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Freedom Water Filtration System: a Solution to the Arsenic and Pathogen Contaminated Water Crisis in Bangladesh & Other Underdeveloped Nations

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Abstract: Arsenic, pathogenic bacteria and various types of inorganic and organic contaminants in surface and groundwater remain a significant health concern in Bangladesh and countless other nations around the world. Each year more than four million children die from cholera, diarrhea and other water borne diseases while millions of people continually suffer from contaminated drinking water. Despite global initiatives, currently about one billion people around the world do not have access to clean and healthy water. More than 500 million people in Bangladesh, India, Nepal, Cambodia, Pakistan, Vietnam and other nations have been exposed to the groundwater arsenic poisoning for the last few decades. Groundwater arsenic poisoning in Bangladesh is among the largest disasters in the history of human civilization. Many scientists from around the world are working extensively to discover a solution to the problem, but no one has conducted integrated and comprehensive investigations thus far. The most common misconception is that the arsenic crisis in the Bengal Basin is a natural disaster and that the poisoning has been present in the groundwater of Bangladesh for thousands of years. The analysis of geochemical, hydrogeological, arsenic toxicity data, surface and groundwater use data in Bangladesh revealed that the groundwater arsenic poisoning in Bangladesh is a recent man-made disaster. The exposure and subsurface oxidation of arsenic bearing minerals previously below the water table appear to be the principal mechanism for releasing arsenic into groundwater. The subsequent migration of arsenic oxides in solution to the groundwater through the upper layers of deltaic sediments is the principal cause of arsenic poisoning in water sources throughout Bangladesh. Arsenic bearing minerals of several kinds are associated with the organic rich sediments present in deltaic environments. The groundwater table is significantly lowered for the last 35 years by increased irrigation during dry season. Over the years, a cone of depression was formed by pumping tube wells and irrigation wells below the thousands of year's old zone of fluctuation. Increased irrigation become necessary during India's 35 years of unilateral harvesting of river water from the Ganges, Teesta and 28 others common rivers of Bangladesh and India. Dams and barrages were built, such as those on the Ganges and Teesta rivers, which cut the normal flow of more than 30 rivers during the dry season. The arsenic bearing minerals in the newly exposed sediments oxidize and release the arsenic during the wet season when the water table recovers and exposes the oxidized minerals to a reducing environment. The Freedom Water Filtration system is capable of combating the international arsenic crisis.It helps address the issue of waterborne diseases caused by arsenic, pathogenic bacteria and other organic and inorganic pollutants present in water. It is a mini-water treatment system which is cost effective and

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environmentally friendly and can be manufactured and used by small communities around the world. The system consists of a water filter for removing contaminants from water, a tube well for wet seasons above the recently created oxidation zone free of arsenic contamination and a tube well for dry seasons within the arsenic contamination zone due to lack of water above the newly created oxidation zone. The filter beds consist of layers of activated carbon, manganese dioxide, ferric oxides and coarse and fine grained sands and pebbles. Three models of the filter have been developed for small communities with a daily requirement of 25 liters of water per family per day which may cost as low as 3 to 4 US dollars per family per year. Over two dozen pilot projects of the Freedom Water Filtration system are currently operating in urban and rural areas in Bangladesh. The system was designed by the WATC International Water and Environment Research Center, Kansas, USA. It is based on the principles of water treatment plants for removing organic and inorganic contaminants, pathogenic bacteria, groundwater geochemistry of trace metals, remediation of arsenic, uranium, nitrate, chromium, TCE, PCE, volatile organic compounds and other organic and inorganic pollutants by Permeable Reactive Barriers. In addition, the system effectively disposes of arsenic and other harmful waste as per United States EPA waste disposal regulations. The implementation of this system will substantially reduce the waterborne diseases and prevent the recontamination of air, water resources, soil and sediments, fish products, agricultural products, poultry products, ecosystem and environment from the indiscriminate disposal of arsenic wastes and residues from arsenic removal filters and treatment units currently operating in Bangladesh, Nepal, Cambodia, Vietnam and other countries. Putting this project into effect will also help scientists, policymakers, NGOs, WHO and others understand the sources and causes of the arsenic disaster in the Bengal Basin and other arsenic affected nations. This in turn will enable the development of permanent, sustainable and environmentally friendly solutions to the problem. It will also help organizations take immediate necessary measures for the proper disposal of arsenic waste as per proven and established scientific laws and principles of geological, hydrological, hydrogeological, geochemical, biological, meteorological, toxicological, environmental and medical science as well as U.S. EPA arsenic waste disposal regulations. Strict adherence to these principles will protect the global public health, ecosystem and the environment. An integrated and comprehensive plan will be presented for the implementation of the Freedom Water Filtration System in Bangladesh and replication of the system in other arsenic and waterborne disease prone nations.

Key words: Arsenic • Aquifer • Oxidation • Geochemical • Bengal delta

INTRODUCTION

Bangladesh is located in one of the major disaster and environmentally endangered areas of the world. Prior to 1975, the country never encountered an environmental crisis of the present magnitude. More than 85 million people are being poisoned by consuming groundwater contaminated with arsenic and more than forty thousand people have been sufferings from numerous arsenic diseases such as arsenic lesions, gangrene, cancer and gastrointestinal diseases. Thousands die each year. The source of the arsenic in the groundwater that caused the poisoning has not been determined beyond a reasonable doubt by any known investigation conducted in Bangladesh to date. The source of arsenic contamination and when or how long it has been present should be determined in order to remedy the problem and prevent future occurrences.

The WATC Research Center has searched and analyzed historical groundwater use data from dug wells and tube wells in addition to medical, geological, hydrogeological, geochemical and arsenic toxicity data in order to answer the questions concerning the source and time of arsenic contamination. Until scientists thoroughly collect and analyze this information, a solution to the arsenic crisis will not be found.

Arsenic poisoning was not widely reported until the 1990s and was originally attributed to arsenic contaminated ground water obtained from tube wells installed in the 1970s to prevent disease from polluted surface water. Unfortunately no chemical analyses were made of the tube well water when they were first installed. The exact source of the arsenic that is poisoning the tube well water is not delineated, but several possible sources have been suggested based on incomplete data.

The groundwater arsenic contamination in Bangladesh is getting worse day by day. The food chain is being poisoned by irrigation water tainted with arsenic (Duxbury *et al.* 2007)[1], (Smith *et al.* 2006)[17] and (Alam *et al.* 2003)[29] . Duxbury and others reported that

"Rice yields and grain arsenic concentrations were 1.5 times higher in the boro (winter) than the summer (monsoon) season, consistent with the much greater use of groundwater for irrigation in the boro season.

