MSc Program
Environmental Technology & International Affairs

The Groundwater Arsenic Crisis in Bangladesh, Impacts & Challenges for SDG (s) 2030 Development Agenda.

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 14.11.2019

Affidavit

I, **TANVIR KABIR**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE GROUNDWATER ARSENIC CRISIS IN BANGLADESH, IMPACTS & CHALLENGES FOR SDG (S) 2030 DEVELOPMENT AGENDA.", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract:

Ground water has significant impact on society, environment and the economy. In Bangladesh the ground water level is high which has led numerous wells being sunken into the aquifer. However, the monitoring of the chemical qualities of the ever-expanding ground water coverage in the households never got due attention until the diagnosis of patients with skin lesions. The skin lesions got the attention of public and scientific community leading to a wide range of research. Arsenic in Bangladesh's ground water is a natural phenomenon but its toxicity is enhanced via microbiological mechanisms. 30 million people of Bangladesh are exposed to unsafe levels of arsenic ingested directly and through the Soil-Water-Plant nexus. The vulnerable malnourished people live in rural arears and struggle with extreme poverty. The mitigation measures taken by the government, NGOs and international donor agencies have covered the most visible short term effects such as skin lesions. However, there are long term public health risks including cancers which might evolve from apparently safe wells due to long term exposure. The impaired intellectual development of the children related to arsenic exposure, loss of work years, exhausting of savings for treatment of arsenic related diseases do have negative effects in the economy. The skin lesions have bearings for a developing society such as discrimination against affected women. The extraction of ground water from deeper aquifers for ensuring arsenic free water and the running diesel run pumps for irrigation will result in enhanced emission of GHG gases and other pollutants. The thesis found that although the expansion of coverage of ground water both at the household levels and agricultural fields enabled attaining of some of the targets of MDGs such as reduction of child mortality, access to improved water, decline of extreme poverty through increased agricultural yields by multiple harvests, the SDG era will be complicated. The arsenic contaminated ground water of Bangladesh will negatively affect the environment, the economy and the society in the long run through irrigated agriculture via the water-soil-plant nexus and pose formidable challenges for fulfilling goals of the Sustainable Development Agenda 2030.

Key words: ***MDG, SDG, Ground water, MICS***

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List of abbreviations:

As: Arsenic

BGS: British Geological Survey

BAMWSP: Bangladesh Arsenic Mitigation Water Supply Project

BRAC: Bangladesh Rural Advancement Committee

BUET: Bangladesh University of Engineering and Technology

DANIDA: Danish International Development Agency

DFID: Department for International Development

DPHE: Department of Public Health Engineering, Bangladesh

HEALS: Health Effects of Arsenic Longitudinal Study

MDG: Millennium Development Goals

MICS: Multi Indicator Cluster Survey

HEALS: Health Effects of Arsenic Longitudinal Study

mg/l: milligrams per liter

NGO: Non-governmental organization

PPB: Parts per billion

R&D: Research and Development

SDG: Sustainable Development Goals

UN: United Nations

UNICEF: United Nations Children's Fund

US: United States of America

USEPA: United States Environmental Protection Agency

WHO: World Health Organization

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1. Introduction

The purpose of this thesis is to provide an in-depth analysis of the relationship between arsenic contamination of ground water in Bangladesh with the county's pursuit for sustainable development and hence discuss the impact of arsenic contamination in ground water for attaining of different SDG goals and analyse the challenges arsenic crisis could pose to the three dimensions of sustainable development: social, economic and environmental.

Natural resources and biodiversity in most of the developing countries of the world has been facing depletion, contamination and threats of extinction as a result of the unsustainable trade-off between trade-development-environment, unsustainable industrialization and unplanned urbanization. Bangladesh is no exception. The quality of air, soil and water in Bangladesh has been compromised by natural and anthropogenic sources. Water in Bangladesh in particular is increasingly becoming a scarce resource with respect to both quantity and quality. The once abundant water resources in Bangladesh have received most stress due to unplanned exploitation of both groundwater and surface water resources. A significant part of the accessible and available surface water resources in Bangladesh is polluted by various anthropogenic sources and a growing percentage of groundwater is contaminated by organic and inorganic pollutants (Ahamed, et al., 2006). Agriculture and its related activities dominate the overall impact on water quality in rural areas whereas waste from industrial and domestic sectors dominates in the urban areas. The rapid depletion of groundwater, due to excessive extraction for drinking, irrigation in agriculture, usage in industries, electricity production will only further aggravate availability of it at an accessible depth. The geogenic contaminants include salinity, iron, fluoride and above all arsenic which have long term impacts on health and cause severe carcinogenic and non-carcinogenic diseases. Arsenic-contaminated drinking water causes skin pigmentation and skin cancer, and long-term use of fluoride in drinking water leads to tooth decay and crippled bones. The degraded water quality of both surface and ground water not only leads to scarcity of usable water but also may result in desertification in the long run affecting the whole ecosystem.

Arsenic contamination in groundwater is a global problem ranging from Chile to Mongolia (Mukherjee et al.,2006). There is estimation that 150 million people are affected globally by arsenic contamination; the crisis comprises of 70 countries, out of which 50 million people in Bangladesh are at severe risk (Ravenscroft et al., 2009). The shift of Bangladesh from the usage of surface water to groundwater with the assistance of international donor agencies and UNICEF has resulted in attaining a coverage of 97% pathogen free drinking water by installation of 10 million tube-wells since 1973 .The access to pathogen free water impacted in reduced child mortality rates in the short run (Chowdhury et al.,1999) but exposed a large population to unsafe arsenic ingestion (water-soil-plant) and hence increased vulnerability to economic, social and environmental consequences in the long run .

Arsenic contamination can be caused by geogenic, biogenic or anthropogenic sources. Scientific observations suggest that arsenic contamination of ground water occurs in Bangladesh under anoxic conditions (Bhattacharya et al., 2009; Wu et al., 2015;). Various scientific field surveys estimate that very probably 27 million and 55 million inhabitants in Bangladesh are exposed to possible intake of inorganic arsenic of 50 microgram/L and 10 microgram/L respectively through drinking water (Ahamed, et al. 2006; Ravencroft et al. 2009). There is a large number of literatures that exhibit the harmful effects of excessive inorganic arsenic on human health (Ahamed et al., (2006); Argos et al.,2014; Chakraborti et al.,2010;Ferreccio, et al.,2006). Inorganic arsenic can cause serious skin lesions at the initial stage leading to skin cancer at the advanced stage (Argos, et al. 2011; Argos, et al. 2013; McDonald, et al., 2006). Arsenic can also impact in the reproductive system, prenatal defects (Rahman, et al., 2010). Arsenic exposure during pregnancy can impact children at birth and also future intellectual development (Rahman, et al., 2015;; Mukherjee ,2006; Roy, 2008 ; Wasserman et al.,2006).

The scientific studies concerning the impacts of arsenic contamination on the quality of irrigated soils in Bangladesh are limited (Ullah, 1998). The issue of degradation of quality of soil due to arsenic contamination requires policy attention for further scientific research. Country-wise concentration of arsenic in uncontaminated agricultural soils in Bangladesh was found ranging between 2.6 and 7.6 mg per kg whereas the worldwide variation of arsenic in soil ranges from 0.1 to 40 mg per kg (Mandal and Suzuki, 2002). There is evidence that arsenic contaminated water is affecting the food chain in Bangladesh (Brammer,2008; Heikens, 2006; Huq et al., 2006; Khan et al., 2009 ;Sambu et al.,2006). It is noteworthy to mention that most of the mitigation policies have suggested to reduce arsenic contamination and hence focused on treatment of arsenic contaminated ground water (Anstiss, et al., 2006; Flanagan et al 2012; George, et al 2012; Howard et al., 2006, Joya et al., 2006; Khan & Yang, 2014; Milton et al., 2012,; Van Geen et al. 2006).

There are also economic bearings such as treatment of water, installation of deep tube-wells, extra electricity bill for extraction of deep water, productivity loss, and the treatment costs of various health problems originating from excessive arsenic ingestion through drinking water and food web and hence reduced consumer welfare (Ahmad et al., 2002; Adams, 2013; Barakat, 2004; Flanagan et al. 2012; Khan, 2007; Roy, 2008).

The environmental costs in terms of emission of greenhouse gases from the electricity generating power plants stations for the extra amount of electricity needed to extract deep water and the polluting gases emitted from diesel run pumps operating in the irrigation purposes in the agricultural fields require research for estimation and due consideration.

There are also studies that found significant social impacts of arsenic contamination in women and men that impacted on social lives and nuptial relations (Brinkel et al., 2009 Keya,2004)

Access to Clean Water and Sanitation (Goal 6) received a lot more attention in comparison to MDGs and hence included as an dedicated goal in the Sustainable Development Agenda 2030 adopted by the world leaders in 2015(United Nations, 2015).Since water has an important role in agriculture, industry and ecosystems, the ground water quality will be one of the most important factors for attaining of many of the goals of SDGs, including SDG 6. Extraction of shallow Groundwater in household/community level have fulfilled the requirements of improved drinking water in MDGs, reduced water-borne diseases and affected in reduction of high child mortality rates in Bangladesh. The subsidies in agriculture patronized the usage of shallow and deep pumps for extraction of ground water in irrigating the dry season crops, assisted multiple harvests in the same piece of land and supported Bangladesh in the so-called green revolution. Since the surface water is often inaccessible for irrigation and unusable for household purposes in Bangladesh whereas ground water is highly accessible for 97% households for daily consumption and usage, it requires dedicated and special attention.

The availability, affordability, accessibility, equitability, safety and drinkability (public/private connections) of ground water in Bangladesh could be regarded as one of the most important driving forces in sustainable Development Agenda 2030. Arsenic contamination could also be regarded as the most important factors in deterioration of ground water quality even though considering the other natural contaminants, presence of e-coli, salinity, presence of heavy metals etc.

1.1 Scope

This study will investigate the effects of arsenic contamination in the water-soil-crop nexus and its subsequent effects on attaining of various SDG goals in the 2030 Development Agenda of Bangladesh. Most of the research so far concerning the arsenic crisis concentrated on the scientific reasoning of the evolution of arsenic contaminated ground water, effects on the soil, effects on the agricultural production, health consequences, mitigation techniques or future directions but currently there is no substantive research available concerning the effects of arsenic contamination on attaining of various goals of SDG Development Agenda of Bangladesh and the future directions.

Bangladesh which has significant success in meeting most of the goals of MDG will face severe crisis of supply of fresh surface water and hence will extract excessive ground water for irrigation (95%) for its food security, reduction of poverty through enhanced crop yield and reduce malnutrition meeting SDG 2030 : Development Agenda . The arsenic crisis can be aggravated in two ways in the long run: under the extremity climate change conditions in Bangladesh in future, the contamination of the deep aquifer due to over-extraction. The over-pumping of ground water will introduce excessive low pressure in the overstressed aquifers which will eventually pull the water out of the clays having higher arsenic concentrations (Smith et al., 2018). The second issue might be land subsidence aggravating the crisis which requires research/attention in Bangladesh as significant arsenic concentration was found in 200-500 meter Pliocene–Miocene-age aquifers of Sothern Vietnam in Mekong Delta by a group of researchers (Erban et al.,2013). The excessive extraction of ground water in urban areas can also result in flow of river water into the aquifers in Bangladesh as recharging of aquifer by river water along with arsenic containing sediment was observed in Hanoi, Vietnam (Stahl et al., 2016).

1.2 Current Situation

Bangladesh has remarkable success in lowering the under-five mortality rate per 1000 live births which is lower than that of India and Pakistan. Bangladesh has ensured 97 percent of its population access to improved drinking water sources(UN MDG Report 2015) but the question lies whether children who would have died due to water-borne diseases before are not vulnerable to arsenic contamination in the long run as access to safe drinking water is limited to access to pathogen free i.e. ground water .The over dependence of groundwater for drinking and domestic purposes evolved in the past forty years for the scarcity of usable and accessible surface water due to growing number of construction of hydro-electric projects , massive diversion of river water projects by higher riparian countries of the region and lack of policy interventions.

However, different country-wise surveys were conducted by collecting water samples from hand tube-wells and analyzed for arsenic (As) by flow injection hydride generation atomic absorption spectrometry (FI-HG-AAS) from all 64 districts of Bangladesh . Jiang et al.,2013 constructed the map (Figure 1) from the data collected by Chakraborty et al.,2010:

Table 1.1: Arsenic concentration in household drinking water in Bangladesh

Study /Authors	Study population (No. of households/sample)	Arsenic concentration in household drinking water <=10 ppb (%)	Arsenic concentration >10<=50 ppb (%)	Arsenic concentration >50 ppb (%)
BGS-DPHE,2001	3534	57.9	17.1	16.1
MICS-2009	13,423	76.9	10.5	12.6
Chakraborti et al.,2010	52,202	57.0(<10 ppb))	15.8(=10<=50 ppb)	27.2
MICS-2012	59,718	75.3	12.4	12.4

It could be noted from the above table that the arsenic concentration in the household ground water actually increased (>10<=50 ppb) from the MICS 2009(10.5 ppb) to MICS 2012 (12.4 ppb). It is also very important to be noted that the arsenic concentration (>50 ppb) decreased a bit MICS 2009(12.6 ppb) to MICS 2012 (12.4 ppb). However, the arsenic concentration below 10 ppb improved 76.9 to 75.3 .

