalence of arsenicosis and hence risk to the rural populations. The findings indicate that efforts to remediate groundwater can be focused on locations where the ratios of arsenic/iron concentrations are the highest.

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