Mean values for the boro and aman season rices were 183 and 117µg/kg, respectively. The variation in arsenic concentrations in rice was only partially consistent with the pattern of arsenic concentrations in drinking water tube wells. There was no evidence from yield or panicle sterility data of arsenic toxicity to rice. Processing of rice (parboiling and milling) reduced arsenic concentrations in rice by an average of 19% in 21 samples collected from households. Human exposure to arsenic through rice would be equivalent to half of that in water containing 50µg/kg for 14% of the paddy rice samples at rice and water intake levels of 400g and 4L/cap/day, respectively"(Duxbury, J.M, et.el, 2003)[2.]

Hossain and others conducted investigation on the effects of arsenic contamination in food chain. They stated that "The arsenic levels in soil varied substantially in different locations and also in rice growing seasons. The accumulation of arsenic was higher in irrigated boro (December-June) season than rain fed aman (July-November) season."

The level of arsenic ranged from 7.37-10.97 mg kg^{-1} in study areas. The highest concentration was found in Monirampur Upazilla in the Jessore district during the boro season followed by Chapainawabgonj Sadar in Chapainawabgonj district in the same season. The successive irrigation with arsenic contaminated water increased the level of arsenic accumulation of soil during the boro season. The arsenic concentration in water also varied greatly in different locations of Bangladesh. Out of 8 locations, the tube well water of 6 locations was found to be higher than the safe limit (0.05 mg L^{-1}). The tube well water from two locations of Chapainawabgonj was highly contaminated having concentrations of 0.48 mg L^{-1} and 0.46 mg L^{-1}, respectively. The accumulation of arsenic in rice grain was lower than the rice straw in all cases. The contaminated rice straw might increase the arsenic in cattle raised in areas where straw is used as feed. The leafy vegetable amaranth had higher arsenic accumulation than the fruit vegetables tomato, brinjal. Therefore, the use of leaf vegetables in arsenic contaminated areas would greatly increase health concern"(Hossain, K.M.D., et.al, 2005)[3.] Many other investigators revealed similar results on the food chain in Bangladesh.

On January 4, 2010, Meer Husain discovered arsenic levels of 40-50 ppb in coconut juice and 70-80 ppb in date juice in the Mallikpur, Jinaidha district of Bangladesh. In the Hazra village of Jenaidah Sadar Upazila, they also found arsenic concentrations of more than 100ppb in Date palm juice, 15-20 ppb in coconut juice and 15-25 ppb in cow milk. These new findings further revealed that the food security in Bangladesh is deteriorating very rapidly.

Many scientists have proposed use of arsenic removal water filters in order to provide arsenic free water to affected communities, but they have failed to address the proper disposal method of arsenic waste. The indiscriminate disposal of arsenic waste from current arsenic removal filters and treatment units, including the Sono Filter, are causing recontamination of air quality, soil and sediments, surface and groundwater, fishes, agricultural products and poultry products etc. in Bangladesh(Husain *et al.*2009)[4.] In order to protect the public health, ecosystem and environment of Bangladesh and other adjacent countries, the scientific community should immediately address the contamination and recontamination issues of the arsenic disaster in Bangladesh.

Methodology: The prevention of groundwater arsenic contamination for future generations, remediation of existing contamination and development of a permanent, emergency water supply solution to the arsenic affected communities require identification of the source and cause of the arsenic crisis. Such investigations must adhere to reliable geological, hydrological, hydrogeological, geochemical, arsenic toxicity data, historical medical data and historical groundwater use data.

We have successfully and thoroughly examined this data to find the source of the arsenic disaster in Bangladesh and a solution to the problem.

In order to develop a sustainable water supply solution to arsenic and pathogen contaminated communities, we designed a small community based water treatment system based on Zero valiant iron (ZVI), ferric oxides, manganese dioxide, activated alumina and activated carbon. About two dozen systems are currently operating in eight districts in Bangladesh. The current flow rate of arsenic free water of the filtration system is 3 to 4 liters per minute and the flow rate may be increased to 6 to 8 liters per minute by utilizing chemical and electro chemical methods.

We also established a monitoring network of seasonal changes of arsenic levels in groundwater aquifers in 12 districts. The monitoring data will assist scientists for the development of sustainable, cost effective and environmentally friendly solution to the arsenic crisis in Bangladesh. The concentration of arsenic in groundwater and filtered water is currently measured by the HACH Arsenic Test Kit, USA. In addition to the HACH testing kit, a government laboratory in Bangladesh, a university and a USEPA certified laboratory in the United States will cooperate for the analysis of split water samples. The HACH test kit has been extensively used in the U.S. The establishment of the operation and waste management system is very critical in Bangladesh and other underdeveloped countries due to the lack of arsenic waste disposal regulations. As a result, we have initiated a method of water supply and waste management through the Freedom Water Filtration system in Bangladesh.

Source, Cause and Mechanism of Groundwater Arsenic Poisoning: There are two schools of hypotheses presented by scientists regarding the source and cause of the problem. They include the Natural Disaster Hypothesis and the Recent Man-made Disaster Hypothesis.

Natural Disaster and Oxyhydroxide Reduction Hypothesis: Nickson *et al.* and BGS/DPHE investigators and others attribute arsenic contamination to the reduction of arsenic in oxyhydroxides present in sediments that were washed into valleys, cut by rivers when the sea-level was lowered during the last glacial maximum (18 ka BP). During the glacial maximum the rivers had base levels some 100 meters lower than during interglacial times. The original sediments were deposited during the Pleistocene-Holocene time and oxidized and flushed during the low-stand of sea level during this last glacial maximum. The sediments in-filling the valleys as the sea level rose during glacial melting consisted of the weathered red brown Pleistocene-Holocene sediments.

They further stated that ,"The As derives from reductive dissolution of Fe oxyhydroxide and release of its absorbed As. The Fe oxyhydroxide exists in the aquifer as dispersed phases, such as coatings on sedimentary grains. Recalculated to pure FeOOH, As concentrations in this phase reach 517 ppm. Reduction of the Fe is driven by microbial metabolism of sedimentary organic matter, which is present in concentrations as high as 6% C. Arsenic released by oxidation of pyrite, as water levels are drawn down and air enters the aquifer, contributes negligibly to the problem of *As* pollution" (Nickson *et al.*1998)[5,] (Nickson *et al.* 1999)[6], (BGS/DPHE, 1999)[7,] (BGS/DPHE,2001)[8].