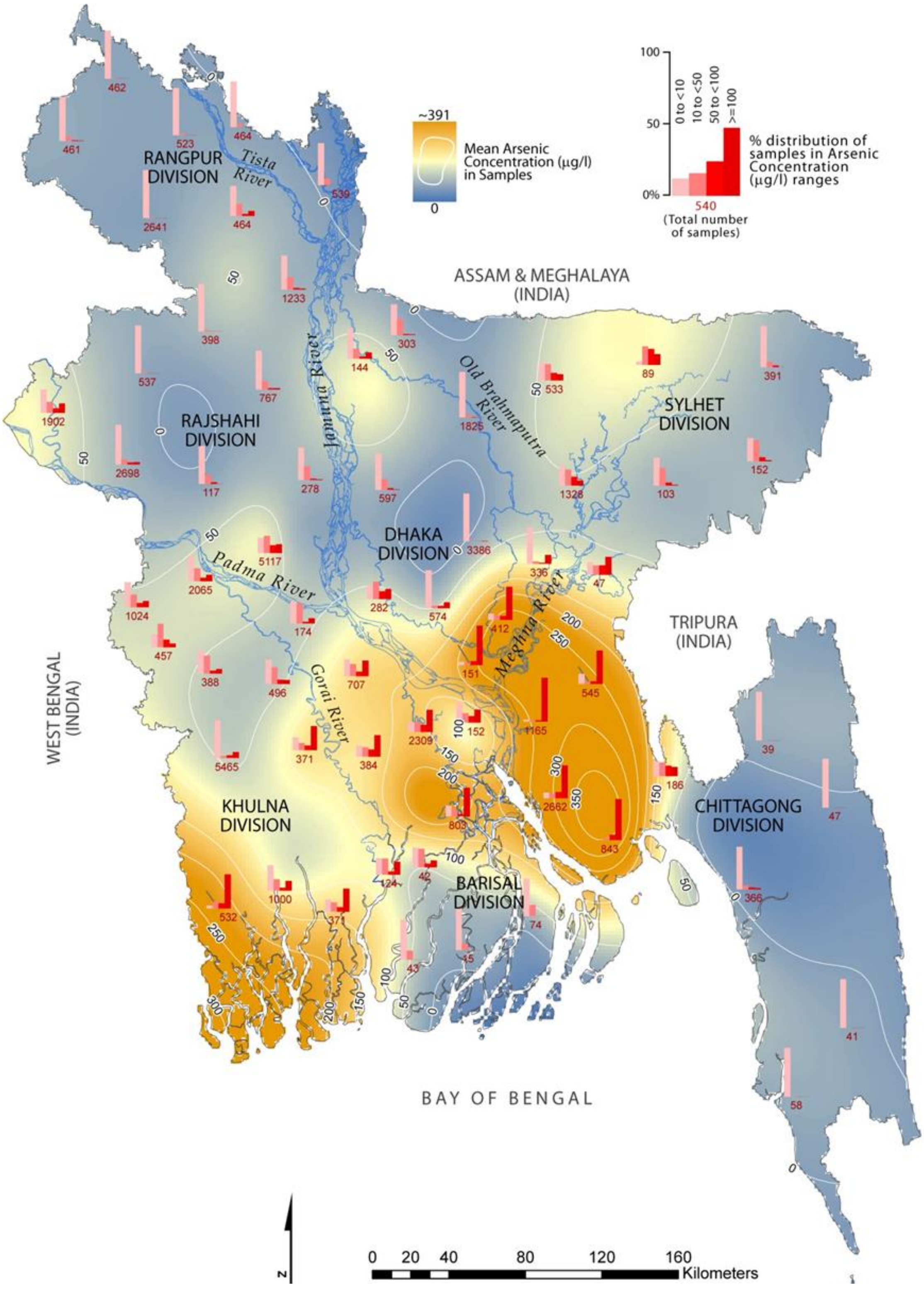

Figure 1:Map of Arsenic contaminated regions of Bangladesh(Credit: Jiang et al.,2013)

1.3 Significance of the Research

The research is important as the National Policy of Arsenic Mitigation of Bangladesh (2004) focuses only on supplying improved drinking water to mitigate the visible health effects (skin lesions among the affected people drinking contaminated drinking water. The issue of the long run implications of arsenic contamination on health through food chain and thus the integrated water-soil-crop concept of the arsenic contamination requires to be incorporated in the development policy plan of the government under the context of the 2030 Development agenda of SDG goals and indicators. A holistic Policy on Arsenic Mitigation according to the findings of scientific research concerning the arsenic crisis in different parts of the world including the Mekong-Delta countries such as Cambodia and Vietnam with analogous Delta characteristics needs emphasized attention as BAMWSP(Bangladesh Arsenic Mitigation Water Supply Project) could not address the water-soil-plant nexus of the arsenic exposure and also the new scientific findings such as land subsidence, contamination of deeper aquifers were not discovered in the early 2000. The financing from various development partners is required to build water infrastructures for rural/urban areas, R&D on mitigation technologies, improvement and development of efficient appliances related to water consumptions at households, efficient technologies in agriculture and industries, development of field-testing kits, introduction of water-metering to reduce consumption, and consistently monitoring of arsenic concentration/water quality parameters in distribution channels and installations .

1.4 Research Questions

How does the ground water contamination with arsenic affect attaining the SDG goals for Bangladesh?

1.5 Research Objectives

The research would like to analyse the adverse effects of arsenic crisis with attaining of different SDG goals of Bangladesh along the future challenges for mitigation as furnished below:

(i) Analysing the availability of Clean water (surface/ground/alternative sources) (Goal 6: Clean Water and Sanitation).

(ii) Analysing Social problems originating from Arsenic crisis and its effects on Gender Discrimination (SDG Goal 5: Gender Equality).

(iii) Analysing Economic Effects originating from the arsenic crisis and thus affecting attaining of different SDG goals related to : increased expenditures for using filters at household levels, increased consumption of diesel & the increased costs in irrigation, eventually increasing poverty affecting (Goal 1:No Poverty ; Goal 2: Zero Hunger ; Goal 8: Decent Work & Economic Growth & Goal 10: Reduced Inequality)

(iv) Analysing the Health issues related with arsenic contamination & its effects on SDG (Goal 3:Good Health and Well-being)

(v) Analysing the Agricultural productivity due to arsenic contamination of soil (SDG Goal 2: End Hunger, achieve food security, improve nutrition and promote sustainable agriculture)

1.6 Research Limitations

a)More than 54% of preschool-age children, equivalent to more than 9.5 million children, are stunted, 56% are underweight and more than 17% are wasted in Bangladesh because of malnutrition (WHO). It has been found by the scientific research that the effects of arsenic contamination vary in accordance with physical conditions. So the carcinogenic effects could be different in Bangladesh in comparison to Argentina, Chile, India, Mexico, Taiwan, Vietnam & USA.

b) Most of the literatures concerning mitigation techniques focused on filtering the arsenic contaminated water and there requires more research on the efficiency of the mitigation techniques implemented in the affected areas.

c) There is a few numbers of literatures concerning ground water depletion of Bangladesh under the prevailing extraction rate to mitigate arsenic contamination and in the context of climate change.

d) Spatial and Temporal Variability of arsenic concentration throughout Bangladesh require extensive surveys and monitoring for conducting estimations.

e) The availability of latest data in water resources management of Bangladesh is a major constraint to construct projections of water usage.

1.7 Outline of the order of the information of the thesis

The thesis is organized in the following way. Chapter 2 deals with causes and sources of water pollution and arsenic contamination. Chapter 3 presents the extent of arsenic contamination in Bangladesh. Chapter 4 is Analysis on the effects of arsenic contamination on various goals of SDG 2030 Development Agenda. Evolution of Health problems due to exposure to arsenic, agricultural productivity loss through the water-soil-plant nexus and the economic consequences of those have been covered in details. Chapter 5 comprises of discussion and chapter 6 consists of conclusion and the way forward.

1.8 Research Methodology

The research pursued to analyse the effects of arsenic contamination on different goals of Sustainable Development Agenda 2030 through literature reviews. The quantification and estimation of some of the indicators of SDGs which will be affected by the arsenic contamination were very limited due to scarcity of time-series data related to water resources management of Bangladesh.

2. Water Quality in Bangladesh

Bangladesh has one of the largest network of rivers in the world with 700 rivers including tributaries and distributaries with a length of 24,100 km covering 7% of the total land area. It is often referred to as the “land of rivers,. The economy, culture and society of Bangladesh is greatly influenced by the Ganges-Brahmaputra-Meghna (GBM. The distribution of water courses of the country varies greatly regionally where the numbers and the size change significantly from the northwest to the southeast region. Although surface water is abundant in the monsoon season almost all over the country, it lacks in quality for consumption. Bangladesh has been relying on groundwater from the Indo- Gangetic Basin (IGB) aquifer as the safest source of daily consumption and usage in the agriculture sector since the 1970s through the assistance of UNESCO and other international donor agencies. However, the apparent safest option of the water source is contaminated by naturally occurring inorganic arsenic, chloride, fluoride, iron, manganese, organic microbes or salinity affecting the lives of everyone irrespective of economic status.

2.1 Ground Water Quality

In Bangladesh there are very few studies concerning the chemical properties of water excepting some on arsenic and microbial qualities. In this research we will use the arsenic concentration and microbial qualities of water.

2.1.1 Microbial water quality

The microbial quality of drinking-water can be verified through testing for Escherichia coli (E-coli) as an indicator of fecal pollution, bacteriophages and/or bacterial spores etc. In developing countries like Bangladesh where 55% of the population has access to improved sanitation, testing for thermos-tolerant coliform bacteria is more viable option although it has limitations because enteric viruses and protozoa are more resistant to disinfection (World Bank, 2018).

Table 2.1: E. coli level of household water by observed storage (Source: MICS 2012-2013)

Observation on source of drinking water sample	E-Coli Risk level in household Drinking Water				Total	Number of Households
	Low	Medium	High	Very High		
Direct from source outside home	50.4	22.0	21.6	6.1	100	701
Direct from source inside home	54.7	20.9	17.3	7.1	100	1844
From Filter inside home	(43.8)	(28.7)	(11.3)	(16.3)	100	221
From uncovered storage container	34.5	26.9	24.3	14.3	100	3591
From covered storage container	33.9	22.5	27.9	15.8	100	5393
Unable to observe	(*)	(*)	(*)	(*)	100	56
Missing	(*)	(*)	(*)	(*)	100	49
Total	38.3	23.8	24.4	13.5	100	11854

() figures are based on 25-49 unweighted cases, (*)Figures that are based on less than 25 unweighted cases

2.1.2 Chemical quality of Ground water

WHO has published a guideline concerning the naturally occurring chemicals such as arsenic, barium, boron, chromium, fluoride, selenium and uranium along with limiting values depending on the negative effects on people. The number of comparable research concerning the other inorganic pollution of water in Bangladesh is very limited. However, a table from a research study (Akter et al., 2016) exhibiting the chemical parameters (pH values, manganese, iron, salinity) in ground water is furnished below:

Table: 2.2: The chemical characteristics of ground water in Bangladesh (Credit: Akter et al.,2016)

Characteristics	WHO drinking water standard(mg/L)								Bangladesh drinking water standard(mg/L)							
	Mn		Fe		NaCl		As		Mn		Fe		NaCl		As	
	≤0.4	>0.4	≤0.3	>0.3	≤250	>250	≤0.01	>0.01	≤0.1	>0.1	≤1.0	>1.0	≤600	>600	≤0.05	>0.05
Division																
Dhaka	6.6	12.7	11.7	6.8	36.0	40.1	9.1	67.9	6.5	8.9	7.4	8.5	38.1	39.7	22.7	76.7
Chittagong	25.4	39.7	50.8	23.0	1.6	0.0	16.5	9.2	28.7	26.9	27.2	28.4	0.8	0.0	15.6	0.0
Rajshahi	9.3	17.2	10.2	10.8	2.7	0.0	-	-	8.3	13.1	10.8	9.0	1.4	0.0	-	-
Khulna	9.5	1.5	0.0	9.8	1.0	19.8	20.2	16.5	6.5	9.7	7.1	9.5	9.0	25.9	20.9	0.0
Barisal	32.3	5.2	20.3	29.0	24.1	38.5	54.1	0.0	32.9	22.5	41.2	6.9	32.2	34.5	40.8	0.0
Sylhet	16.9	23.6	7.1	20.4	34.6	1.7	0.0	6.4	17.2	19.0	6.3	37.6	18.5	0.0	0.0	23.3
p value	0.000***		0.000***		0.000***		0.000***		0.000***		0.000***		0.000***		0.000***	
HH[a] member (%)	82	18	17.8	82.2	40.6	59.4	68.9	31.1	48.7	51.3	61.4	38.6	81.6	18.4	91.5	8.5
HH (%)	82	18	18	82	41	59	69	31	49	51	61	39	82	18	91.5	8.5

Table 2.2 was constructed from the results of a study on “The status of household WASH behaviors in rural Bangladesh”(Akter et al., 2016) conducted in 24 randomly selected upazilas (administrative sub -divisions consisting of 5 % of total subdivisions of Bangladesh) scattered through Bangladesh with a total of 960 households (40 households in each upazila) . For data collection all the randomly selected subdivisions were used for socio-economic survey and arsenic test and twelve out of 24 sub-divisions were considered to collect water samples from drinking water sources and to test chemical parameters in the laboratory.

The researchers (Akter et al. 2016) concluded that drinking water in Bangladesh has alkalinity (median pH value of 7.4) , median value of manganese content of 0.2 mg/L against the Bangladesh standard of 0.1 mg/L, the median iron concentration 0.3 mg/L , the mean salinity (presence of NaCl exceeding the WHO standards resulting in poor WQI. In this research the e-coli was not addressed. The water quality was determined considering only some chemical parameters.

