Human Health Risk Assessment: Arsenic Exposure Risks in Bangladesh

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Abstract: Arsenic-caused cancers in Bangladesh, arising from both water and food sources of arsenic (*As*) are characterized. The results indicate countrywide incremental *As* cancer cases as 1.27 million, a number which will increase by 1.2% per year unless a sustainable removal technology for *As* from groundwater is implemented. The site-specific magnitude of the incremental cancer, driven by local groundwater conditions is demonstrated where, for example, in Chandpur, 4% of the districts' population will develop cancer due to *As* intake.

On average, 46% of the *As* body burden for Bangladeshis comes directly from water and 54% from food, although the range of percentages varies significantly from one district to the next, from a low of 0% water-based intake (indicating entire body burden from food sources) in the district of Dhaka, to a high of 91% in Chandpur. It is noteworthy that residents of Dhaka, since they are only exposed to food-related *As*, will see an estimated 42,000 incremental cancer cases.

Treating drinking water to the Bangladeshi standard of 50µg/L would decrease incremental cancer cases in Bangladesh by 353,000; further reduction to the WHO standard of 10µg/L would reduce the number of incremental cancer cases by an additional 298,000.

Keywords: Risk, arsenic, cancer, Bangladesh.

1. INTRODUCTION

Among the ninety-eight naturally-occurring elements, metalloid arsenic (*As*) ranks 20th and 12th for its presence in the earth's crust and the human body, respectively [1]. Since arsenic is carcinogenic, concern exists with long-term exposure to high levels of arsenic due to the increased risk of cancer in the skin, lungs, bladder and kidney. Arsenic is lethal for humans in high doses; additionally, chronic exposure may cause a debilitating condition called arsenicosis, a disease which is characterized by moderate to severe skin lesions, vascular problems such as blackfoot disease, heart disease and diabetes [2]. The oxides of arsenic pose the greatest threat to human health, since arsenite and arsenate salts are the most toxic. These forms of *As* are components of geologic formations and enter the ambient ground water, a phenomena which is evident in many countries, including Bangladesh, India, Cambodia, Vietnam, and Nepal. Hence, although arsenic poisoning can be related to human activities such as mining and ore smelting, the most serious problems to populations-at-large are exposures resulting from water wells drilled into aquifers that have high concentrations of naturally occurring arsenic and/or foods irrigated with *As*-contaminated water. The UN has declared sustainable development goals (SDGs) pertaining to both safe drinking water and food [3]. The SDGs outline specific benchmarks to be achieved by 2030. Specifically, goal 2.1: the provision of nutritious and safe food to people in vulnerable situations; and goal 3.3: to end the epidemic of water-related diseases; require addressing the issue of *As* contaminated food and groundwater [3].

Starting three decades ago, to decrease exposure of the Bangladeshi population to microbial contamination in surface water, ten million tubewells have been implemented in Bangladesh, with the intent to access shallow groundwater for water supply [4]. The result is that presently, the rural populations of Bangladesh rely on the *As*-contaminated groundwater for drinking, cooking, and irrigation. The shallow groundwater in the Bengal basin, which covers most of Bangladesh and part of the Indian state of West Bengal, is severely contaminated with *As* [5, 6]. As a result, with the change to reliance upon groundwater, preventing exposure to arsenic is difficult in Bangladesh, one of the most densely populated countries in the world. It is noted that the water supply of Dhaka is drawn from very deep hydrogeologic horizons, and hence the exposure to *As*-impacted groundwater is only relevant to the remainder of the Bangladeshi population.

The World Health Organization has called arsenic contamination of groundwater in Bangladesh "the largest mass poisoning of a population in history, as countless new wells continue to be dug here daily

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without testing the water for toxins" [7]. The terrible irony is that this problem is the result of an idealistic push to clean up drinking water (i.e. avoid exposure to waterborne pathogens in the surface water) for some of the world's poorest people. A recent study published in a British medical journal, The Lancet, stated that up to 77 million people in Bangladesh are being exposed to toxic levels of arsenic, potentially taking years or decades off their lives [8].