Pauline Smedley stated that "Several Bengali workers have proposed that the *As* contamination of groundwater in Bangladesh is due to the oxidation of pyrite in the aquifers, brought about by over abstraction of groundwater over the last few decades as result of increased irrigation demands (e.g. Das et.al, 1996; Mandal; *et al.* 1996). While this is a plausible mechanism for *As* release, the strongly reducing groundwater chemistry with low dissolved SO4 concentrations and the lack of evidence for significant seasonal groundwater draw down in the worst -affected areas of Bangladesh make the pyrite oxidation hypothesis unconvincing. Although sulphide minerals have been identified, albeit rarely, in some alluvial sediments from Bangladesh, this does not provide evidence for pyrite oxidation as an important mechanism of arsenic release. Indeed, sulphide minerals are an expected product of sulfate reduction under the strongly reducing conditions. Alternative mechanisms, including reductive dissolution of iron oxides (Nickson et al 1998) and coupled reduction and desorption of As from iron oxides (BGS and DPHE, 2001) have been proposed as the dominant mechanisms driving the *As* mobilisation under the reducing aquifer conditions in Bangladesh. Phyllosilicate minerals (notably chlorite, biotite and Al hydroxide) have been suggested to play an additional role in the cycling of *As* in the Bangladesh aquifers, Breit *et al.* 2001" (Smedley,P.L.,2003)[9].

The BGS/DPHE investigators collected about 21 sediment and soil samples. Based on their analysis, they suggest that arsenic bearing minerals are not present in the Bangladesh's sediments. The BGS/DPHE accepted Nickson's explanation of the source of arsenic poisoning in Bangladesh. In their report, BGS/DPHE stated that "the pyrite oxidation hypothesis proposed by scientists from West Bengal is therefore unlikely to be a major process and the 'oxyhydroxide reduction' hypothesis (Nickson, R. et. el, 1998 in Nature; v395:338) is probably the main cause of arsenic mobilization in groundwater. It is difficult to account for the low sulfate concentrations if arsenic had been released by the oxidation of pyrite. Moreover, mineralogical examination suggests that the small amount of pyrite present in sediments have been precipitated since burial" (BGS/DPHE, 1999)[7].

The proponents of the natural disaster hypothesis firmly believe that groundwater arsenic poisoning in Bangladesh had been present for thousands of years, since the last glacial maximum and that oxyhydroxide reduction is the principal mechanism for the mobilization of arsenic into groundwater sources throughout Bangladesh.

Recent Man-Made Disaster and Oxidation Hypothesis: Husain and Bridge raised serious questions about the validity of the "Natural Disaster Hypothesis" for the generation of groundwater arsenic poisoning in Bangladesh. They thoroughly examined the data and evidence that the proponents of the natural disaster hypothesis presented in support of the natural disaster hypothesis. The analysis of historical groundwater use data from dug wells and tube wells, historical medical data, geological, hydrological, hydrogeological, geochemical and arsenic toxicological data and evidence disprove the natural disaster theory and support the recent man-made disaster theory for the generation and mobilization of arsenic into groundwater(Husain and Bridge, 2006)[10].

Proponents of the natural disaster hypothesis believe that arsenic bearing minerals in the Bengal delta were oxidized during the last glacial maximum. As a result, many scientists failed to examine the recent oxidation mechanism for the arsenic crisis in Bangladesh.

In order to examine both the reduction and oxidation mechanism for the mobilization of arsenic into groundwater in Bangladesh and West Bengal of India, Husain and Bridge developed the following questions and requested that the proponents of the natural disaster theory answer them.

The Questions Are as Follows:

- If the Oxyhydroxide Reduction hypothesis proposed by BGS is correct and if arsenic was present in an adsorbed form on iron hydroxide for thousands of years and existed in a solution for thousands of years in the aquifer groundwater of the Bengal Basin without being flushed out to sea, how did the people of Bangladesh and West Bengal of India avoid the arsenic poisoning prior to the 1970s when thousands of people drank water from dug wells for thousands of years and from thousands of tube wells for 60 to 70 years?
- How do you explain how millions of people in Bangladesh who drank water from millions of tube wells during the interval between the 1960's and prior to 1975, before the construction of dams and barrages and diversion of surface water by India from the Ganges, Tista and 28 other common rivers of Bangladesh and India, lack signs of arsenic poisoning?

The following information and data rejects the natural disaster hypothesis for the mobilization of arsenic into groundwater for the following reasons:

- The lag time for the development of arsenic lesions (karatosis, melanosis, etc.) in Bangladesh and West Bengal of India varies from 2 to 5 years according to S.K. Shaha, 10 years according to BGS/DPHE and 8 to14 years according to other investigators around the world.
- In Bangladesh and West Bengal, prior to 1975 and 1960, no significant abstraction of groundwater occurred. Extensive use of groundwater in Bangladesh started after 1975, where as in West Bengal it started after 1960.
- Prior to 1960 both in Bangladesh and West Bengal, millions of people drank water from thousands of dug wells for thousands of years.
- According to DPHE, in 1948 there were 50,000 tube wells in Bangladesh. According to Dipankar Chakrabortti there were 50,000 tube wells in West Bengal in use from which millions of people drank water.
- In order to establish the groundwater arsenic poisoning in Bangladesh as a natural disaster theory, BGS/DPHE investigators presented pre-1975 hydrological data of three major rivers of Bangladesh, but did not include post-Farakka or post-1975 data of any rivers of Bangladesh despite our repeated requests.
- BGS/DPHE investigators presented only a few groundwater hydrographs, but failed to present pre-Farakka/pre-1975 hydrogeological data. They mentioned significant draw down of water tables in Bangladesh and presented some hydrographs of groundwater levels in Dhaka, Bogra, Jessore, Joydebpur and Kishoreganj (BGS/DPHE, 2001)[8].
- BGS/DPHE investigators conducted mineralogical studies only in three "hot spot" locations based on only 21 samples of 55, 000 square miles of Bangladesh and reported the absence of arsenopyrite minerals. However, they reported the presence of pyrite minerals in the sediments, but did not investigate the conditions for the presence of arsenic bearing minerals in the "Neo-oxidation zone" that was created after 1975. They did not map the vertical and aerial extent of the "Neo-oxidation zone" in Bangladesh and West Bengal of India.

- The first people poisoned by arsenic were first detected in 1985 in West Bengal and in 1994 in Bangladesh.
- BGS/DPHE investigators did not investigate the pre- and post-Farakka surface water and groundwater relationship in Bangladesh and West Bengal of India.

We developed answers to the above questions based on the following sound scientific data and evidence. This information supports the recent man-made disaster theory and rejects the natural disaster theory for the generation of groundwater arsenic poisoning in Bangladesh.

Arsenic Toxicity Data in Bangladesh and West Bengal: Asian Arsenic Network reported that in 1983 and 1987, Dr. K.C. Shaha, Professor of Dermatologyof School of Tropical Medicine in Calcutta, conducted surveys in seven districts in West Bengal of India. In 1983, Dr. Shaha identified patients poisoned by arsenic who had been drinking tube well water with concentrations of arsenic ranging from 0.06-1.25 PPM and a mean concentration of 0.32 PPM. According to Dr. Shaha's survey, the time required for the symptoms of arsenic poisoning to appear varies from six months to two years and is dependent on age.