A research group (Frisbie et al. 2002) collected Groundwater samples from 112 tubewells (one sample from one tube-well) throughout Bangladesh during 20 December 1998 to 18 January 1999 and analyzed for Ag, Al, As, Ba, Bi, Ca, Cd, Co, Cr, Cs, Cu, F ion, Fe, H ion, K, Mg, Mn, Mo, Ni, Pb, Rb, S, Sb, Si, Se, Sr, Tl, V, W, and Zn. They concluded that approximately 50% of Bangladesh might contain groundwater with Mn concentrations greater than the recently discontinued WHO standards for Manganese, 3% of Bangladesh's area has unsafe levels of Pb, less than 1% of Bangladesh's area has Ni, and less than 1% Bangladesh's area has Cr concentrations exceeding WHO health-based guidelines. This study is also similar to the results of the joint national-scale study by the British Geological Society (BGS) & DPHE that also exhibited the percentages of concentrations of Mn, Pb, Ni, and Cr found in the ground water extracted through tube wells throughout the country. In addition, the BGS/DPHE study conducted between 1998-2001 suggests that Bangladesh's tube wells exceed the WHO health-based drinking water guidelines for boron (5.3%), barium (0.3%), and molybdenum (unspecified) respectively. Moreover, the BGS/DPHE study also indicated that 12–50% of Bangladesh's tube wells exceed the safe limit of uranium (WHO health-based drinking water guideline).

It is also worth to mention that Bangladesh has about a third of the nationwide wells that met the standards for arsenic but are exposed to unsafe levels of manganese (Hasan and Ali, 2010) although WHO has discontinued the global acceptance level of Manganese in ground water since its fourth Guideline for drinking water quality.

Moreover, in the coastal areas of Bangladesh a significant proportion of the population lack access to freshwater sources due to the contamination of drinking water sources with high levels of chlorides (Akter et al., 2016; Ayers et al., 2016).

2.1.3 Overall Ground water quality in Bangladesh

The microbial quality of drinking water deteriorates from source to household, with an estimated 65.5 million people relying on microbiologically contaminated drinking water at source and 97 million people at the household level respectively. The percentage of households that use treated unimproved water sources reported at household level stands at 25%. Arsenic contamination exceeded the Bangladesh standard of 50 ppb in 12.4% of households, and all 64 districts had some households with arsenic concentrations above 50 ppb. Sylhet, Chittagong and Khulna divisions had the highest proportion of inhabitants using water sources contaminated with arsenic above 50 ppb. Progress in reducing arsenic contamination has been slow with approximately a one percentage point reduction in population exposed to arsenic above the Bangladesh standard between the 2009 and 2012-2013 MICS surveys. The survey reveals that 19.5 million people use drinking water that contains arsenic levels above the Bangladesh standards (50 ppb) and 20% people in Sylhet, Chittagong, and Khulna divisions had arsenic concentrations above 50ppb in their stored drinking water (MICS 2009, MICS 2012-2013).

2.2 Water Infrastructure in Bangladesh

The river system of Bangladesh is extremely dynamic. The discharge carried by those rivers has a wide seasonal fluctuation peaking at the monsoon (July to September). Bangladesh has predominantly four major river systems: Brahmaputra-Jamuna, the Ganges-Padma, the Surma-Meghna, and the Chittagong Region river system.

Although Bangladesh has made significant success in recent years towards achieving the goal of universal access to improved water through the investments of Public-Private Partnership (PPP), the water infrastructure throughout the country is still underdeveloped. The percentage of population having access to pipe water is only 10% with only meagre 7.1% having access to the households.

3. Arsenic in the Water-Soil-Plant Nexus

Arsenic is the 20th most abundant element in the earth crust. The primary source of arsenic in the natural environment is arsenic containing minerals or ores. Arsenic reaches surface, ground water and sediments through weathering of rocks through conversion from arsenic-rich metal sulfides. Arsenic concentrations in suspended solids and sediments can be up to 200 times higher than in river water as suspended solids act as scavenging agent (Mok ,1994). Arsenic in sediments is released under certain conditions and can contaminate groundwater.

More than 70 countries with an estimated population of 200 million are affected directly or indirectly as they are exposed to arsenic concentrations in drinking water and food chain that exceed the WHO recommended limit of 10 µg/l (George et al., 2014; Thakur et al., 2013).

Bangladesh's success in attaining remarkable agricultural production through usage of irrigation water over the last decade has contributed remarkable progress in poverty reduction from 44.2 percent in 1991 to 13.8 percent in 2016(World Bank, 2018). The success in agrarian economy resulted in increased life expectancy, remarkable literacy rates and improved Human Development Indicators. The arsenic contamination in ground water may impact in crop productivity through the water- soil-plant nexus. The findings of recently concluded two year field studies conducted on various fields of a severely arsenic affected in collaboration with the local farmers researchers from the University of Dhaka in Bangladesh, Cornell University, and Columbia University exhibited a yield loss of between 7.4 percent and 26 percent of the annual dry season harvest due to contamination of soil by arsenic(Huhmann et al., 2017; World Bank, 2018).

3.1 Arsenic Contamination Mechanism (Water-soil-Plant)

Low levels of As are naturally present in the soil at an average concentration of about 5-6 µg/kg worldwide (Bhumbla and Keefer, 1994) which varies substantially depending on the nature of the soil (Mandal and Suzuki, 2002). Arsenic behaves distinctly under anaerobic and aerobic soil conditions. The anaerobic conditions are most suitable for the uptake of As by plants. The production of rice in Bangladesh requires flooded conditions. The irrigation water is significantly the shallow and deep ground water. The arsenic from the irrigated ground water is up taken by the rice plants under anaerobic conditions.

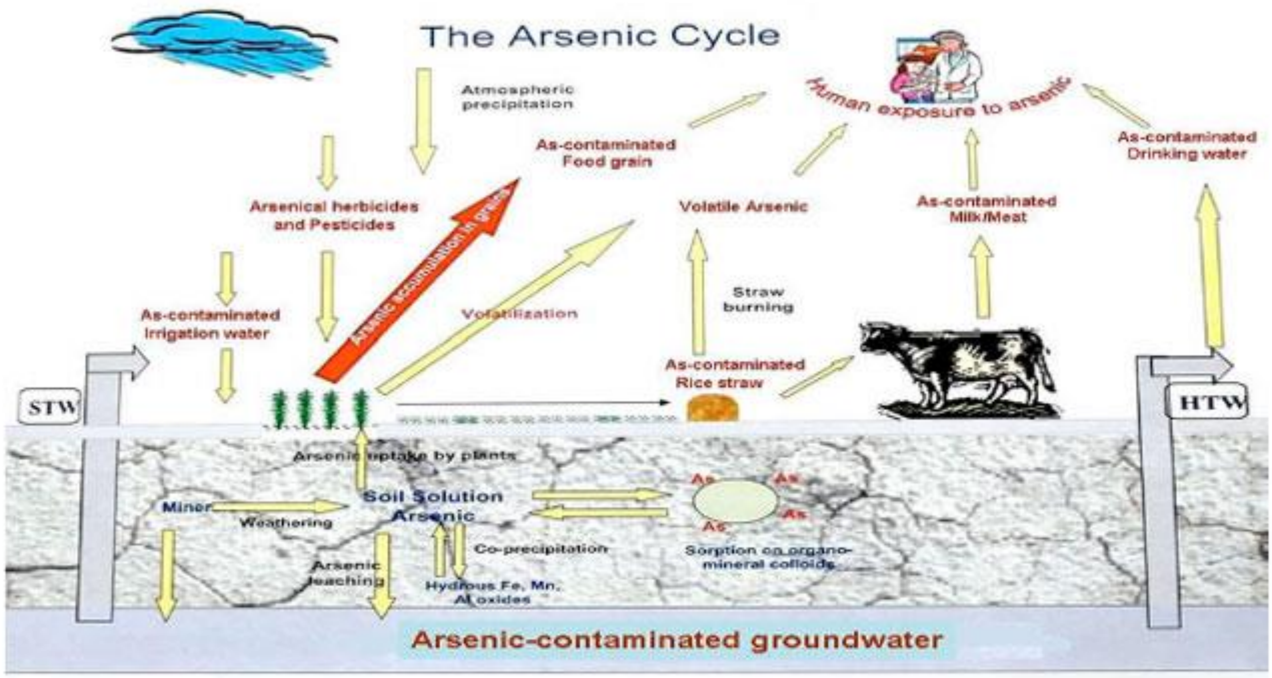

Fig 3.1: Arsenic in Soil-Water-Plant Nexus(Source: Akinbile & Haque,2012)

Presence of Arsenic in the rice grains is a common phenomenon all around the world but the paddy in Bangladesh contains more toxic inorganic arsenic facilitated by the flooded conditions of arsenic contained ground water used for irrigation (Mehrag et al.,2004).

To describe the human intake of arsenic in water-soil-plant nexus : We could begin from the agricultural fields where the agro-based rural population invest significant time of their daily lives. The rural people are exposed to volatile arsenic present in the rice fields in two ways: firstly; they often work bare footed at the flooded paddy fields for long hours(Muehe & Kappler,2014) which could be described a minor pathway of arsenic exposure through skin and the volatile arsenic in the air evaporated from the arsenic contaminated irrigation water (Zheng, Sun & Zhu ,2013). The cattle that roam around the fields are also exposed to this volatile arsenic (Abedin et al,2002). A significant part of the arsenic present in the irrigation water is also absorbed by the soil and reaches the stems of the plants which would be described in the later parts of this chapter. At the household level , the rural people have different exposure pathways: firstly a large part of Bangladeshi population use dried cow dung and rice straw as fuel in cooking purposes (Ghosh et al.,2013) which could be considered indoor presence of volatile arsenic .Secondly, the arsenic contaminated rice intake in Bangladesh is also significant (.42 kg dry weight rice per person per day)which is cooked with arsenic contaminated water . It has been estimated that this amount of rice consumed in Bangladesh might have 13.4-525 µg of arsenic or even higher quantities as some studies showed that the dissolved As in water used for cooking rice is non-selectively absorbed the rice grains (Ackerman et al.,2005, Juhasz et al.,2006). Moreover, the people also have also vulnerability of arsenic exposure through the meat of the cattle which are fed rice straw ,rice grains, rice water etc. in Bangladeshi households(Abedin et al.,2002).

3.1.1 Arsenic in the soil

Arsenic is found as organic/inorganic compound in nature. Arsenate (AsV) and arsenite (AsIII) are the most abundant inorganic compounds in the soil in comparison to the most significant organic forms such as monomethyl arsenic acid (MMA) and dimethyl arsenic acid (DMA) (Abedin et al., 2002).

Evolution of inorganic As in the soil is mainly dependent on the redox reactions where AsV dominates in aerobic (oxidizing) conditions and AsIII dominates under anaerobic (reducing) conditions (Takahashi et al., 2004).

The role of iron hydroxides

As (V) and As (III) are absorbed by iron (hydr)oxides (FeOOH) present in the soil. FeOOH dissolves instantly under anaerobic conditions, releasing As whereas FeOOH is relatively insoluble under aerobic conditions and serves as a sink for As. The As concentrations in irrigation water differs from those in the water-soil context (Takahashi et al., 2004).

Phosphate

Phosphate (PO_4) may be considered analogous to As (V) in aerobic soils (Lambkin and Alloway, 2003). The uptake of As depends on the balance between competition for sorption sites and competition for uptake brought by the additions of to (PO_4) aerobic soils. As (III) does not possess analogous behavior to (PO_4) which leads As behavior under anaerobic soil conditions irrelevant (Takahashi et al., 2004).

Volatilization

As may evaporate from the soil through the formation of volatile As compounds (Abedin et al., 2002). As summarized by WHO (2001), this can contribute a removal of 12 to 35 percent of arsenic per year.

3.1.2 Soil-Plant Interface

There is inconclusive research to calculate As uptake by plants from the soil as most papers only include total As concentrations in the soil and the As concentration in the irrigation water (Jahiruddin et al., 2005). A lot of research concentrated on the potential bioavailability of total arsenic in paddy fields where most of it is bound to FeOOH.

Rhizosphere

Plants and Micro-organisms in the rhizosphere influence the pore water composition by uptake and excretion of substances (Fitz and Wenzel ,2002; Nicolas et al., 2003). Plant processes related to Fe uptake may also influence As bioavailability and uptake as Fe and As behaves analogously in the soil. The rhizosphere can still remain aerobic under flooded conditions of a rice field as rice plants can transport oxygen from the leaves to the roots, resulting in the transfer of to the rhizosphere and a number of micro-organisms could influence oxidizing the rhizosphere. The oxidized conditions can result in the precipitation of FeOOH around the roots, also known as Fe-plaque (Meharg, 2004).

Uptake

As(III) is actively taken up by water channels (aquaporins) in the roots (Meharg and Jardine, 2003) and As(V) is taken up via the high affinity phosphate uptake system (Meharg, 2004).PO_4 additions have therefore been suggested to reduce uptake because of competition between PO_4 and As(V) for uptake.

Metabolism

After uptake, AsV is rapidly reduced to AsIII inducing the formation of certain antioxidants which might be regarded as a detoxification mechanism that is also activated by heavy metals such as cadmium (Meharg and Hartley-Whitaker, 2002; Sneller et al., 2000) . In spite of the rapid reduction of AsV to AsIII, high levels of AsV have been found in plant material.

Most toxicity experiments have been carried out with plants grown in water only which might be considered useful to study uptake mechanisms, internal transport, metabolism, and toxic effects but do not have the suitability to generate toxicity data for evaluating concentrations in the environment because of soil matrix influences bioavailability.