As Joseph *et al*. [9] has indicated, exposure pathways to arsenic are not restricted to the consumption of contaminated groundwater. *As* intake into the human body may occur through ingestion of contaminated food, beverages, drinking water, and soil, through inhalation of contaminated air and dust and potentially, through dermal contact with contaminated environmental media. However, as Joseph *et al*. [9] has shown, for the adult population in Bangladesh, *As* intake occurs primarily through consumption of contaminated water and food (incidental soil ingestion, betel quid chewing, and cigarette smoking offer additional intake pathways, but their individual contribution to daily *As* intake is of lesser significance).

"The magnitude of the arsenic problem is 50 times worse than Chernobyl" (985,000 cancer-related deaths), said Richard Wilson, president of the nonprofit Arsenic Foundation and a physics professor emeritus at Harvard University who was not involved in this study but, as Wilson says"…it doesn't have 50 times the attention paid to it."

Given the exposures related to water supply and food, this paper examines the incremental excess lifetime cancer risk of the Bangladeshi population.

2. MATERIALS AND METHODS

To characterize the country-wide exposure pattern to *As*, one must understand the variability in groundwater concentrations. Specifically, Bangladesh is grouped into divisions, which are subdivided into districts, which are then further subdivided into upazilas. In the entire country, there are 483 upazilas, 64 districts, and seven divisions. Arsenic concentrations in groundwater show a large degree of spatial variability as indicated in Table **1** (see Columns I through IV, indicating *As* groundwater concentrations from the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) [10]). Substantial variabilities in *As*-concentrations are evident; the spatial variability is the result of many factors including varying tubewell depths, local and regional geology, and local redox conditions [11]. Attempts to relocate groundwater withdrawals to avoid the groundwater impacted by arsenic have been found to be impossible in many locales. As an example, more than 90% of all tubewells in Samta, Bangladesh were contaminated with arsenic exceeding the Bangladesh standard of 50µg/L for drinking water [12]. It is estimated that 42 – 60 million people consume water at arsenic levels greater than 10µg/L [4,13]. The correlations between hydrogeological and chemical data from the National Hydrochemical Survey and arsenicosis patient data from the BAMWSP at the upazila level have been considered [14,15] and the report by Ahmed and Ravenscroft [16] provided the data on arsenicosis patients obtained during the BAMWASP project, indicating that 35 million people were likely to be affected by arsenic in Bangladesh.

While the above information is important, as groundwater is the originating exposure source of the arsenic in Bangladesh, the groundwater is used for irrigation of crops which, in turn, become contaminated with arsenic. Importantly, taking into consideration the current nutritional status of the adult population in the country, a critical assessment of the effect of desirable dietary intake recommendations on *As* exposure is described in Joseph *et al*. [9]. Joseph *et al*. [9] qualifies and quantifies these arsenic intake pathways through analysis of the range of arsenic levels observed in different food types, water, soil, and air in Bangladesh, and highlights the contributions of dietary intake variation and cooking method in influencing arsenic exposures. Joseph *et al*. [9, 17] also highlight the potential of desirable dietary patterns and intakes in decreasing arsenic exposure, which is relevant to Bangladesh, where nutritional deficiencies and lower-than-desirable dietary intakes continue to be a major concern. In evaluating the contributions of each intake pathway to average daily arsenic intake, the results show that food and water intake combined, make up approximately 98% of the daily arsenic intake with the balance contributed to by intake pathways such as tea consumption, soil ingestion, and quid consumption.