Asian Arsenic Network conducted skin examinations on 167 people from the West Bengal of India who drank tube well water for a period of time from 4 months to 45 years. The largest group (63) drank the tube well water for 6 to10 years.163 people out of 167 (97.6 %), ranging in age from 3 to 80 years, were found to have skin lesions related to arsenic poisoning (Nobuyuki Hotta,1996)[11]. Based on Dr. Shaha's survey, the AAN estimated arsenic contamination in West Bengal began around 1980-81. Other investigators, however, reported that the first arsenic patient in West Bengal of India was detected in 1985. It is important to note that in Bangladesh the youngest person poisoned by arsenic was found to be an 18 months old baby girl poisoned by breast feeding through her mother (NGO Forum).

In West Bengal of India, another group of scientists conducted arsenic toxicity study on several age groups. They reported that "we determined that the average latency for skin lesions varied from 19 to 23 years, with shortest being 10 years from first known exposure to >100 ug/liter. Conversely, prior case reports have suggested that arsenic-induced skin lesions typically occur 5 to 10 years after exposure and even shorter latencies have been observed" (Haque, R. and Smith, A.H., *et al.*2003)[12].

Historical Medical Data in Bangladesh and West Bengal: The Bangladesh Public Health and Engineering's investigator reported the identification of the first arsenic patient in Bangladesh in 1994. Fariduddin Miah a professional health engineer of DPHE, in his article "In Quest of Safe Water for Rural Bangladesh," stated "Groundwater of Bangladesh contain arsenic was known to the community only in 1994. The patients with arsenic pollution were initially detected in the bordering area of Bangladesh with primary initiative of Dhaka Community Hospital and NIPSOM. Increasing numbers of patients have been identified through limited field survey with the assistance of UNDP and Ministry of Health.

The Department of Public Health Engineering also initiated water sampling program through 4 zonal laboratories with assistance of WHO / UNICEF/ DFID since 1994"(Fariduddin,M.,1998)[13.]

The above medical data clearly reveals that the groundwater arsenic poisoning in Bangladesh and West Bengal of India is a very recent environmental disaster. If arsenic poisoning had been present in groundwater aquifer of Bengal Basin for thousands of years (since last glacial maximum), the people of these nations would have witnessed the presence of arsenic poison patients in Bangladesh and West Bengal of India thousands of years ago.

Historical Groundwater Use Data from Dug Wells and Tube Wells: There is a very strong correlation between consuming arsenic poison groundwater and the development of arsenic diseases. Prior to 1960, people Bangladesh drank groundwater from 280,000 dug wells for thousands of years. There were no arsenic poison patients detected prior to 1960. According to the DPHE record, in 1948, there were 50,000 tube wells in use in Bangladesh and according to Dipankar Chakraborti, there were another 50,000 tube wells in use in West Bengal of India. These tube wells were installed during British rule in India. The Farakka barrage was built on the Ganges river and was commissioned in 1975(Bridge and Husain, 2000)[14].

Millions of tube wells were installed between the mid sixties and seventies before the commission of the Farakka barrage constructed on the Ganges river, the common river of Bangladesh and India. During these ten years, millions of infants, children and adults drank water from the same tube wells. During that time in Bangladesh, no arsenic related diseases were known or reported. If any arsenic related diseases developed at that time, doctors would have probably diagnosed the diseases as eczema or other skin disorders because of their lack of knowledge and experience regarding arsenic related diseases. By prescribing the wrong medication and treatments, they could not cure the deadly arsenic related diseases at that time. If the arsenic poisoning was present in Bangladesh prior to 1975 before the construction of the Farakka dam and other dams in the common rivers of Bangladesh and India, we would have seen the people of Bangladesh suffering from arsenic diseases prior to 1975.

We know from Dr. Shaha's survey in West Bengal that the lag time for the appearance of arsenic diseases is two to five years. The people of Bangladesh and West Bengal have similar physical conditions and their food habits and intake of water are similar. If groundwater arsenic poisoning was present in Bangladesh prior to 1975, then millions of tube well water users between 1965 and 1975 would have certainly been poisoned by arsenic. If arsenic poisoning was present for thousands of years in groundwater aquifers, then the dug well water users would had been suffering from arsenic related diseases for thousands of years and the tube well water users for hundred of year before the construction and commission of the Farakka barrages in 1975.

In order to disprove the recent man-made disaster hypothesis proposed by Meer Husain *et al.* the proponents of the natural disaster hypothesis further postulated that dug wells are free from arsenic contamination where tube wells were found to be highly contaminated with arsenic.

Arsenic Contamination in Dug Wells Versus Tube Wells: The proponents of the natural disaster hypothesis have failed to collect and analyze representative groundwater samples from dug wells. They collected stagnant water samples from dug wells and as a result they could not find arsenic contamination in dug wells. The diameters of dug wells are very large in comparison to tube wells. The oxidation process is very efficient in dug wells than the one inch diameter tube wells. The dissolved arsenic oxidizes and precipitates at the bottom of the dug wells. The water samples that they collected appears to be arsenic free, but the samples were not representative of groundwater samples. On the other hand, in tube wells, the oxidation process was very low in comparison to dug wells and as a result, tube well water is found to be highly contaminated even at the same hydrogeological and geochemical regimes and at the same depth of dug wells.

Dipankar Charaborti of Jadabpur University, India collected more dug well water samples than any other investigators working in Bangladesh and India. Based on his survey data, he also stated that dug wells were found to be uncontaminated. The authors fully disagreed with Chakraborti's findings and interpretation. In 2004, Chakraborti revealed more dug well data that supports the notion that dug well water is not free of arsenic contamination.

Dipankar Chakrabortti reported that "So far we have analyzed more than 700 dug wells from the arsenic affected areas of West Bengal and Bangladesh. We have found 90% dug wells are safe with respect to arsenic (< 3 - 35 microgram per litre; Average 15 microgram per litre).

There are some areas where we have found arsenic contamination above 50 microgram per litre (maximum 330 microgram per litre). One such area in Bangladesh is Samta village where many dug wells are arsenic contaminated and the dug wells are shallow (10- 20 ft), recent and 2-3 ft diameter and waters have foul smell" (Chakrabortti, 2004)[15].

Chakrabortti's data clearly shows that some dug wells are not free of arsenic contamination in arsenic contaminated areas in Bangladesh and West Bengal. It is important to note that Chakraborti did not collect representative groundwater samples from any of the dug wells.