The results from some of the studies (Abedin et al., 2002; Ali et al.,2003;Huq et al., 2006 carried out in arsenic affected areas indicate that presence of arsenic in irrigation water can result in significant increase of arsenic concentration in the top layer of the irrigated soil and the soil content of arsenic will be further aggravated by the inefficient and excessive irrigation practices which requires further studies as different soil types as well as plant varieties might have different absorption capacities of arsenic. A number of green-house based studies in Bangladesh have shown stunting of plants cultivated in highly arsenic contaminated soil and irrigation water (Abedin et al.,2002).

3.2 Current status of arsenic contamination in the context of water-soil-plant nexus in Bangladesh

In Bangladesh, higher concentration of arsenic was found in root, stem and leaves of rice plants (Ali et al., 2003). However, the arsenic concentration in rice grains of some particular varieties was found to be relatively low (Ali et al., 2003). Even though significant arsenic concentration was not found in the rice grains of this study, there lies risks of arsenic exposure to human beings through the plant-animal-human pathway as contaminated rice straw is used as cattle fodder in large parts of Bangladesh and India. However, the study argued that chemical form of arsenic in crops/vegetables could not be ascertained through this study although some studies such as Abedin et al., 2002 suggested the predominant presence of arsenic (V) followed by arsenite and dimethyl arsenic (DMAA) acid in rice straw.

The study of Haque et al., 2003 conducted in 15 districts (sub-divisions) consisting of four different soil types of Bangladesh: Gangetic alluvium flood plain, Teesta alluvium flood plain, Meghna-Brahmaputra alluvium flood plain and Pleistocene flood plains suggested that the soil of the conducted study areas of Bangladesh have less than 10 mg/Kg average of As content and also indicated that the soil behaves to have more arsenic with irrigated ground water contaminated with arsenic. The study also suggested a positive relationship of As adsorption depending on the clay content and pH values.

3.3 Analysis of various hypotheses, theories concerning the arsenic crisis in Bangladesh

The formation of Bangladesh on the Ganga–Brahmaputra–Meghna (GBM) basin by the deposition of large volumes of arsenic-containing sediments eroded from the Himalayas and subsequently carried down by the GBM rivers during the Pleistocene and Holocene periods has caused the leaching of arsenic into the groundwater aquifers (Ahmad et al, 2018; Hossain, ,2006; Nickson et al. ,2000; Singh,2006). A lot of studies concerning the evolution, mobility and distribution of As in groundwater aquifers in Bangladesh providing relationships between the geo-chemical parameters of the subsurface aquifers and the transportation of arsenic in ground water (Stollenwerk et al., 2007; Zheng et al.,2004). Among the contrasting views on the mechanism of the arsenic leaching into groundwater ,there lie three prominent hypothesis in explaining the process of leaching of arsenic in the groundwater in Bangladesh (Ahmad et al,2018: Jiang et al., 2013): 1) reductive dissolution facilitated by microbial metabolism of organic matter or electron donors or dissolved organic carbon (DOC), under varying reducing conditions leading to reduction of iron oxy-hydroxides (FeOOH), and subsequently resulting in the release of arsenic into the groundwater. (Ahmad ,2004, McArthur et al.,2004;Ma et al.,2015, Ravenscroft et al.,2005.; Zheng et al., 2004) 2) Oxidation of Arsenical pyrites in the alluvial sediments and subsequent release of arsenic into the groundwater which might have occurred due to the entry of atmospheric oxygen into the aquifers by subsequent heavy withdrawal of ground water through shallow and deep tube wells (Ahmed et al.,2004; Chowdhury et al.,1999) 3) Exchange of Arsenic anions from the chemical fertilizers (PO_4^{3-}) resulting in dissolved arsenic in groundwater. (Islam and Islam, 2018; Uddin et al.,2011). When arsenic was first detected in ground water in Bangladesh, the hypothesis of atmospheric oxygen oxidizing arsenic-rich pyrite mobilizing As due to lowering of water table by excessive pumping of groundwater was assumed to be the principal cause of arsenic contamination in ground water which lost ground to be considered as main mechanism due to the following reasons (i) absence of widespread arseno-pyrite in Bangladesh(ii) the most affected areas of Bangladesh does not withdraw high amount of ground water (iii) the low concentration of (SO_4^{2-}) in groundwater samples, and the inverse relationship between dissolved As and (SO_4^{2-}) concentrations (Harvey et al., 2005; Anawar et al. ,2003).

3.4 Global status of Arsenic contamination

The most affected people belong to South-Eastern Asian countries such as Bangladesh, Cambodia, India, Nepal, Viet Nam and Taiwan (Thakur et al; 2013). Some parts of the USA, Mexico and southern American countries like Argentina, Bolivia, Chile and are exposed to arsenic levels higher than 50 µg/l (George et al., 2014). However, the approximation of Peruvian population exposed to arsenic contamination through drinking water is yet to be determined (George et al., 2014). In the Asian and global context, 13 Asian countries are arsenic affected. Bangladesh, China and India (GBM basin) countries have the largest total population exposed to arsenic contamination in the world. Among the 38 most affected countries of the world the drinking water in Bangladesh is worst affected by arsenic contamination extracted through hand-held tube wells (Dhar et al., 1997).

Table 3.1: Top 10 affected countries of Arsenic contamination in Ground water (Source: Yosim et al., 2015)

Country	Estimated Population (Millions)	Arsenic concentration(micrograms per liter
Argentina	2.0	<1 to 7,550
Bangladesh	35 to 77	<1 to >2,500
Chile	0.4	600 to 800
China	0.5 to 2.0	<50 to 4400
Ghana	<0.1	<2 to 175
India	>1.0	<10 to >800
Mexico	0.4	5 to 53
Taiwan	N/A	<1 to >3,000
United States	>3.0	<1 to >3100
Vietnam	>3.0	<0.1 to 810

4. The Arsenic Crisis & Challenges for Bangladesh for attaining of SDG Goals

The 2030 Agenda for Sustainable Development was adopted by the world leaders in September 2015 consisting of 17 Sustainable Development Goals (SDGs), 169 targets and

232 indicators focusing on balancing the economic, social and environmental dimensions of sustainable development (United Nations General Assembly , 2015).

Water received more emphasis in the 2030 agenda due to its role in agriculture, industry and ecosystems, which will serve as a basis for attaining of many of the SDGs, including SDG 6, the goal dedicated for water having six technical targets and two modes of implementations than it did under the MDGs, where only one target under the "Environmental Sustainability'' goal addressed drinking water (Johnston,2016; Guppy et al., 2018). Bangladesh attained 97% access to improved drinking water and met one of the targets of MDG which will significantly be affected with the introduction the indicator 6.1.1(**Table 4.1)** when the factors such as (i) the location of the water points on the household premises, (ii) 24/7 continuous access to water, (iii) chemical and microbial quality of water are considered as three essential components of the improved drinking water. It means that Bangladesh needs to revisit its policy of supply of improved water for attaining the SDG goals.

Table 4.1 Comparison of drinking water in MDGs & SDGs (Source: Johnston R.B.,2016, UN-Water)

MDG	SDG
Target 7c: to halve , by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation	Target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all
Indicator7.8: proportion of population using improved drinking -water sources	Indicator: 6.1.1 Proportion of population using safely managed drinking water services (defined as an improved source of drinking water which is located on premises, available when needed and free of fecal and priority chemical contamination.

The arsenic contamination problem was not addressed in the MDGs as those focused on the usage of improved sources i.e. microbiologically safe drinking water. Two essential dimensions of water quality, the e-coli contaminations which are prevalent developing countries and chemical qualities of drinking water were not addressed in Bangladesh while providing improved water supply for the people. Patients having Skin lesions such as melanosis, keratosis, and hyperkeratosis were detected in Bangladesh before arsenic contamination was officially found in drinking water (Chowdhury et al., 1999). Those patients specially women from the lower income background of the rural areas has troubled social life (marriages, employment, social acceptance) as the skin lesions due to arsenic poisoning were considered as leprosy or other contagious skin diseases by people (Thakur et al., 2013). The children are the worst sufferers as arsenic contamination during pregnancy could affect the neurodevelopment of children and the intellectually less developed children exhibited increased risk of drowning in one particular arsenic affected area of Bangladesh (Rahman et al., 2015).

The arsenic contamination has both primary and secondary effects upon attaining the SDG targets. The evolution of diseases through usage of arsenic contaminated water for drinking, non-drinking purposes in the households, intake of arsenic contaminated food (contaminated through irrigation water), contamination of soil can be termed as primary effects while secondary effects are work –productivity, increase of poverty, increase of inequality, decrease of economic growth, discrimination against women, emission of green-house gases due to increased usage of fossil fuels for extraction of ground water for household consumption, irrigation and other purposes and subsequent change of available ground-water depths can be termed as secondary effects (Figure 4.1). The primarily affected SDG goals are: Availability of safe Drinking water for all (Goal-6), Food Security (Goal-2), Health problems (Goal-3). The cultivation of crops with arsenic contaminated irrigation water result in reduced agricultural productivity, soil fertility, and lead towards malnutrition. On the other hand both drinking water and the arsenic contaminated food can create non-carcinogenic health problems such as skin lesions, vascular diseases, liver diseases both carcinogenic disease such as lung and bladder cancers in the short and long run.

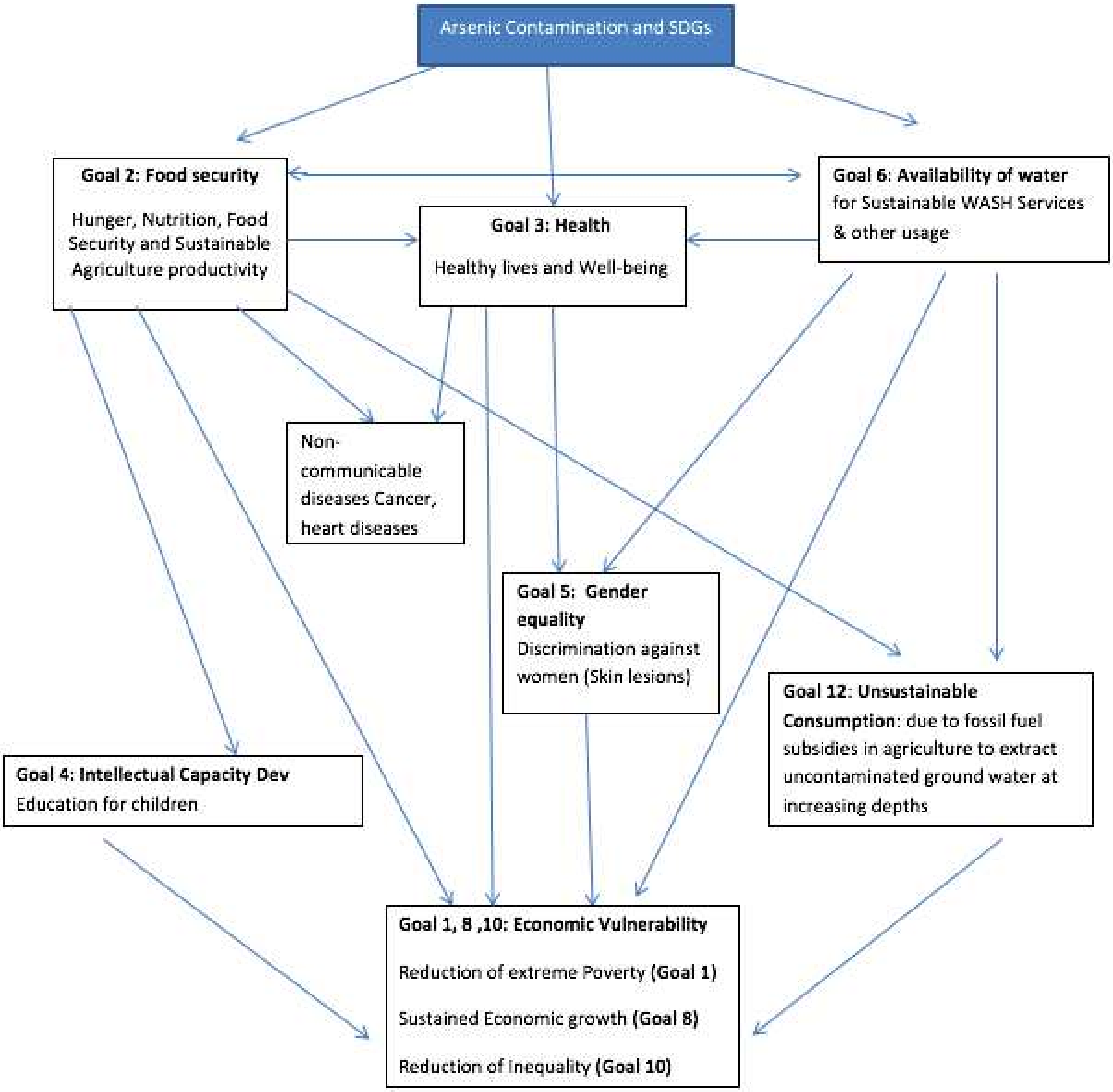

Figure 4.1: **The Arsenic Crisis & the 2030 Development Agenda for Sustainable Development (Source:Kabir,T,2019)**

Table 4.3: Arsenic contamination in ground water & its effects on Sustainable Development Goals