It is noteworthy that given the relatively recent knowledge of arsenic presence in groundwater, many attempts have been taken to remove arsenic from the groundwater; unfortunately, many of these methodologies have not performed as intended. For example, Arsenic-Iron Removal Plants (AIRPs) have the potential to provide a simple and relatively inexpensive method of removing arsenic from drinking water; however, these decentralized water treatment

Table 1: The population of Bangladeshi Districts, Arsenic Contamination of Water Supply Wells (Bangladesh Arsenic Mitigation Water Supply Project) and Relevant Human Health Risk Assessment Data

I	II	III	IV	V	VI	VII	VIII	IX
Division	District	Population (2011)	Arsenic Conc. (µg/L)	IECLR	# of Cancer Cases	Population Affected (%) (Current)	Population Affected (%) (50µg/L treatment)	Population Affected (%) (10µg/L treatment)
Barisal	Barguna	892,781	1	3.60E-03	3210	0.36%	0.36%	0.36%
	Barisal	2,324,310	92	1.27E-02	29507	1.27%	0.85%	0.45%
	Bhola	1,776,795	10	4.50E-03	7987	0.45%	0.45%	0.45%
	Jhalakati	682,669	23	5.80E-03	3956	0.58%	0.58%	0.45%
	Patuakhali	1,535,854	3	3.80E-03	5829	0.38%	0.38%	0.38%
	Pirojpur	1,113,257	30	6.50E-03	7231	0.65%	0.65%	0.45%
Chittagong	Brahamanbaria	2,840,498	101	1.36E-02	38617	1.36%	0.85%	0.45%
	Chandpur	2,416,018	366	4.01E-02	96870	4.01%	0.85%	0.45%
	Chittagong	7,616,352	32	6.70E-03	50991	0.67%	0.67%	0.45%
	Comilla	5,387,288	142	1.77E-02	95328	1.77%	0.85%	0.45%
	Cox's Bazar	2,289,990	3	3.80E-03	8691	0.38%	0.38%	0.38%
	Feni	1,437,371	54	8.90E-03	12785	0.89%	0.85%	0.45%
	Lakshmipur	1,729,188	179	2.14E-02	36996	2.14%	0.85%	0.45%
	Noakhali	3,108,083	162	1.97E-02	61214	1.97%	0.85%	0.45%
Dhaka	Dhaka[1]	12,043,997	41	3.50E-03	42094	0.35%	0.35%	0.35%
	Faridpur	1,912,969	140	1.75E-02	33467	1.75%	0.85%	0.45%
	Gazipur	3,403,912	4	3.90E-03	13258	0.39%	0.39%	0.39%
	Gopalganj	1,172,415	187	2.22E-02	26022	2.22%	0.85%	0.45%
	Jamalpur	2,292,674	14	4.90E-03	11223	0.49%	0.49%	0.45%
	Kishoreganj	2,911,907	52	8.70E-03	25319	0.87%	0.85%	0.45%
	Madaripur	1,165,952	191	2.26E-02	26345	2.26%	0.85%	0.45%
	Manikganj	1,392,867	24	5.90E-03	8211	0.59%	0.59%	0.45%
	Munshiganj	1,445,660	189	2.24E-02	32376	2.24%	0.85%	0.45%
	Narayanganj	2,948,217	48	8.30E-03	24455	0.83%	0.83%	0.45%
	Narsingdi	2,224,944	41	7.60E-03	16898	0.76%	0.76%	0.45%
	Netrokona	2,229,642	40	7.50E-03	16711	0.75%	0.75%	0.45%
	Rajbari	1,049,778	49	8.40E-03	8813	0.84%	0.84%	0.45%
	Shariatpur	1,115,824	151	1.86E-02	20749	1.86%	0.85%	0.45%
	Sherpur	1,358,325	22	5.70E-03	7736	0.57%	0.57%	0.45%
	Tangail	3,605,083	20	5.50E-03	19810	0.55%	0.55%	0.45%
Khulna	Bagerhat	1,476,090	156	1.91E-02	28186	1.91%	0.85%	0.45%
	Chuadanga	1,129,015	79	1.14E-02	12865	1.14%	0.85%	0.45%
	Jessore	2,764,547	70	1.05E-02	29014	1.05%	0.85%	0.45%
	Jhenaidah	1,771,304	46	8.10E-03	14339	0.81%	0.81%	0.45%
	Khulna	2,318,527	35	7.00E-03	16218	0.70%	0.70%	0.45%
	Kushtia	1,946,838	104	1.39E-02	27051	1.39%	0.85%	0.45%
	Magura	918,419	28	6.30E-03	5781	0.63%	0.63%	0.45%
	Meherpur	655,392	116	1.51E-02	9893	1.51%	0.85%	0.45%
	Narail	721,668	88	1.23E-02	8873	1.23%	0.85%	0.45%
	Satkhira	1,985,959	133	1.68E-02	33354	1.68%	0.85%	0.45%