Bridge and Husain's experience with groundwater sampling as geochemist and environmental geologist indicates that if representative groundwater samples are collected from similar geological, hydrogeological and geochemical environments as in hand dug wells and tube wells in the same sampling period, then both hand dug wells and tube wells will reveal similar types of contamination. From Chakraborti's findings, it is evident that arsenic is present in dug well water today. If arsenic contamination had been present for thousands of years in groundwater in Bangladesh as suggested by BGS/DPHE investigators, then arsenic would have been present in dug wells for thousands of years as well.

There is no difference between hand dug wells and tube wells when large amounts of water are abstracted and consumed within a short period of time. Hand dug well water is collected by a balti, kalshi/ bucket with a rope, where as tube well water is collected by hand pump or electric pump. The source of water for both hand dug wells and tube wells is groundwater. Both wells are sitting in an unconfined aquifer. In hand dug wells, water comes in contact with air, oxidizes and precipitates arsenic, thus decreasing the level of concentration in comparison to the tube well water. This is because groundwater is directly abstracted from tube wells. Prior to the 1960's, about 250 to 300 gallons of water would have been abstracted from a single hand dug well and about 25 to 40 people would have consumed that water three times a day; in the morning, at noon and in the evening. The agitation and limited contact of water with oxygen occurring in hand dug wells are not sufficient enough to completely precipitate arsenic. If groundwater arsenic contamination had been present for thousands of years, as suggested by the BGS/DPHE report, then both shallow hand dug wells and tube wells would extract arsenic contaminated water. As a result water users would have been impacted with arsenic poisoning prior to 1975.

If the BGS/DPHE investigator's statement on the age of arsenic poisoning was true, then prior to 1965 the people of Bangladesh, who had been drinking hand dug well water for thousands of years, would have certainly been poisoned by arsenic. Furthermore, today we would see people suffering from arsenic diseases for generations before 1965. If proper tests are conducted on hand dug wells, we will see that high levels of arsenic concentration are present in dug well water in areas where other investigators found tube wells are highly contaminated and hand dug wells uncontaminated in similar geological, hydro-geological and geochemical conditions. The time between continuous extraction and consumption of water from hand dug wells is not adequate enough to precipitate arsenic in areas of low concentration of iron in groundwater. In other words, dug well water is not safe to drink without proper treatment.

Chakraborti's findings clearly revealed that dug wells are not free of contamination. This data also revealed that the arsenic disaster in Bangladesh and West Bengal of India is a recent environmental episode and this data rejects the natural disaster hypothesis for the presence of arsenic poisoning in groundwater aquifers of the Bengal delta for thousands of years.

Geology and Tectonics of Bangladesh: The groundwater arsenic poisoning in Bangladesh is a geological problem associated with recent human activities. Prior to 1975, the country never faced an environmental crisis of the present magnitude. Millions of tube wells in upper shallow unconfined aquifers have been contaminated with arsenic. Out of 64 districts, millions of tubes wells have produced arsenic contaminated water from 61 districts, higher than Bangladesh drinking water standards of 50 ppb (Fig. 1).

Bangladesh is located between latitude 20 degrees, 34 minutes and 26 degrees, 38 minutes, and longitude 88 degrees, 01 minute and 92 degrees, 41 minutes. The total area of Bangladesh has an area of 55,000 square miles. It is bounded by India on all sides, except near the south and a small part next to Myanmar.

Matin, Husain and others based on seismic, gravity, aero-magnetic, drilling and logging along with other geological data presented new concepts on the tectonic frame work of Bangladesh.

They asserted that "The Bengal Foredeep is a submontane Foredeep of the Arakan Yoma geosyncline, that entered the organic stage of its development in the Paleocene and Eocene time. The NE-SW trending Eocene Hinge line divided the basin into two distinct zones. The western part of the foredeep, i.e., between the Hinge zone and Indian shield outcrops, where the molasses sediments were deposited on a platform (shelf) basin, are considered as the "External Zone". Areas east of the Hinge Zone up to Arakan-Yoma Mesozoic sedimentary outcrops, where molasses accumulation on geosynclinal (Flysh) basin are considered by the authors as the "Internal Zone" (Matin&Husain *et al.* 1986)[16]. Further the Internal zone is divided into (I) The Eastern Chittagong Folded Subzone and (II) the Western Dhaka Subzone, whereas the external zone is divided into (I) The Rajshahi Subzone, (II) The Hinze Subzone and (III)The Upper Assam Subzone.

About three fourths of the country is covered by quaternary-recent alluvial sediments deposited by the Ganges-Brahmaputra-Meghna river system. The Paleocene to Pleistocene sediments are exposed in Tertiary hill ranges of Chittagong, Chittagong hill tracts, Sylhet, the Plesistocene terraces of the Madhupur tract of Mymenshing, Barind Tract, Lalmai hills in the approximately one fourth of the country.

The sediments in the External zone have been deposited on the "Basement Complex" and the age of the rocks ranges from the Permian to the Pleistocene periods. The Internal zone of basin consists of Jenam formations of the Oligocene age, Bhuban and Bokabil formations of the Early Miocene age, Tipam Sandstone and Girujan Clay formations of the Middle Miocene age, the Lower and Upper Dupi Tila formations of the Late Miocene to Middle Pliocene age, the Modhupur Clay formation of the Late Pliocene to Pleistocene age and Alluvium formations of the Pre-Holocene to Holocene age [16].