Target	Target theme	Link with arsenic contamination and the consequences	Degree of Linkage	Effect
1.1	**Eradication of Extreme Poverty**	Treatment of water, treatment of diseases increase household expenditures.	Secondary	Economy /Society
1.2	**Reduction of Poverty**	The arsenic crisis would affect the poverty level due to increase in treatment costs.	Primary	Economy /society
2.1	**End of hunger**	The crop yield will affect the lowering of hunger	Primary	Economy /Society
2.2	**End of malnutrition**	Arsenic contamination will result in Malnutrition due to decreased crop yield	Secondary	Economy /Society
2.3	**Doubling of agricultural productivity**	The agricultural productivity will be affected.	Primary	Economy /Society
2.4	**Sustainable Agriculture**	The fertility loss, increased usage of fossil fuels at higher depths for safe water for irrigation , the contamination of crops through water-soil-plant nexus etc.	Primary	Economy/ Environment
3.1	**Reduction of maternal mortality**	Some research has found increased maternal mortality related to arsenic concentration level in water.	Secondary	Economy /Society
3.2	**Reduction of child Mortality**	Some research has found increased child mortality related to arsenic concentration level in water.	Secondary	Economy /Society
3.3	**Reduction of water borne diseases**	The water borne diseases might actually increase during the transportation of water from community wells /reservoirs at home if the piped water supply at the households is not ensured.	Secondary	Economy /Society
4.1	**Equitable education**	The reduced income, water collection at the community wells which are arsenic safe could create burden on the girl child in poor families to dedicate more time in household chores.	Secondary	Economy /Society
5.1	**Discrimination against women**	The reduced income will result in non-attendance of girls at the schools.	Primary	Economy /Society
6.1	**Access to safe Drinking water**	The access to drinkable water will be difficult to assess unless water is not supplied through utilities suppliers.	Primary	Economy /Society
6.2	**Sanitation & Hygiene**	The sanitary health of women and girls will be affected due to reduced access to safe water.	Primary	Economy /Society
8.1	**GDP growth**	The less productivity will result in less income and enhance reduced GDP/HDI.	Secondary	Economy /Society
10.1	**Income growth**	The net family savings will be reduced for expenditures related to medical treatments.	Secondary	Economy /Society
12.c	**Rationalization of inefficient fossil-fuel subsidies**	The fossil fuel subsidies will increase due to extraction of water from higher depths for households/irrigation.	Secondary	Environment
15.1	**Terrestrial ecosystems**	The terrestrial eco-system will be affected due to the affected /depleted ground water.	Primary	Environment

4.1 Health Issues and Challenges (Goal 3)

The toxicity of arsenic is well recognized which is often termed as the "king of poisons" and the "poison of kings". It had been used as an untraceable poison (approximately tasteless and odorless) during the Middle Ages by the nobility to take power or wealth. The presence of arsenic in drinking water and the food chain has several adverse short term and long term health effects. The short term effects could be listed as abdominal pain, high blood pressure, weakness, vomiting, weight loss, convulsions etc. (Zaldivar& Guillier, 1977; Thakur et al.,2013). The long term effects could be listed as respiratory problems; intestinal, arterial and skin lesions, chronic bronchitis, cardiovascular problems, arterial diseases, diabetes, lung mal-functioning, kidney complications, maternal health and consequent problems to children born, intellectual ability of the children, cancers of bladder, kidney and lungs (Zaldivar& Guillier,1977; Thakur et al.,2013).

Table 4.3: The effects of arsenic on Health

Health problem	Reference Literatures
Maternal health during pregnancy and effect on the children	Ahmad et al.,2001, Harrari et al.,2013; Laine et al.,2014; Milton et al.,2005; Rahman et al.,2007;Rahman et al.,2015; Skröder et al.,2016
Skin lesions	Ahsan et al.,2006,Argos et al.,2011; karagas et al.,2015; McDonald et al.,2006,Yunus et al.,2014;
Cardiovascular Diseases	Chen et al.,2006,Chen et al.,2011
Respiratory systems & Lung problems	Argos et al.,2014;Parvez et al.,2016
Immune system	Ahmed et al.,2011
Kidney problems	Chen et al.,2011
Diabetes	Bräuner, et al.,2015
Cancers	Argos et al.,2013; Chakraborti et al.,2017; Lopez-Carillo et al.,2015;Chen et al.,2004;Leonardi et al.,2012;Gamboa-Loira et al.,2017;Steinmaus et al.,2010; Smith et al.,2000.

4.1.1 Dermatological Problems

The arsenic related dermatological problems such as skin lesions which lead to skin color change or darkening over different parts of the body detected in Bangladesh led to investigations concerning the arsenic concentrations in drinking water. The high number of cases of skin lesions in children were first found in Antofagasta, Chile in 1962 (Zaldivar,1974). The skin lesions could continue even after the patients start taking arsenic free water and transform into disability such as bowen's disease, gangrene etc. (Ahamed et al.,2006). There are also studies that suggest that most patients with skin lesions are highly vulnerable to cardiovascular complications, lung cancers depending on the degree of skin lesions (Argos et al.,2014; Zaldivar,1980) .

Researchers found that the population of Bangladesh is even vulnerable to skin lesions with the arsenic concentration in drinking water as low as 10 µg/L. In the same study "**Health Effects of Arsenic Longitudinal Study (HEALS) in Bangladesh"**, it was found that the increase of risk of skin lesions linearly varied with increase in concentration if comparison is drawn between the group of people having exposure to 50–100 µg/L from drinking water and those having the exposure of <10 µg/L. Various researchers found a 3-fold increased risk for the highest exposed group (≥200 µg/L) (Argos et al.,2011;Kile et al.,2011, McDonald et al.,2006).

If we look into other countries, we also find that there is evidence of dermatological problems related to arsenic contamination in drinking water. The researchers also found that skin lesions prevalence vary by factors including gender, diet etc. (Ahsan et al.2006; Chen et al.,2006; Pierce et al.,2010).

It was also found that the risk for skin lesions increase with the increased concentrations (>50 µg/L) of arsenic in water in West Bengal, India which is consistent with the results of studies conducted in Bangladesh (Haque et al., 2003). There is also evidence of increased skin lesions in Sindh region of Pakistan having increased level of arsenic in drinking water (Fatmi et al., 2013).

The studies conducted in Inner Mongolia, China showed the directly proportional relationship between concentration of arsenic in drinking water and magnitude of skin lesions (Xia et al., 2009).

4.1.2 Effects on Pregnancy and the children

Arsenic contamination may cause long term health consequences among the neo-natal children carried through high level of di-methyl-arsenic acid (DMA), monomethylarsonic acid (MMA) and lower level of DMAs during pregnancies (Drobná et al., 2016). There are a number of studies which show that Arsenic contamination during pregnancy could result in adverse pregnancy outcomes such as low birth weight ,child mortality (less than 5 years) and affect child development (Ahmad et al., 2001; Milton et al., 2005; Mukherjee 2006; Skröder et al.,2016; Thakur et al.,2013; Yunus et al.,2015).These studies also showed that a correlation exists between arsenic exposure, spontaneous abortions ,still-birth, pre-term births which might be credited to enhanced placental inflammatory responses, reduced placental T-cells counts, and changed cord blood cytokines through maternal arsenic exposure during pregnancy (Ahmed et al.,2011). A study in Bangladesh found that there is an inversely proportional relationship between the arsenic concentration of drinking water ingested by a pregnant woman and the birthweight of a new-born baby where the concentrations below the Bangladesh standard can also affect (Kile et al. ,2016). A research conducted in the arsenic-affected areas of Bangladesh showed that prenatal arsenic exposure is associated with elevated risk of mortality from Lower Respiratory Tract Infection (LRTI) and diarrhea during infancy (Rahman et al., 2010). Furthermore, arsenic exposure during pregnancy could also affect the intellectual development of the children (Rahman et al., 2015).

4.1.3 Cardiovascular, Respiratory and Lung Problems

There are studies that found the relationship between arsenic contamination and decrease of (HDL-C) protein, increase of (Ox-LDL) protein and other related indices for cardiovascular functionalities (Chen et al., 2011; Islam et al.,2015,). Some researchers found co-relation between arsenic exposure and mortality from cardiovascular disease, at even lower level of arsenic exposure in Bangladesh and Myanmar (Chen et al., 2011; Htway et al., 2014).

A research in Taiwan found that there is significant increase of Chronic Kidney Disease (CKD) observed through dose-response from people vulnerable to arsenic contamination

(Hsu et al., 2016). The study estimated cumulative arsenic exposure (CAE) by multiplying arsenic level of well water with duration of drinking the arsenic contaminated well water. The arsenic concentration in drinking water varied from undetectable to 3590 µg/L. From a total sample size of 6153 participants people were divided into three groups depending on the condition of kidney functions. The CKD incidence of each group was calculated through division of number of new CKD patients by the total number of patients . The arsenic exposure was estimated through COX regression by calculation of hazard ratios associated with arsenic contamination.

Chronic arsenic exposure could also cause mal-functioning of the lungs and respiratory infections (Rahman et al., 2011).The arsenic exposure and the related studies in different regions of Chile in the 70s also show increased deaths from pulmonary tuberculosis and chronic bronchitis (Dauphiné et al.,2011).

A group of researchers conducted a study on **"Arsenic exposure, non-malignant respiratory outcomes and immune modulation in the Health effects of Arsenic Longitudinal study(HEALS)"** and observed that children living in households with non-smokers but have exposure to arsenic contaminated water are even vulnerable to acute Respiratory Tract Infections (Parvez et al.,2016)

A research also found that population exposed to low levels of arsenic in drinking water in a middle Banat region in Serbia was susceptible to type-2 diabetes which was contrary to the findings of a research conducted in Bangladesh (Chen et al.,2010) but similar to one study in Bangladesh (Pan et al., 2013)

4.1.4 Carcinogenic Effects

Inorganic arsenic (iAs) has been classified as carcinogenic basing on both the epidemiological evidence and investigations exposing the bio-transformation of iAs producing monomethylated acids (MMA) and Dimethylated acids (DMA) which are responsible for cancers (IARC,2004; Gamboa-Loira et al.,2017). A large number of studies have shown that arsenic in drinking water can cause bladder, lung, kidney, liver and skin cancer (ASHRAM Study Group ,2016; Lopez-Carillo et al.,2016). It was estimated that the lifetime risk of dying from cancer from daily intake of 1 liter of water containing 50 µg/L of As can be as high as 13 per 1,000 people exposed(Smith et al.,1992) . The carcinogenic risks associated with intake of arsenic persist for a long time even after the contaminated people is no longer exposed to arsenic contamination (Ahsan et al., 2007).

The evolution of skin cancer was associated with cumulative arsenic exposure from drinking water through a cross-sectional study of 1081 individuals from a village in south-west Taiwan (Hsueh et al.,1995). Moreover another investigation found the death incidents form skin, lung, bladder, and kidney cancers in Taiwan (Chen et al., 1985). A research also found the susceptibility of breast cancer among the Northern Mexican women who are exposed to arsenic contaminated drinking water (Lopez-Carillo et al.,2016).

The relationship between arsenic in drinking water and increased risk of kidney and lung cancers in Argentina was found (Hopenhayn-Rich et al.,1998). Another study found the relationship of bladder and kidney cancers and the exposure to As in drinking water in Finland (Kurttio et al.,1999).

The number of researches on the evolution of cancers through arsenic contaminated water or food chain in Bangladesh is very limited. However, the population based cohort study conducted in one of the severely arsenic affected sub-divisions in Bangladesh,(Chen & Ahsan,2004) has shown that lifetime mortality risk from liver, bladder, and lung cancers (229.6 vs 103.5 per 100000 population) could be doubled due to ingestion of arsenic. The researchers estimated the risks basing and comparing the distribution of arsenic exposure, death probabilities, and cancer death rates in Bangladesh and those data from Taiwan.

The health problems associated with arsenic contamination through water-soil-plant nexus will affect the income of the families as the studies show that the poor people are more vulnerable to arsenic contamination as they neither have financial ability to continuously monitor the arsenic level in the water, treat the water, meet sufficient dietary requirements nor they could access the treatment facilities or afford the treatment expenditures. As the carcinogenic effects are latent and affect the people in the long run, the health effects will be a huge burden for Bangladesh in near future.

4.2 Agricultural Productivity & Food Security (Goal 2)

Farm Agriculture is one of the most important factors in reducing Bangladesh's poverty from 48.9% in 2000 to 31.5% by 2010(World Bank, 2016). The agricultural activities generate 87% of rural income although two thirds of rural households rely on both farm and non-farm incomes. It contributes 90 percent of poverty reduction versus 6 percent reduction from non-farm income. However, World Bank considers that Pro-poor agriculture growth has stimulated the non-farm economy in Bangladesh: a 10 percent rise in farm incomes generates a 6 percent rise in non-farm incomes.

As most of the groundwater in Bangladesh is contaminated with high levels of arsenic (As) the number of research concerning the effects of harmful human health through ingestion of arsenic contaminated ground water exceed that of those concerning the agricultural productivity, food security and arsenic concentration in the food-stuff**.** However, the arsenic contaminated groundwater(79% in 2008,FAO Aquastat,2019) is predominantly used for irrigation of rice and other crops in Bangladesh(FAO-Aquastat,2019) which might result in reduced agricultural productivity , create constraints on agriculture land use due to arsenic storage in soils, result in spatial variability in soil As, Fe and P levels and enhance exposure of the population to As through agricultural products significantly rice, and through food system and environmental pathways of arsenic; such as through livestock fodder used in poultry, fisheries and cattle farming as the rice straw is in Bangladesh as cattle fodder, grains are used in poultry and fisheries (Duxbury et al., 2005). In Bangladesh rice is cultivated in both dry and wet seasons requiring variable quantity of ground water irrigation .The dry season rice is cultivated in flooding conditions through ground water irrigation and the wet season rice is cultivated with the assistance of rain water resulting in two contrasting scenarios of the amount of arsenic present in the irrigation water .However, the rain-fed rice of the monsoon season (aman) could still be exposed to high concentrations of soil As built up during the dry season through the cultivation of winter season rice (boro) (Huhmann et al.,2017). It has been estimated that ground water irrigation through shallow aquifer contributes of adding extra 1 million kg of As to the arable soil of Bangladesh, predominantly used for paddy cultivation. Most of the soil in Bangladesh has uncontaminated arsenic levels in natural conditions with levels less than 5 µg per kg (Mandal and Suzuki, 2002; Smith et al., 200). However, the worst affected zones under the confluence of the Ganges and Brahmaputra rivers have concentration of 5 µg of arsenic per kg of soil in Bangladesh (Duxbury et al.,2017). A study in India shows that the arsenic build-up in soil dose not only solely depend on arsenic concentration in irrigation water rather a set of factors such as agriculture practices(flooded/non-flooded conditions) and presence of organic matter in agricultural field (Farooq et al.,2012).