Table 1 continued…

I	II	III	IV	V	VI	VII	VIII	IX
Division	**District**	**Population (2011)**	**Arsenic Conc. (μg/L)**	**IECLR**	**# of Cancer Cases**	**Population Affected (%) (Current)**	**Population Affected (%) (50μg/L treatment)**	**Population Affected (%) (10μg/L treatment)**
Rajshahi	Bogra	3,400,874	18	5.30E-03	18008	0.53%	0.53%	0.45%
	Dinajpur	2,990,128	3	3.80E-03	11348	0.38%	0.38%	0.38%
	Gaibandha	2,379,255	22	5.70E-03	13550	0.57%	0.57%	0.45%
	Jaipurhat	913,768	1	3.60E-03	3285	0.36%	0.36%	0.36%
	Kurigram	2,069,273	22	5.70E-03	11785	0.57%	0.57%	0.45%
	Lalmonirhat	1,256,099	1	3.60E-03	4516	0.36%	0.36%	0.36%
	Naogaon	2,600,157	6	4.10E-03	10648	0.41%	0.41%	0.41%
	Natore	1,706,673	1	3.60E-03	6135	0.36%	0.36%	0.36%
	Nilphamari	1,834,231	2	3.70E-03	6777	0.37%	0.37%	0.37%
	Pabna	2,523,179	32	6.70E-03	16893	0.67%	0.67%	0.45%
	Panchagarh	987,644	3	3.80E-03	3748	0.38%	0.38%	0.38%
	Rajshahi	2,595,197	8	4.30E-03	11146	0.43%	0.43%	0.43%
	Rangpur	2,881,086	8	4.30E-03	12374	0.43%	0.43%	0.43%
	Sirajganj	3,097,489	31	6.60E-03	20428	0.66%	0.66%	0.45%
	Thakurgaon	1,390,042	1	3.60E-03	4997	0.36%	0.36%	0.36%
Sylhet	Habiganj	2,089,001	22	5.70E-03	11897	0.57%	0.57%	0.45%
	Maulvibazar	1,919,062	20	5.50E-03	10545	0.55%	0.55%	0.45%
	Sunamganj	2,467,968	48	8.30E-03	20472	0.83%	0.83%	0.45%
	Sylhet	3,434,188	22	5.70E-03	19558	0.57%	0.57%	0.45%
Districts missing well data[2]		7,622,271	57	9.20E-03	70087	0.92%	0.85%	0.45%
Total		143,269,964				1,267,000[3]	913,000[3]	615,000[3]

[1]The water supply of the district of Dhaka is drawn from very deep hydrogeologic horizons, hence the population of Dhaka is exposed to arsenic only *via* food consumption.

[2]Bandarban, Khagrachhari, Rangamati, Mymensingh and Joypurhat were not assessed for well *As* contamination during the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP). These Districts were assigned the Bangladeshi average for *As* for this assessment.

[3]Total Incremental Cancer Cases.

systems produce arsenic-rich wastes that are currently released back to the environment, and hence not well managed. Additionally, many AIRPs are poorly maintained and thus commonly fall into disrepair. As Sorensen and McBean [18] reported, there is currently low sustainability of household AIRPs in rural areas of Bangladesh. In the village studied, Sorensen and McBean [18] report that less than 40 of 135 AIRPs are still being used and maintained regularly, and for those still functioning, performance has decreased by 10%, in terms of arsenic removal, three years after installation. As further evidence, Kleemeier [19] found that it was not unusual for less than 50% of tapstands to be functioning after approximately 15 years in use – a time disproportionally low, relative to the lifetime of the hardware. Point-of-Use (POU) technologies, or household water treatments (HWT), have also been susceptible to abandonment. Sobsey *et al.* [20] reviewed six POU technologies and found a sustained usage rate as low as 10% for some methods. Sobsey *et al*. [20] suggest that the success of POU technologies hinges on their capacity to produce sufficient quantities of low cost water from various sources, and on the ability of users to access replacement parts. Few studies, however, have focused on the behavioural motivations of users who choose to continue or discontinue use of a particular technology. Given these types of findings, remediation measures such as AIRPs are likely contributing only modest reductions of *As*-exposure (they fall into disrepair, people don't continue to use them, etc.). As a result, for the calculations to follow, it is assumed that there are minimal removals of *As* from the groundwater, as used for drinking water and irrigation.