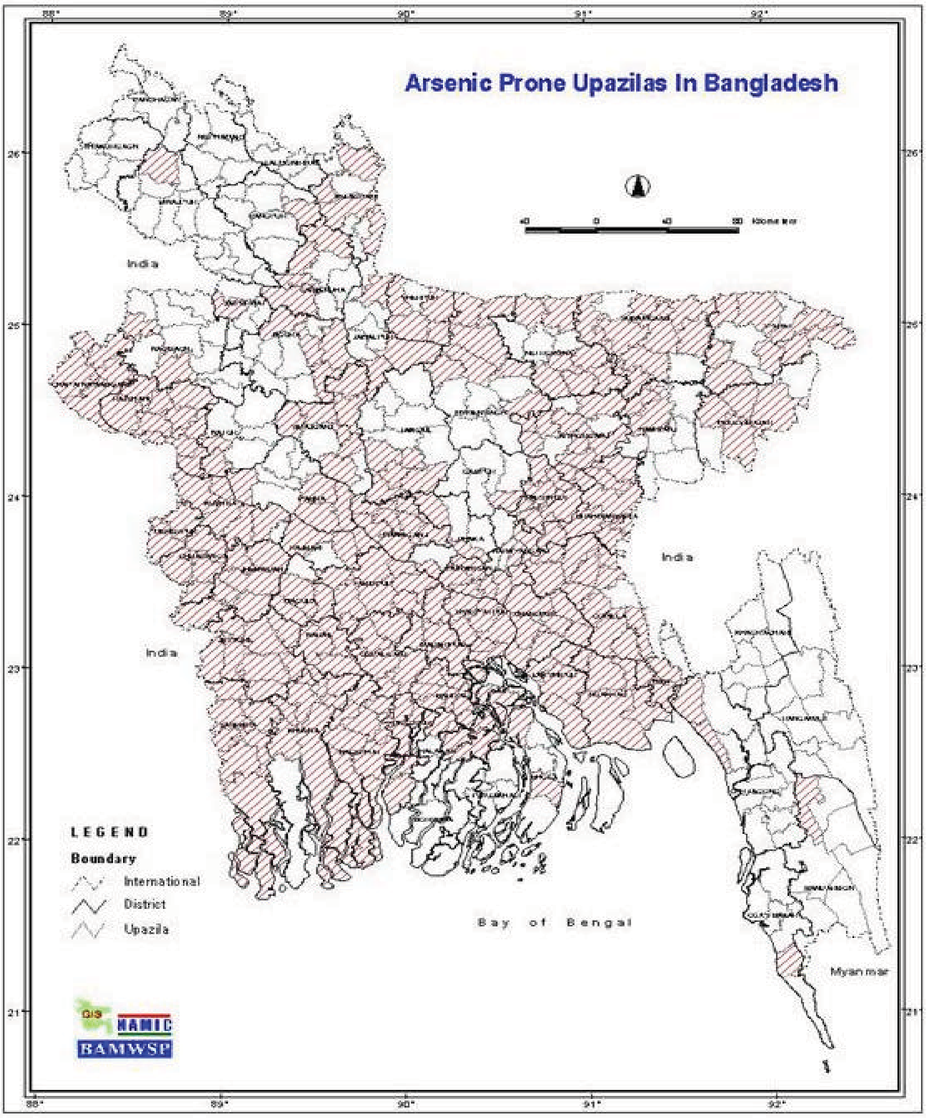


Fig. 1: Shows the arsenic affected areas in Bangladesh

Mineralogical and Geochemical Aspects of Arsenic Poisoning in Bangladesh: The proponents of the natural disaster hypothesis rejected the recent oxidation mechanism for releasing arsenic into groundwater based on inadequate mineralogical data and very poor analysis of their data. According to their study and investigation, they could not find enough arsenic bearing minerals in the aquifer sediments. Pauline Smedley, stated that "Several Bengali workers have proposed that the *As* contamination of groundwater in Bangladesh is due to the oxidation pyrite in the aquifers, brought about by over abstraction of groundwater over the last few decades as result of increased irrigation demands (e.g. Das et.al, 1996; Mandal; *et al.* 1996). While this is a plausible mechanism for *As* release, the strongly reducing groundwater chemistry with low dissolved sulfate concentrations and the lack of evidence for significant seasonal groundwater draw down in the worst -affected areas of Bangladesh make the pyrite oxidation hypothesis unconvincing. Although sulphide minerals have been identified, albeit rarely, in some alluvial sediments from Bangladesh, this does not provide evidence for pyrite oxidation as an important mechanism of arsenic release. Indeed, sulphide minerals are an expected product of sulfate reduction under the strongly reducing conditions. Alternative mechanisms,including reductive dissolution of iron oxides

(Nickson *et al.* 1998) and coupled reduction and desorption of As from iron oxides (BGS and DPHE, 2001) have been proposed as the dominant mechanisms driving the As mobilization under the reducing aquifer conditions in Bangladesh. Phyllosilicate minerals (notably chlorite, biotite and Al hydroxide) have been suggested to play an additional role in the cycling of As in the Bangladesh aquifers, Breit *et al.* 2001"(Smedley, P.,2003)[9].

The process described by Nickson and McArthur *et al.* and Smedly and Kinniburgh *et al.* suggest that the arsenic remains in solution for thousands of years and that movement of ground water through the delta sediments did not flush the arsenic from the system. They also state that the arsenic correlates well with the dissolved iron in the groundwater.

Arsenic substitutes freely for sulfur in iron sulfides (pyrites or marcasite) and the chemical analyses of water from wells contaminated with arsenic do not rule out an iron sulfide source.

Prior to the recent installation of deep tube well, the arsenic contamination with one or two exceptions was restricted to shallow aquifers (less than 80 meters). The arsenic contamination is not uniform in distribution. Some wells have high concentrations and others have low concentrations. Some wells that are relatively free of arsenic and were used for domestic use, have become contaminated with arsenic. These observations suggest that environmental changes have occurred recently and near the surface. This also suggests a non-uniform distribution of source material. A non-uniform distribution of organic matter in the sediments with arsenic pyrites would be expected.

Das,Chakraborti and others conducted a geochemical survey in six districts of West Bengal bordering the western part of Bangladesh. These districts include Mulda, Murshidabad, Bardhaman, Nadia, North 24-Pargana and South-24 Pargana. They did a subsurface investigation, some laboratory analysis and observed the presence of arsenic rich pyrite minerals in the sediments. They stated that the source of arsenic in groundwater and in the soil is from pyrite minerals containing arsenic (Das,D., *et al.*1996)[18].

The climate of Bangladesh is conducive to the formation of laterite type soils from which most of the elements have been leached out leaving behind only the most insoluble oxides such as aluminum hydroxide (gibsite), ferric oxides and hydroxides. The minerals present in saturated zones below the water table could be similar to minerals found in some marshes. Drainage of some tidal marshes or the exposure of acid-firming underclays results in acid sulfate soils (cat clays) that contain pyrite, jarosite, mackinawite and alunite (Dost, 1973: Iverson and Hallberg,1976) Some of the minerals groups present include {Beudantite group (Sr, Be, Ca, Al, Pb) FeO_3 (AsO_4, SO_4)$(OH)_6$ Jarosite [K Fe_3(SO_4, $AsO_4)_2(OH)_6$]} Alunite Group: AB3(XO4$(OH)_6$ Apatite Group.

Arsenic present in trace amounts in ground water would be concentrated in some of these minerals and released when the water table is lowered exposing this layer to oxidation.

An extensive sampling and analysis of the iron hydroxide zones at the interface of water table and reducing zone would reveal the presence of these arsenic bearing minerals (Bridge and Husain, 2000)[14] and (Bridge and Husain,2001)[19].