In Bangladesh, the presence of arsenic in soil and irrigation water and its effects in crop yield/productions were investigated both in field and pot experiments /studies through simulated rice/wheat production (Duxbury et al., 2007; Huhmann et al., 2017) where both showed the negative effects of arsenic contamination in crop yields.

The continuous application of phosphatic fertilizers in agriculture and pesticides used for protection of livestock can cause arsenic contamination of soil (McLaren et al., 1998) and eventually contaminate the food chain through plant uptake (McLaughlin et al. 1996). It has been suggested that arsenic-contaminated agriculture irrigation is a health concern due to the presence of inorganic arsenic the food-chains of India, Bangladesh and Nepal (Brammer, 2008;Thakur et al.,2015). The pursuit of increased agricultural production (13.4% of GDP in 2016,World Bank) for poverty reduction ,sustained food security for a large malnourished population supply of nutrition , the creation of employment opportunities, house-hold expenditure for education could be thwarted due to loss of crop yield from arsenic-contaminated soil and irrigation water .

4.3 Economic Vulnerability (Goal 1, 8, 10)

The arsenic contamination has adverse direct and indirect economic effects. The direct effects could be the deteriorating health, loss of productivity and reduced income, social exclusion and absence from schools and hence reduced income, mitigation cost for the contaminated water at house-hold level, agricultural productivity loss and the reduced income etc. The indirect effects will be the extra cost for irrigation due to lowering of the ground water level i.e. change of height of the water level and the need of more energy for water extraction , the environmental costs in extracting deep ground water in households, utilities, factories and agriculture due to the mostly fossil-fuel based electricity in Bangladesh and the operation of the irrigation pumps by diesel fuel. However, the literatures are limited which exhibit the complete estimations of the economic costs of the arsenic contamination in Bangladesh and therefore the estimations economic consequences of arsenic poisoning will not produce the complete picture. It has been found that most of the patients diagnosed with arsenicosis are often suffer from poverty (Argos et al., 2007).

About 12.4% (within Bangladesh standard but above WHO standard), 9.6 % (above Bangladesh standard), of the population in Bangladesh is yet to have access to arsenic free drinking water which has increased in accordance with the MICS survey of 2009 and 2012-2013 implying that the continued usage of the contaminated source might be related to lack of financial capacity of switching to arsenic free tube wells.

A household survey conducted in 274 sample households drawn from four arsenic affected sub -divisions of Bangladesh in the year 2001 showed that arsenicosis has negatively affected in economic activities of people such as such as reduction in income, change of occupations, unemployment rates, discrimination at work places , reduced protein intake ,increase of health related expenditures for treatment ,distressed selling of household livestock and poultry, capital withdrawal from business, mortgage of land ,taking credits form people and eventual rise of poverty in rural areas (Barakat,2004). Household surveys for all over Bangladesh are necessary to estimate the household economic losses or welfare losses due to arsenic contamination.

A study (Flanagan et al., 2012) estimated the economic losses of US $ 12.5 billion in 20 years in Bangladesh considering the arsenic-related mortality burden and projected productivity loss in terms of per capita gross domestic product (GDP). The study of Flanagan et al., 2012 assumed that arsenic exposure (> 10 µg/L) will be remaining throughout the projected period considered a per capita GDP of USD. 1465 purchasing power parity dollars, a steady economic growth, an average loss of 10 years of productivity per arsenic-related death, 1 of every 18 deaths associated with arsenic-related mortality and a discount rate of 5%. The researchers assumed an average loss of 10 years of productivity per arsenic-attributable death in considering the deaths from four types of cancer (skin, bladder, kidney and lung related to arsenic exposure) and estimated it by comparing the data of average person dying of cancer in the United States of America lose 15.4 years of life. The rising of life expectancy in

Bangladesh may significantly increase the expenditures related to arsenic treatment and adversely affect the economy.

The environmental costs associated with the usage of fossil fuels for extracting ground water for different purposes at increasing depths need to be estimated. There are a few factors that need to be considered for estimating environmental costs such as increased consumption of energy and emission of greenhouse gases during the electricity production, loss of soil quality and increased usage of fertilizers and water for high yield, increased energy consumption for treatment of the patients, emission of greenhouse gases by the usage of diesel operated pumps in irrigation, increased household consumption of energy for extraction of ground water from higher depths . Studies are needed to estimate the environmental costs associated with arsenic contamination.

4.3.1 Intellectual Capacity Development of the Children & Education (Goal 4)

Arsenic contamination can severely affect cognitive performance, visual perception, attention, speech and memory (Rosado et al., 2007). Several studies have reported the effects of chronic arsenic contamination on intellectual ability in adults and children in China, India, Mexico, Thailand (Calderon et al., 2001; Siripitayakunkit et al.,1999; Tsai et al.,2003; Von Ehrenstein et al.,2007). Wasserman et al. (2004, 2006) in two separate studies showed that exposure of inorganic arsenic from drinking water affected intellectual function conducted in an arsenic affected area of Bangladesh which is consistent with the studies conducted in Mexico (Calderon et al., 2001) and Taiwan (Tsai et al., 2003) .

Table 4.4: Intellectual Development of Children vs Arsenic exposure

Researchers and the year of publication	Sample size (target population) and study design	Interpretation
Asadullah and Chaudhury;2008	n=7,710 (Secondary school children (enrolled in grade 8) in Bangladesh); Cross-sectional	The performance of children in mathematics was found to be negatively correlated with arsenic exposure.
Wasserman et al;2011	n=299 (8-11 years old children);cross-sectional	The arsenic presence in blood was found to be associated with poor verbal comprehension while the Mn exposure was associated with poorer perceptual reasoning and working memory scores among the children.
Wasserman et al;2006	n=301 (6 years old children in Bangladesh); Cross-sectional	Children's intellectual function through Wechsler Intelligence Scale for Children, (version III), was used to asserss Intellectual function in a dose responsive manner and resulted with negative correlation

4.3.2 Mitigation cost (Increase of Poverty, Inequality: Goal 10)

Arsenic contamination has created additional expenditures to the rural population. A World Bank study estimated the costs associated with treatment of arsenic contaminated water at both individual household level and the community level. In different parts of the world various arsenic removal technologies such as ion exchange, activated alumina, reverse osmosis, membrane filtration, modified coagulation/filtration, and enhanced lime softening (Jiang et al.,2013; Berg et al., 2006). However, developing countries like Bangladesh needs simple, low capital and maintenance cost technologies. The mitigation technologies recommended by US Environmental Protection Agency (USEPA) which require sophisticated technical systems are not practicality adoptable in a broad scale in most of the developing countries regions. The most common and useful technologies for As removal in Bangladesh as well as in other developing countries rely on oxidation, co-precipitation and adsorption onto coagulated flocs, and adsorption onto sorptive media (Ahmed ,2001). The oxidation processes transform neutral arsenite to arsenate ion which can easily be removed from the contaminated water. Due to availability of Potassium permangenate in developing countries and its stability, durability of shelf life, it is often preferred as an oxidizing agent(Ahmed,20010. Precipitation, co-precipitation and adsorption process involves with coagulation with metal salts ,lime and filtration which can remove arsenic as well as many suspended and dissolved solids, microorganisms, odor and turbidity and improve water quality to a great extent (Ahmed ,2001).

Table 4.5: Comparison of Arsenic Mitigation Costs in Bangladesh (Source: Ahmed, Minnatullah & Talbi,2005)

Type of Unit	Removal Mechanism	Type	Capital Cost/unit(US $)	Operation & Maintenance cost family/year(US $)
Sono 45-25	Adsorption by oxidized iron chips and sand	Household	13	0.5-1.5
Shapla Filter	Adsorption of iron-coated brick chips	Household	4	11
SAFI filter	Adsorption	Household	40	6
Bucket Treatment Method	Oxidation and coagulation-sedimentation-filtration	Household	6-8	25
Fill and Draw	Oxidation and coagulation-sedimentation-filtration	Community (15 households)	250	15
Arsenic Removal Unit for Urban water Supply	Aeration,Sedimentation & Rapid Filtration	Urban water Supply (6000 households)	240,000	1-1.5
Sidke	Adsorption by granualr ferric hydoroxide	Community (75 households)	4,250	10
Apyron	Adsorptionby Al-Mn oxides (Aqua-Band)	Community(65 households)	BDT 0.1/L/100 ppb arsenic concentration in water	
Iron-Arsenic removal Plant	Aeration, Sedimentation, Rapid Flitration	Community(10 Households)	200	1

4.3.3 Health expenditures:

The management of arsenicosis is a challenging task due to lack of specific treatment or management measures for the patients. Nutritional factors may modify detrimental health effects of chronic exposure to inorganic As from drinking water (Smith et al., 2000; Hsueh et al., 1995). The patients undergoing the treatment is generally advised for non-exposure to inorganic arsenic through drinking water and there are studies that exhibit substantive improvement of mild and moderate cases by intake of arsenic-free water, improved (protein enriched) diet and supplementary doses of vitamin A, E, and C(Ahmad et al.,2018). Department of General Health Services(DGHS), a public health concern of the Government of Bangladesh provide vitamin A, E, and C and some other antioxidants and keratolytic ointment for the patients which are often not sufficient enough.

A study measured the household expenditure for treatment of arsenic exposure related ailments in Bangladesh and it is estimated that households spend BDT 1,057 (USD. 15) per year for arsenic related ailments, which is nearly 0.73 per cent of the income of the household which is significant for the people living in poverty having a daily income of USD. 2 (Khan & Hossain,2011).

Table 4.6: Average annual number of patients evolving from arsenic contamination in Bangladesh (Source : Maddison, Luque, and Pearce 2004, p. 32.)

Impact on health/type of illness	Males	Females	Combined
Cancer cases: fatal cancers/year	3809	2718	6528
Non fatal cancer cases	1071	1024	2095
Total cancer fatalities accumulated over 50 years	190,450	135,900	326,400
Arsenicosis cases: Keratoses	277,759	74,473	352,233
Hyperpigmentation	654,718	316,511	971,230
Cough	21,823	68,887	90,712
Chest sounds	144,831	67,025	211,858
Breathlessness	93,247	176,874	270,122
Weakness	132,927	240,176	373,104
Glucosuria	67,887	63,551	131,439
High Blood Pressure	94,396	88,366	182,762
Total arsenicosis cases in each year	1,487,588	1,095,863	2,583,460

4.3.4 Effects on Work Efficiency (Goal 8)

The arsenic contamination may create physical weakness, sleeplessness, body pain and itching, sore in legs, headaches, dizziness. A cross-sectional study (Molla et al.,2004) carried out on 168 people in Chandpur district(sub-division), Bangladesh to assess the socioeconomic consequences and disease burden in terms of Disability Adjusted Life Years (DALYs) due to arsenicosis found strong relationship ($p<0.005$) between duration of suffering and occupation of the affected people. The study also found the future possibility of 47% of the patients living with disability for more than 51 years ,existence of a strong relation ($p<0.002$) between educational level and Years Lived with Disability (YLDs) and significant loss of total 7930 YLDs were lost due to arsenicosis.

4.3.5 Added Expenditure in Irrigation (Goal 8)

The agriculture sector which employs 45 percent of Bangladesh's workforce (11.06 million farmers) depends on both electricity run and diesel run pumps for extraction of ground water for irrigation. About 1.34 million diesel pumps consuming 1 million tons of diesel (25% of the total diesel usage)and 270,000 electric-run pumps (consuming 4.58% of the total electricity generation in Bangladesh) were in operation for irrigation purposes in Bangladesh (Bangladesh Petroleum Corporation (BPC),World bank,2015).

The available depth of available arsenic –free ground water has been changing in Bangladesh for various reasons. Some arid regions of Bangladesh rely on extensive usage of ground water for irrigation and there are estimation of depletion of renewable ground water in those regions .The supply of arsenic free water for the usage in households, industries, agriculture and other purposes is resulting in increased expenditures for the water extraction, the increased usage of fossil fuels and extra import costs meaning the welfare loss for the people as the fuel used in irrigation sector is subsidized by the government.

4.4 Environmental Cost (Goal 7)

Emission of CO_2 is associated with production of electricity from non-renewable sources. In Bangladesh electricity is mainly produced from non-renewable sources. Electricity is used for extraction of ground water in households, agriculture and industries. The irrigation activities in Bangladesh involve diesel operated pumps as most of the rural agricultural fields do not have access to electricity. It is estimated that the increased usage of irrigation pumps add 0.25 million ton CO_2 in dry season (Al-Masum, 2012). The installation of solar pumps in recent years for irrigation might decrease CO_2 emission in future but the current rate of substitution of diesel operated pumps will need substantive amount of investment and time.