High arsenic exposures, prevalent through dietary and non-dietary sources in Bangladesh, present a major health risk to the public. A quantitative human health risk assessment (HHRA) is described as a result of *As* exposure through food and water intake, while people meet their desirable dietary intake requirements throughout their lifetime. The assumptions implicit in this analysis include:

- Average Bangladeshi body weight: 60kg [21].
- Life expectancy: 70 years.
- Daily water intake: 4 L /day.
- Full lifetime exposure (365 days a year for 70 years).
- Arsenic intake from food: 0.14mg/day (0.00233mg/kg of food/day) [9].
- Arsenic intake from soil, tobacco and betel quid considered negligible [9].
- Inorganic arsenic is a human carcinogen (Group A). EPA's estimate of carcinogenic risk slope factor (CSF): 1.5 $(mg/kg_{BW}/d)^{-1}$.
- The *As* concentration data from Table **1** are indicative of the exposure concentration (not everyone drinks water from the same well) and the population of the districts and the associated arsenic concentrations are as listed.
- Population of Dhaka has not been included as the water supply for Dhaka is obtained from very deep groundwater (i.e. beneath where the arsenic deposits exist) but calculations recognize the citizens in Dhaka eat the food grown in the surrounding regions.

For *As*, as a carcinogen, the intake is described by the lifetime average daily dose (LADD) (see (2)), the total intake averaged over a lifetime. This approach is adopted since carcinogenic risks are cumulative – each additional exposure increases the likelihood of developing cancer, even if the exposures are separated by a period of years. The total LADD is calculated as the sum of the LADD attributed to water intake and food intake (see (1)). The LADD attributed to food consumption ($LADD_{(f)i}$) is adopted from Joseph *et al*. [9].

$$LADD_{(total)i} = LADD_{(w)i} + LADD_{(f)i} \tag{1}$$

$$LADD_{(w)i} = \frac{IR \times EF \times ED}{BW \times AT} \tag{2}$$

Where:

$LADD_{(w)i}$ = Lifetime average daily dose (mg $/kg_{BW}$ /d) in the i^{th} district (water consumption).

$LADD_{(f)I}$ = Lifetime average daily dose (mg $/kg_{BW}$/d) (food consumption) [9].

C = Concentration in water (w) (mg /L).

IR = Intake rate of contaminated water (L /day, taken as 4L /day).

EF = Exposure frequency (days/year).

ED = Exposure duration (years).

BW = Body weight (kg).

AT = Averaging time (days).

Values of $C_{w(i)}$ were taken as the *As* concentration (column IV of Table **1**) for individual districts, a $LADD_{(f)i}$ of 0.00233mg/kg_{BW}/d was assumed [9], which characterizes the *As* concentration representative of the Bangladeshi diet.

The Incremental Excess Lifetime Cancer Risk (IELCR), an estimate of the increased carcinogenic impact of arsenic on the Bangladeshi population, is then calculated in [3] as:

$$IELCR_i = LADD\ total_{,i} \times CSF_{As} \tag{3}$$

Where:

$IELCR_i$ = Individual excess lifetime cancer risk in i^{th} district.