George Breit and other discovered the presence of arsenic in iron oxides and sulfides in the sediments above and below the capillary fringe zone at the Brahmanbaria area adjacent to the Tripura State of India. They also reported that "Holocene sediments collected above the capillary fringe are yellow-brown and characterized by abundant 0.5 N HCl extractable ferric iron. Sediment below the water table is grey to black and contains 90% of 0.5 N HCl extractable iron as ferrous. Pleistocene sediment recovered from one borehole is also characterized by a yellow-brown color due to grain coating ferric oxides. Total arsenic concentrations range from <1 to 16 ppm in most brown and grey samples. An exception to this range is the high contents of arsenic (200 to 500 ppm) found in orange brown ferric oxides bands a few centimeters thick that develop in clayey-silt above the capillary fringe." They further stated that "Exposure of some grey Holocene sediment to humid air for one week oxidized 50% of the extractable iron and arsenic emphasizing the sensitivity of these elements to redox environment. A few samples of cuttings collected near Brahmanpara (south of Brahmanbaria) are substantially enriched in sulfur (0.3 wt. %) likely due to deposition in an estuarine environment. XAFS analyses of these sediments are consistent with arsenic contained in a sulfide phases"(Breit, *et al.* 2001)[20].

The Breit *et al.* findings revealed that arsenic bearing minerals are present in the Bengal delta sediments. BGS/DPHE and other proponents of the reduction hypothesis have failed to collect adequate mineralogical and geo-chemical data to find the presence of arsenic bearing minerals in the sediments. Arsenic bearing minerals of different kinds are present in the sediments.

The distribution and the abundance of minerals in the Bengal Delta sediments vary with geologic conditions and the recent abstraction of groundwater and harvesting of river water. The Breit *et al.* findings clearly revealed that the oxidation mechanism has been playing a major role in releasing arsenic in the groundwater of Bangladesh and West Bengal.

Bridge and Husain reported that "The mineral pyrite occurs in several different morphological forms and the grain sizes ranging from invisible to several inches in size. The "framboidal" form is considered highly reactive and characterized by a small grain size and large surface area. Frequent lithofacies change, vertical and horizontal distribution of thickness is common in a delta. Water table elevations in the Bengal delta fluctuate in response to seasonal conditions forming a zone of cyclic wetting and drying. This provides optimal conditions for the oxidation and subsequent leaching of pyrite and associated weathering products. Bangladesh has been experiencing an abnormal cyclic wetting and drying for the last 35 years which allows enough time for oxidation of pyrite minerals. The sulfate concentration level in water depends on many factors:

- Pyrite grain size and type of minerals.
- Length of time (35 years in Bangladesh) of cyclic wetting, drying and leaching.
- Pyrite abundance, reaction rate, migration time from generating area to the sample collection location.
- Residence time, dilution factor due to precipitation, water table fluctuations and addition or loses from other sources.
- Sediment types.
- Depth of sampling .
- Time of oxidation.
- Time of sampling.

Depending on the geological and hydrogeological and geochemical conditions, there may be high or low concentrations at different sampling events, but low concentration of sulphate into groundwater does not reject the recent oxidation mechanism for releasing arsenic into groundwater in Bangladesh"(Bridge and Husain,2000)[14].

Jamal Anwar reported the findings of Ahmed *et al.* "Mineralogical and sedimentlogical studies of core samples from contaminated aquifers insignificant amounts of pyrite present in the aquifer sands(Ahmed, *et al.* 1998). Pyrite occurs mainly as authigenic minerals in Bangladesh and it contains a low amount of arsenic. Investigations by the BGS and MML (UK, 1998) show that any significant amount of arsenic in sediments that could lead to such massive groundwater contamination:

Lithology/Geologic Unit	Arsenic Conc. ppm (mg/Kg)
Silt or Clay	5.7
Sandy Clay	4.6
Clayey sand	21.2
Fine Sand	6.5
Fine-Medium Sand	0.3
Igneous Rocks	2.0
Upper Deltaic Plain, West Bengal of India	15.8
Ganges Alluvium	8.7
Ganges Mahanandha Alluvium	3.9
Meghna Alluvium	2.9
Older Alluvium	22.9
Barind Clay Residuum	10.0
Basement Complex	2.0
Recent marine sediments	10.3"

(Anwar, J., 2000)[21].

BGS/MML investigators have failed to understand the reason behind low concentrations of arsenic in the aquifer sediments because of their bias in support of the natural disaster hypothesis. They did not properly study the reasons for low concentrations of arsenic in the sediments. They did not study the geological, hydrological and hydrogeological, mineralogical and geochemical conditions of recent oxidation mechanisms for releasing arsenic into groundwater. Instead, they presented arguments in support of the natural disaster theory [1] based on inadequate, false data and evidence.

Isotopic Studies and the Age of the Groundwater Arsenic Poisoning in Bangladesh:

The age of the groundwater arsenic poisoning in Bangladesh and West Bengal of India is important in finding the source and cause of the poisoning and solution to the arsenic disaster. Proponents of the reduction hypothesis (BGS/DPHE, 2001)[8], (Agarwall *et al.*1999)[22], (Agarwall *et al.*2003)[23] and (Geen *et al.*2003)[24] believe that the groundwater arsenic poisoning in Bangladesh has been present prior to 1960, before the massive increased irrigation and diversion of river water began after 1975 from more than 30 common rivers of Bangladesh and India.

We do not disagree with BGS/DPHE, Aggarwal *et al.* and Geen *et al.*'s isotopic findings regarding the age of the groundwater, but we do not agree with their findings regarding the age of groundwater arsenic poisoning. The age of the water and the time arsenic entered the water are two entirely different things.

The arsenic was tied up in minerals which were stable below the water table when the sediments were first deposited and released, when oxidation occurred as the groundwater table was lowered at a later date. Therefore, the date of arsenic contamination relates to the groundwater lowering, not the age of the water. Some of the wells were below the WHO limits for arsenic when they were first tested and later tests detected an increase in concentration of arsenic above safe limits, indicating that recent local changes in the environment caused the change.

Many scientists and the people in Bangladesh have been misguided by Aggarwal *et al.* BGS/DPHE and Geen et.al's. isotopic studies. Aggarwal *et al.* in support of their isotopic data for the presence of arsenic poisoning prior to the1960's, presented a groundwater hydrograph (Faridpur-FA01, 2001) that shows no lowering of the water table occurred in Bangladesh after 1975, i.e., after the unilateral diversion of river water by India from the Ganges and other common rivers of Bangladesh and India. All the other hydrographs in Faridpur and other areas they presented, however, show that a significant lowering of the water table occurred in Bangladesh after the commission of Farakka, Teesta and other dams/barages built by India. The hydrograph appear to be constructed based on poor data. The significant lowering of water table and drying up of many rivers after 1975 in Bangladesh revealed that the recent oxidation of arsenic pyrite and other arsenic bearing minerals is one possibility for the change. If the water diversion from rivers and the over pumping of groundwater are continued, this process will contaminate both new and old uncontaminated water whether the water is 25 years old or millions of years old (Husain, 2001)[25].