Table 4.7: Emission of Pollutants from a 500W Diesel pump(adapted from Al-Waeli et al.,2018)

Pollutant	Emission (Kg/yr)
CO_2 (carbon-Dioxide)	924
CO(carbon Monoxide)	2.28
HC(Unburned hydrocarbons)	0.253
PM(Particulate Matter)	0.172
SO_2 (Sulphur Dioxide)	1.86
NO_x (Nitrous Oxides)	20.4

4.5 Social Exclusion & Discrimination against women (Goal 5)

Arsenic contamination not only affects physical health of the people but also creates extensive social implications such as increase of poverty, discrimination, ostracism, social exclusion among the people who are predominantly poor and less educated (Brinkel et al., 2009; Chowdhury et al., 2006 , Hassan et al., 2005). The arsenic contaminated poor people often remain untreated due to financial constraints, social superstitions and result in social problems which often lack in recognition and cognizance (Argos et al., 2007, Chowdhury et al., 2006.). Visible skin lesions through arsenic contamination create social stigmatization and discrimination as the unaffected people consider the affected people as leprosy patients and hence avoid and isolate them (Grunner, 1990; Sarker, 1999; Tsutsumi et al., 2004). The Children of the people having skin lesions are often discouraged from attending school (Brinkel et al.,2009; Keya ,2004).

The people with skin lesions are discriminated in their marriage lives as there are cases of divorce or separation due to the arsenicosis (Brinkel et al.,2009; Chowdhury et al., 2006; Keya, 2004). Women with skin lesions are most discriminated and their families suffer for dowry, physical torture, and polygamy and often abandoned by their spouses and families (Chowdhury et al., 2006).

Table 4.8: Arsenic Contamination & Society (Source: Brinkel et al.,2009)

Social problems	References
Social Instability, Superstition & Ostracism	Brinkel et al.,2009;Chowdhury et al.,2006; Hassan et al.,2005; Keya,2004; Sarker,1999;Tsutsumi et al.,2004;
Nuptial problems(Discrimination against Women)	Brinkel et al.,2009;Chowdhury et al.,2006; Keya,2004;
Mental health	Asuki,2003; Brinkel et al.,2009;Fujino et al.,2004;Khan et al.,2006;Keya,2004;Zierold et al.,2004

5. Discussion

The concept of sustainable development is based on three essential components: social, economic and environmental, which are interlinked and are not mutually exclusive i.e. one component cannot be analyzed without taking consideration of the others. This thesis intended to explain how these three essential components of sustainable development will be affected by the arsenic contamination quantitatively and qualitatively through literature reviews. The availability of the time-series data in Bangladesh on various indicators concerning these three components could have explained the adverse effects on the potential goals of Sustainable Development Agenda 2030 comprehensively and conceivably.

The thesis could not provide with a quantitative, comprehensive analysis of the effects of arsenic contamination on attaining various goals of Sustainable Development Agenda 2030 due to the limitations of both scientific and socio-economic research on arsenic contamination in Bangladesh.

Most of the scientific research to date concentrated on geomorphological analysis of the arsenic contamination, treatment options, case control studies on skin lesions, carcinogenic effects, effects on pregnancy and other health effects in some particular areas. The conclusive scientific explanations concerning spatial, temporal and seasonal variability of the arsenic concentration as well the source (anthropogenic/geological) of organic carbon mediating in the reduction process of arsenic from the sediments might have assisted greatly in policy interventions. The conclusive analysis in identifying safe depths for extracting ground water for households and agriculture in the long term will minimize the social, economic and environmental vulnerability. Moreover, studies of the health effects in a large population along different geological regions are required. Most of the studies concerning the health effects on the arsenic contaminated people were conducted in a particular sub-division (Araihazar) of Bangladesh providing non-conclusive results on the extent of health effects on the Bangladeshi population in its entirety, as the severity of contamination not only depends on the concentration level but also on factors such as genetics, health profile and nutritional deficiencies, which vary greatly among regions. The limited availability of scientific data to estimate the total intake of inorganic arsenic through daily intake of water, consumption of arsenic-contaminated rice, non-rice diet and also the water used for cooking for the population of Bangladesh could be considered as one of the major constraints of exhibiting the actual daily exposure to inorganic arsenic in Bangladesh. The total amount might go beyond the prescribed limit of Bangladesh standard and WHO standards of ingestion of arsenic for a larger population. Comprehensive research on the health effects on the population of different regions will provide necessary input for policy intervention. The lack of scientific research on the effects of arsenic contamination on agricultural productivity in Bangladesh is also a significant constraint when analyzing the socio-economic effects of this contamination for the agrarian rural economy of Bangladesh.

However, several studies concerning the socio-economic analysis of the contamination are available. Barakat (2002) analyzed the socio-economic effects of the contamination through a survey conducted in a sub-division of Bangladesh. At least 20 sub-divisions have 20% households with arsenic concentration above Bangladesh standard in accordance with the conducted field data collection results exhibited by the MICS 2009 & MICS 2012-2013. It could be inferred that a full economic analysis of the effects of Arsenic disaggregated to the local level requires data on increased household expenditures due to treatment of water, added expenditures for medical treatment, estimations concerning agricultural productivity loss, quantification of economic productivity loss through loss of work-efficiency, estimations on added expenditures for extraction of ground water for to reach safe water depth, estimations of environmental costs, estimations of the long term health effects on demographic dividends. However, a national set of indicators and methodology for evaluation of socio-economic effects of arsenic contamination on various goals of SDG could have provided a concise explanation.

The social effects of arsenic contamination have not attracted much attention both from researchers and policy makers. A very few notable literatures could be discussed. The social problems generally evolve through skin lesions, the most significant evidence of the arsenic contamination. The socio-economic status of affected people can be credited to superstition and mis-perception related to the acceptance of the skin lesions as a health consequence of regular exposure to of inorganic arsenic. Other notably exhibited social problems as evinced through research are non-attendance of schools by affected children, discrimination against women, social exclusion, complications in nuptial bonds, mistreatment from the family members and negatively affected intellectual development of children require to be supported by empirical evidence through extensive scientific research on a large-enough sample covering spatial and social variance. Extensive research on behavioral economics is required to analyze the acceptance of mitigation options for the population affected by arsenic and subsequent policy formulation. Some of these issues addressed here are discussed in more details below.

5.1 Unavailability of country-wise data for estimating safe limit of total daily inorganic arsenic consumption

The availability of data concerning arsenic exposure through Soil-water-plant nexus for various geographical locations of Bangladesh is needed to determine the vulnerability of people to arsenic exposure. There is no safe limit of arsenic set by the government of Bangladesh concerning the concentration on soil and the food in Bangladesh.

5.2 Spatial variability of arsenic concentration

In Bangladesh, various researchers have found the high variability of arsenic even in the 100 feet range between a safe and non-safe tube-well. (Chakraborti et al., 2010; McArthur et al. 2004, Van Geen et al. 2014).

The spatial variability of arsenic concentration has made the policy formulation tough for the policy-makers.

5.3 New scientific findings concerning arsenic contamination in various countries & its implications for Bangladesh

Most of the recent notable scientific research (on arsenic contamination of ground water in Most of the recent notable scientific research (on arsenic contamination of ground water in Bangladesh have been conducted in Araihazar (sub-division in Bangladesh) and its adjacent areas which lies in flood zone of Bangladesh. Other monitoring centers in different parts of the country could have provided more supportive or less supportive data, as the susceptibility and health consequences will vary with the socio-economic status of the population in other zones of Bangladesh. Recent scientific research has provided new directions. The contamination of deep aquifer stressed from over pumping was observed in California, USA (Smith et al., 2018). The stress initiated high vertical hydraulic gradients, subsequently released large volume of water passing through less-permeable clays and induced high arsenic concentrations in the ground water which is contrary to the horizontal flow of ground water through the sediments with highest permeability under natural conditions. Similar kind of observations were observed in Mekong Delta, Vietnam (Erban et al., 2013). Michael & Voss (2008) suggested that the extraction of deep ground water could be a sustainable option in Bangladesh if the water is extracted for domestic use only. Further research concerning all the geological zones is necessary to confirm this hypothesis. Erban et al, 2013 also found the co-relation between arsenic contamination and land subsidence in the larger parts of Mekong Delta, Vietnam and some parts of Cambodia. The study showed that extraction of deep groundwater extraction causes compression and compaction among the interbedded clays and thus expel water containing dissolved arsenic or arsenic containing compounds. The study showed that extraction of deep groundwater extraction causes compression and compaction among the interbedded clays and thus expel water containing dissolved arsenic or arsenic-

mobilizing solutes to deep aquifers over long period and cause a subsequent land subsidence. The usage of In -SAR analysis in this study estimated subsidence rates throughout the region and these rates were found related to spatially-explicit effects of groundwater extraction. The same study recommended similar kinds of In-SAR based studies to be conducted in South & South-East Asia. If arsenic is also found in deep ground water of Bangladesh as it was found in Vietnam and Cambodia, the policy of using deep ground water will require to be revisited and different arsenic –free drilling recommendations have to be established for different zones of Bangladesh. The incidence of arsenic contamination induced land subsidence in Bangladesh will cause significant loss of bio-diversity, loss of cultivable and usable land.

In a river-aquifer interface; water is discharged from aquifer to rivers. Stahl et al., 2016 observed the opposite scenario in a river-aquifer interface in a village named Van Phuc, situated at 10 km southeast of Hanoi, Vietnam. The research found water and sediment flow from the mentioned river to a heavily extracted aquifer adjacent to the river bank and subsequent increase of arsenic contamination in the aquifer due to extensive abstraction of ground water. The researchers suggested the vulnerability of aquifers from riverine recharge flows carrying recently deposited sediments and elevated level of arsenic concentration throughout South and Southeast Asia. In Bangladesh, many shallow aquifers may reach saturated conditions during the monsoon while some aquifer may have very depleted conditions during dry season and there are evidences of negligible base flow discharges from groundwater to upper reaches of the River Surma-Meghna during the dry season. (Shamsudduha et al., 2011). The depleted conditions of the ground water in some parts of Bangladesh might trigger flow of water along with recently deposited sediments and arsenic from river to recharge nearby aquifers.

Moreover, most of the scientific research on analyzing the presence of arsenic in ground water of Bangladesh has credited microbially mediated oxidation of organic carbon as driving the geochemical transformations that release arsenic from sediments. However, confirmatory results showing the exact circumstances of the release of adsorbed As from the sediment to groundwater by organic carbon is yet to be established after two decades of research. This might be important in policy formulation of arsenic mitigation (Whaley-Martin et al., 2017) . A long—term debate has been going on to ascertain the source of organic carbon as being natural versus anthropogenic. Achieving closure will be important for formulating a holistic policy, as anthropogenic sources such as human waste (Harvey et al., 2002; McArthur et al., 2008), man-made ponds (Lawson et al., 2013; Neumann et al., 2010), or wetland/rice paddy environments (Meharg et al., 2004; Polizzotto et al., 2008; Stuckey et al., 2016) could contribute to the release of organic carbon (Whaley-Martin et al., 2017; Burgess et al., 2010; Michael and Voss, 2008).

The research team of Neumann et al., 2010 suggested extraction of shallow water beneath the ground of irrigated rice field for usage in irrigation and deep water below the ponds for household consumption as those were found to be arsenic safe, albeit only in a particular zone of Bangladesh. If similar kinds of scientific observations could be made for other regions, this hypothesis of Neumann et al., 2010 could provide a decisive decision concerning the sustainable extraction of ground water in Bangladesh.

Scientific research might provide policy-makers the opportunity to take measures to limit the anthropogenic sources of organic carbon responsible for the release of arsenic from the sediments to the ground water. Whaley-Martin et al., 2017 found that the household human and livestock waste is contributing as a source of organic carbon the arsenic release from the sediments to shallow ground water in Bangladesh. Further scientific research concerning the contribution of the human and livestock waste might provide the economic viability of sewerage treatment in the rural areas of Bangladesh in policy-decision making level to recover nitrogen, phosphorus and potassium from human waste to be used in agriculture and hence contribute to agricultural productivity if it is confirmed that the untreated human waste is one of the sources of the organic carbon responsible in the reduction process of arsenic from the sediments .

5.4 Availability of socio-economic data for estimations of economic vulnerability

Work day loss, non-attendance of schools, medical expenditures for arsenic treatment, agricultural productivity loss, water treatment cost on the household level, environmental cost for irrigation and extraction of water use of shallow/deep water in irrigation, estimations of emission of green -house gases all need to be figured into a comprehensive picture of the impact of inorganic arsenic. The concept of WPI (Water Poverty Index) consisting of five components(resource, access, capacity, use and environment) can provide the thesis with more insights as it combines data on qualitative and quantitative availability of ground water, information on the use of natural resources in various sectors i.e. agricultural sector , access to household water (measured as time spent to collect water), access to surface and ground water for irrigation, socio-economic capacity of the population (education, pension, under-5 mortality rate , household water consumption rate etc.).

The usage of WPI in this case could have also provided with the possibility of construction of figures such as pentagons representing five components to depict the effects of arsenic contaminated water situation in understandable pictorial representation. The simplicity of such representation could exhibit the effects of arsenic contamination for a particular region and provide comparability options to measure the effectiveness of policy measures and design possible interventions.

The thesis pursued to estimate WPI for different arsenic contaminated sub-divisions of Bangladesh but could not estimate it as the data on water quantity, quality, access to water, house-hold consumption of water, household income etc. at sub-division level of Bangladesh was not available. Moreover, the time constraints played a big role in doing estimations for the data-gap.

However, arsenic concentration related surveys such as BGS (2001), MICS 2009, MICS 2012-2013 lacked data fields such as chemical water quality, access to water, daily water consumption, and health status of the arsenic affected households.