CSF_{As} = Cancer slope factor for *As.*

3. RESULTS AND DISCUSSION

The incremental number of people affected in each district, i, for the stated conditions, is listed in column VI of Table **1**, from multiplication of $IELCR_i$ by population (column V) in the i^{th} district. Summing over the i = 1,..64 districts indicate the countrywide *As* cancer cases in Bangladesh is 1.27 million. For example, for the Chandpur district, the incremental number of people with cancer as a result of water and food consumption is 96,900. The percentage of the districts' population affected, as a result of *As* in water and food, is listed in column VI of Table **1**. Further, as evident from Table **1**, while the residents of Dhaka don't incur arsenic exposure from their drinking water, there is an exposure to arsenic from food consumption, indicating a population of 42,100 reaching the incremental cancer causing level. The fraction of *As* attributed to water consumption varies greatly from one district to another (see Figure **1**). In the division of Rajshahi, under 20% of *As* intake is attributed to the consumption of contaminated groundwater (approximately 80% attributed to contaminated food). Conversely, in the divisions of Chittagong and Khulna, over 65% of *As* intake is attributed to the consumption of contaminated groundwater (see Figure **1**).

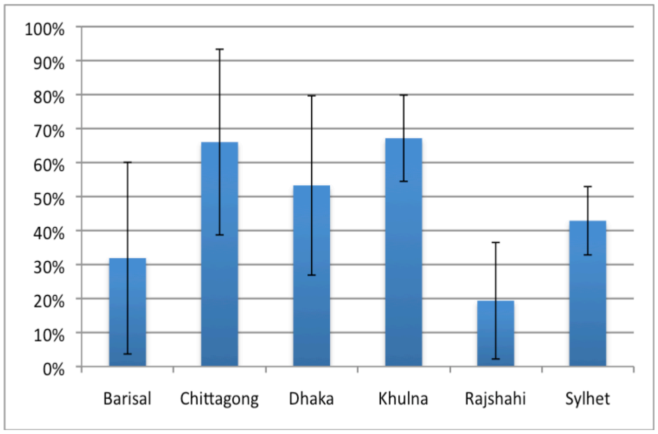

Figure 1: Incremental Arsenic Cancer Cases Associated with Water Consumption as Percent of Total, for Individual Division. Error bars represent standard deviation of Division Values within the Individual Division.

To assess the effects (in the event of implementation of sustainable technologies) of improving *As* removal to meet imposed water quality standards, the incremental number of cancer cases, are listed in columns VIII and IX of Table **1** (where, when the concentrations exceed the stipulated water quality standards are decreased to the specified standards). Treating drinking water to the Bangladeshi standard of 50µg/L, reduces the incremental number of cancer cases by 367,000 (or 913,000 expected cases). Further reduction of *As* levels to the WHO standard [22] of 10µg/L, would further reduce the incremental number of cancer cases by 298,000 (or 615,000 expected cases).

The population of Bangladesh has increased at an average rate of 1.2% from 2011-2014 [23]. Therefore, the incremental numbers of cancer cases, due to *As* exposure, are also expected to increase at this rate if suitable solutions are not implemented. This estimation indicates that by the year 2050, there will be 1,922,000 incremental cancer cases in Bangladesh, due to *As*-exposure.

CONCLUSIONS

Arsenic exposures, *via* drinking water and food consumption, are very real tragedies that are projected to create incremental cancer risks at a level of 1.27 million people in Bangladesh. Further, the numbers of incremental cancer risks are expected to increase at the rate of 1.2% per year, based on current population trends. There is substantial variability in the degree of impact, varying from 4% in Chandpur to 0.4% in Dhaka, where in the latter, the exposure to arsenic is only *via* food, as drinking water is sourced from very deep hydrogeologic horizons (below the *As*-impacted groundwater).

Attenuation of *As* exposures *via* various removal technologies is not proving to be highly effective due to their lack of sustainability. If options become available to reach the Bangladeshi *As* standard of 50µg/L, the incremental number of *As* cancers is projected to be reduced to 913,000. If options become available to meet the WHO *As* standard of 10µg/L, the incremental number of *As* cancers is projected to be further reduced to 615,000. The implementation of effective As-removal technologies would reduce *As*-related deaths by 652,000, as of 2015.

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