5.5 Health status and vulnerability to the adverse effects of arsenic contamination

The presence of As in hair and nail samples in Bangladesh exhibited that that many people living in the As-impacted areas of Bangladesh and West Bengal that are drinking As-contaminated water may not exhibit skin lesions but can be affected sub-clinically (Chakraborti et al., 2017). The severity of health effects due to arsenic contamination Government of Bangladesh has set a threshold value of arsenic concentration, which is well above the limit set by the WHO. If we consider possible ways of ingestion of inorganic arsenic in daily life ((i) drinking water (ii) staple food: rice and (iii) cooking food with arsenic contaminated water (iv) ingestion of food in daily diet excepting rice), the total ingestion of inorganic arsenic by the exposed population will cross the prescribed limit of WHO (provisional tolerable daily intake (PTDI) of 2.1 µg As/kg-day). Some studies estimate that rural people in Bengal delta (West Bengal, India & Bangladesh) consume 3-6 liters of water depending upon their occupation, whereas the WHO limit has been fixed based on the assumption of 2 liters of water consumption by adults (Chowdhury et al., 2001; Milton et al., 2006; Watanabe et al., 2013). The presence of inorganic arsenic in the food chain is based on market based studies in some regions. A direct correlation between As concentrations in irrigation water and common dietary vegetables was found (Kile et al., 2007). The issue of cooking with As-contaminated water also deserves policy attention as an additional source of exposure because rice absorbs twice its weight in water when cooked (Bae et al., 2002).

5.6 Acceptance of Remedial measures

A research (Inauen et al.,2013) conducted in southern Bangladesh concerning the acceptability of eight measures to achieve non-exposure of arsenic contaminated water found that people prefer a piped water connection over all other options (deep tube well, pond sand filters, community arsenic removal, dug-well, well sharing, rain -water harvesting, household arsenic removal) for the supply of household water. People also expressed their affinity towards the use of household level filtering of contaminated water in comparison to other options through collection of the water from DTW. However they have reservations about the usage of DTWs due to the time required to collect water. A comparison of field and laboratory measurements of arsenic in groundwater of Araihazar, Bangladesh indicated that the most widely used field kit correctly determined the status of 88% of 799 wells relative to the local standard of 50 µg/L with some inconsistency which could have been avoided by increasing the reaction time from 20 to 40 minute for filtering the water (Chakraborty et al., 2010).

Table 5.5 . Behavorial Trends towards different arsenic mitigation measures (Source: Inauen, Hossain, Johnston, & Mosler, 2013)

				Overall		Piped water supply		Deep tubewells		Pond sand filters		Community arsenic-removal		Dug wells	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*
Non-users	3.20	0.74	2.72*	0.75	3.24	0.58	3.48*	0.70	3.39	0.70	3.09	1.00	3.25	0.87	2.97*
Users	3.40	0.67	3.45	0.66	3.44	0.57	3.48	0.53	3.45	0.58	3.60*	0.64	3.13*	0.77	3.27
Non-users	0.78	2.04	0.11	1.97	1.15*	2.18	0.22	2.20	0.73	1.79	1.16	1.88	0.47	2.41	0.46
Users	22.28	1.85	22.75*	1.64	22.18	2.07	22.45	1.72	22.34	1.59	21.50*	2.27	22.01	1.77	22.33
Non-users	1.73	0.61	1.71	0.59	1.85*	0.54	1.57	0.66	1.68	0.57	1.25*	0.64	1.69	0.61	2.02*
Users	1.93	0.47	1.90	0.44	1.95	0.48	1.91	0.44	1.92	0.44	1.73*	0.52	1.90	0.47	1.95
Non-users	1.96	1.81	2.50	1.10	2.48*	1.46	1.43	2.18	1.33	2.12	1.05*	2.24	1.42	1.81	2.22
Users	3.11	1.16	3.55*	0.60	3.21	0.90	2.95	1.23	2.78	1.65	2.40*	2.10	2.85*	1.02	3.17
Non-users	1.96	1.67	2.83*	0.79	2.66*	1.15	1.07*	1.86	1.06*	2.15	1.20*	1.87	1.47	1.72	2.16
Users	2.77	1.41	3.20*	1.25	3.15*	0.86	2.77	1.03	2.04*	1.92	2.22*	2.09	2.48*	1.32	2.82
Non-users	2.38	1.20	2.06	0.94	2.83*	1.03	2.77*	1.17	2.61	1.03	2.16	1.13	2.44	1.00	1.13*
Users	1.52	1.04	1.14*	1.00	1.47	1.10	1.56	1.05	1.48	1.02	1.88*	1.03	1.96*	0.85	1.09*
Non-users	1.11	0.89	1.39	0.70	1.07	0.89	1.23	0.74	1.45	0.97	1.27	1.04	1.42*	0.77	0.64*
Users	2.28	1.06	2.60*	0.86	2.72*	1.18	2.42	0.91	2.59*	0.84	1.97*	0.78	1.78*	0.81	1.22*
Non-users	2.40	1.80	2.61	1.09	2.66	1.83	2.60	1.73	3.00*	1.52	2.30	1.84	1.56*	2.03	1.79*
Users	3.13	1.36	3.54*	0.70	3.02	1.54	3.20	1.12	3.27	1.12	3.17	1.61	2.31*	1.72	2.82
Non-users	1.99	0.99	1.50*	0.34	2.94*	0.78	1.21*	0.60	1.29*	0.57	1.46*	0.53	1.39*	0.63	1.51*
Users	1.87	0.87	1.50*	0.64	2.83*	0.75	1.15*	0.46	1.41*	0.47	1.45*	0.48	1.44*	0.00	1.74
Non-users	1.37	1.15	2.50*	1.04	1.18*	1.09	0.93*	0.99	1.45	1.03	1.52	1.15	1.33	1.10	1.56
Users	3.27	0.86	3.68*	0.65	3.10*	0.88	3.42	0.73	3.27	0.65	2.83*	1.17	2.94*	1.02	3.27
Non-users	0.97	0.96	2.39*	0.78	0.63*	0.75	0.95	1.10	1.15	0.91	1.11	0.91	1.11	0.95	1.06
Users	2.06	1.06	2.44*	0.90	1.89*	1.05	2.08	1.06	1.89	0.98	1.76*	1.01	1.69*	1.06	2.04
Non-users	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Users	0.26	0.56	0.21	0.53	0.40*	0.70	0.20	0.54	0.20	0.43	0.43	0.77	0.19	0.40	0.00
Non-users	1.42	1.18	2.06*	0.94	1.06*	1.05	1.62	1.12	1.24	1.20	1.63	1.34	0.97*	1.11	2.06*
Users	3.13	0.89	3.60*	0.53	3.02	0.90	3.28	0.74	3.17	0.81	2.68*	1.32	2.79*	0.95	3.00

5.7 Future vulnerability to arsenic contamination due to exposure throughout pregnancy

Some studies in Bangladesh showed the adverse effects of arsenic on newborn children resulting from the exposure to contamination during pregnancy. Cases of spontaneous abortions, stillbirths, and preterm births have been reported for women from the severely As-affected village, Eruani of Bangladesh (Ahamed et al.,2006; Rahman et al.,2007) This topic requires much attention of research as the demographic dividends of Bangladesh could significantly be affected by defected births.

6. Conclusion & Way Forward

The arsenic contamination in Bangladesh has raised the very basic question of significance of Science-Policy nexus in sustainable development and the indivisible role of coherent policy formulation in ensuring optimum public welfare. The significance of scientific research , observations and empirical evidences of possible adverse effects brought by anthropogenic activities are not often even prioritized in policy formulation in developed countries whereas the science-policy nexus receive minimum attention in the developing countries .The introduction of usage of ground water for consumption in the households in Bangladesh clearly bears the testimony of suppression of prior scientific research in policy formulation .The adverse effects of arsenic contamination in the ground water was evinced from Chile , USA and Taiwan long before ground water was introduced for household consumption in Bangladesh and hence the indifferent attitude of not taking consideration of possible existence of inorganic substances in ground water under varying conditions exposes the vulnerability of the public welfare in developing countries through the patronization of international organizations such as UNESCO ,World Bank and the government itself. The policy recommendation for consumption and usage of ground water having unconfirmed chemical or microbial quantities might have fulfilled some of the goals in the pursuit of MDG agenda of Bangladesh but it might be one of the thousand cases where poor coordination of science-policy nexus exhibited the extent of effects on human health, economy , environment and society aggravated through anthropogenic activities. The naturally occurring high concentration of arsenic in ground water of Bangladesh is a present reality which might seem to be the most prominent lethal inorganic substance but there lies the threat of existence of manganese, chloride and other substance beyond the WHO standards in the ground water and therefore the continuous monitoring of ground water requires policy intervention. The highly vulnerable people of the once worst hit arsenic affected zones in Bangladesh require follow-up health check although the exposure risk might have significantly decreased. The effectiveness of mitigation measures requires much more attention and scientific studies. The continuous testing of soil quality, fixing and testing of the tolerable limit of inorganic arsenic in food chain requires immediate policy actions. Some scientific studies have shown the adverse effects of arsenic contamination on intellectual development of children, loss of work days and efficiency. The arsenic contamination has created social discrimination and exclusion in the affected regions where poverty, malnutrition and attendance of schools are notable which did not receive proper attention in Bangladesh. The studies are required to find the adverse effects on the malnourished and stunted population. There might be significant difference of effects on malnourished population of Bangladesh in comparison to that of Argentina, Chile, Taiwan and USA. The environmental cost of increased electricity consumption of extracting ground water from increased heights also needs to be estimated. In a summary, these actions of continuous monitoring the adverse effects of arsenic on public health, agriculture, food safety, economy, environment and society require integrated policy formulation and establishment of zonal research, development and monitoring centers for ground water. These centers need to be integrated with the supply and distribution of ground water .The fulfilling of many goals in Sustainable Development Agenda would largely depend on the quality and extractable quantity of ground water in developing and developed countries. The deteriorating quality of surface water due to anthropogenic activities ,the chemical quality of ground water contaminated by arsenic, manganese, chloride etc. ,disturbed water cycle due to climate change would put a lot of stress policy makers on finding safe level of ground water for ensuring food security, house-hold consumption and industrialization. These would challenge the attaining of SDG goals in any developing country and the proper Science-Policy-Business nexus would be the key to mitigate the ground water quality crisis in any geographical region.

6.1 Way Forward

The thesis could have provided the effects of arsenic crisis in the social, economy and environmental domains through quantitative interpretation if times-series data was available. The mitigation measures of the arsenic contamination in ground water used in households, agriculture in Bangladesh need to consider the effects of water-soil-crop nexus. and hence require holistic policy attention for development of infrastructure of piped water supply, metering of municipal water supply, international cooperation for river basin management, R&D on efficient technology of arsenic removal in households, invention of water efficient technology for appliances in households, agriculture, industry and significant investment/funds. The priority has to be fixed. The infrastructure development for household water supply needs long term strategic planning and significant investment which is far reaching plan and there are very few alternatives alternative to it to solve the microbial contamination through the transportation media of the ground water and continuously monitoring of it (MICS 2012-2013). Setting up of scientific research centers throughout Bangladesh for continuous monitoring, observations and conduction of scientific surveys in different geological zones of Bangladesh for ground water also requires significant investment and time but it needs to be prioritized and implemented through international cooperation (SDG Goal-17).

The arsenic testing in ground water along with regular health check-up could initially be conducted by setting up laboratory facilities at local high schools in sub-divisions level besides providing the high school students the necessary education concerning filtration, maintenance of the arsenic removal kits etc. The students of the Universities need state of art facilities, research and development opportunities concerning arsenic removal technologies, development of water efficient appliances, conducting research concerning the effects of arsenic on health, economy, environment and society to contribute in policy formulation for the government. Most of the researches concerning the arsenic contamination in ground water and the mitigation technologies have been conducted by the North American researchers and students. Bangladesh needs international cooperation in development of infrastructure for research development of capacity for the research. A recent scientific innovation of developing bio-sensors by a research team led by Dr. Baojun Wang from the School of Biological Sciences, University of Edinburgh could assist greatly in testing the arsenic contaminated water with affordable costs. The researchers developed the bio-sensor manipulating the genetic code of bacteria Escherichia coli which would act as amplifiers in the test kit. The bacteria is suspended in a gel in a plastic device where water has to fed in and produces fluorescent proteins that could be visible in the presence of arsenic (Wan et al., 2019). The led researcher confirmed that the test results through the bio-sensor kit had consistent results through lab-based standard tests and hoped that device could act as a very lost cost solution of arsenic test kits that are used now.

Bangladesh needs to also conduct testing of the arsenic concentration in the food-chain to determine the possible build-up of arsenic concentration.

Bangladesh needs international cooperation in such infrastructure development of state of art laboratories, R&D facilities in high schools and universities rather than financial aid as the country has poor record of proper utilization of development aid in the form of financial means. Germany and South Korea are the only exceptional examples where the international development aid after WWII assisted the reconstruction of those economies.

The effectiveness of international aid which is the public money collected through taxation in developed countries needs to be revisited which are often politically motivated and assists thriving of corruption through misuse of the funds. The arsenic contamination case might be one of the very few cases among thousands which is well exposed but does not get proper attention of the international development agencies and development cooperation of rather some universities of North America. The aftermath of any aid need to be publicly exposed. International aid minimizes the effects of any crisis in the short run and aggravates the problems in the long run due to lack of Science-Policy-Business nexus.

Currently there is one privately operated center for arsenic research established by the Earth center of Columbia University in one of the sub-divisions of Bangladesh. The survey of the health status of the population will not only provide one of the most important tangible benefits of such kind of research but also provide insights for policy interventions. Therefore, Bangladesh needs to establish such kinds of monitoring centers to lessen the negative effects of arsenic contamination on various goals of Sustainable Development Agenda :2030.

The extraction even at household level might seem to be very implementable public policy intervention of improved water supply in a non-existent Science-Policy nexus.

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