Hydrology and Hydrogeological Aspects of Arsenic Contamination in Bangladesh: Bangladesh is riverine country. Out of the 230 water courses in the country, 57 are transboundary rivers that are flowing from India to Bangladesh. These rivers are the major source of surface water and recharge water for the unconfined aquifers in Bangladesh. Prior to 1975, before the construction of dams and barrages in more than 30 common rivers of Bangladesh and India and the harvesting of water in the dry season in the upstream territory of India, Bangladesh used to use mainly surface water for agricultural irrigation, drinking water and industry.

Major river systems such as the Ganges, Bramhaputra and Meghna are being drained in Bangladesh. Before the harvesting of river water from the common rivers of Bangladesh and India, Bangladesh used to receive about 1,105612 Cu.M annually. The main source of water in unconfined aquifer is the recharge water from the rivers in Bangladesh. The country receives huge amounts of water during the monsoon season, which causes floods almost every year. Due to lack of surface water during the dry season for the last 35 years, Bangladesh has been facing numerous problems such as arsenic poisoning, desertification, dying of rivers and agricultural, health, surface and groundwater resource, ecosystem, environmental and economic problems.

The river research survey of Bangladesh terms them seasonal rivers. The rivers which have been silted up contain no water in the dry season. Local people grow different crops on the rivers beds. The rivers that are to the point of dying include Chatnai, Pakuraj, Mohanda upper, Tirnoi, Ramchandi, Khorka, Kurum, Gobra, Petki, Gharomara, Korotua, Berang, Bhersa, Tangan, Talma, Dahuk, Chowyai of Panchgarh, Kulik of Thakurgaon, Chepa, Kankra of Dinajur, Chikly, Manash, Dhaijan, Burikhora, Naotara, Dhum, Buri Tilka of Nilphamari, Ghaghot, Akhira of Rangpur, Fulkumar of Kurigram and Boral upper of Rajshahi districts.

Uddin and Abdullah classify the groundwater aquifers into four categories based on the geological criteria. Others classified the aquifers based on the thickness of the distinct aquifer characteristics. Uddin *et al.* proposed the following categories:

"The Plio-pleistocene Aquifer: The Plio-Pleistocene aquifers of Dupitila Formation lie beneath the Pleistocene Modhupur Clay Formation. This aquifer is composed of light grey to yellowish brown, medium to coarse sand with pebble beds. All of the waters for Dhaka city is withdrawn from this aquifer but the water is still now arsenic free.

The Late Pleistocene-Early Holocene Aquifer: The late Pleistocene-early Holocene aquifers are not continuous all over the country. This to some extent corresponds to the Deep Aquifer. The sediments of this aquifer to some extent correspond to the Late Pleistocene -Early Holocene Unit of the sediment section. Water within this aquifer is found to be arsenic safe but heavy withdrawal from this aquifer needs further study.

Middle Holocene Aquifer: Above the Late Pleistocene-Early Holocene aquifers lies the fine sand which becomes coarser in the upper part. This sandy sequence varies greatly both vertically and horizontally.

The upper part also contains silts and peaty organic matters. Water from this aquifer has been dated as about 3000 years old. Most of the groundwater in Bangladesh is withdrawn from this aquifer and the water is severely affected by arsenic contamination.

Upper Holocene Aquifer: The Upper Holocene aquifers are developed all over the deltaic and flood plain areas. This aquifer somewhat corresponds to the Upper aquifer of the conventional system. Water from this aquifer has been dated as about 100 years old and also affected by the arsenic contamination. Each of the Holocene aquifer contains a number of sand layers/lenses that are stacked and interconnected which makes them of leaky type from which the contamination spread vertically from one place to other" (Uddin,M.H. *et al.* 2002)[26].

Since the early seventy's, about 8 to 10 million tube and irrigation wells were installed in the Middle Holocene and Upper Holocene aquifers. The arsenic contamination is rapidly spreading in these aquifers through faults and fractures and the de-watering process of these aquifers due to the abstraction of groundwater for agricultural irrigation and drinking water.

Prior to the seventy's, the people of Bangladesh mainly used surface water for agricultural irrigation.

After 1975, due to the lack of surface water in Bangladesh from the thirty common rivers of Bangladesh and India, people resorted to groundwater resources. This lead to the over pumping pf groundwater for agricultural irrigation which caused significant lowering of the water table. As a result, shallow tube wells were lowered for the abstraction of groundwater throughout the entire country.

Kinniburgh and others, in order to fully refute the "Recent Oxidation hypothesis" in the context of groundwater arsenic poisoning in Bangladesh and West Bengal of India, presented the following arguments in the book "Arsenic in Groundwater: Geochemistry and Occurrence." They stated that "Pyrite oxidation hypothesis- the hypothesis was strongly advocated by West Bengal Scientists in 1995(Chatterjee *et al.* 1995; Chodhury *et al.* 1997). It is based on the idea that arsenopyrite, or later As-rich pyrite, was initially present in the sediments and has been at least partially oxidized as a result of the recent seasonal lowering of water table. This lowering of water table has been attributed to the use of groundwater for irrigation and, by some, to the construction of the Farakka barrage (a controversial dam that was completed in 1975 across the River Ganges in West Bengal close to the West Bengal-Bangladesh border and which diverts River Ganges water to the Bhagirati-Hoogly River and ultimately to Calcutta). This hypothesis therefore supports the notion that the release of arsenic to the groundwater is a recent phenomenon induced by man's activities. Certainly such a hypothesis is a possibility and needs to be considered. However, proponents of the hypothesis have offered little scientific evidence in support of it other than demonstrating the presence of pyrite in the sediments"(Kinniburgh *et al.* 2003)[27].

Kinnenburg's *et al.* statements are based on incorrect data and poor judgment. They did not collect the pre and post dam/barrage groundwater data and river water discharge data from the 30 common rivers of Bangladesh and India (Fig. 4). Moreover, they have used pre 1975 river water discharge data when there was no surface and groundwater crisis in Bangladesh. They did not construct the map of the new de-watered zone in Bangladesh that was created after 1975. The river water diversion/harvesting during the dry season in the upstream territory of India through dam/barrage construction in more than 30 common rivers for the last 35 years is directly related to the oxidation mechanism (Husain, 1999)[28], (Bridge and Husain, 2000)[14] and (Bridge and Husain,2001)[19].

Water resource systems are dynamic in nature. Surface and groundwater resources are integral parts of the same hydro-geological component. They respond both in quantity and quality to natural changes and human activities such as the diversion of surface water and the abstraction of groundwater. As a result, the water chemistry changes with time when water moves through the changing environment. In some areas, this change is slow, but in other areas where environmental conditions have changed, the change is rapid. The hydro-chemical parameters are not uniform and constant in a deltaic environment such as Bangladesh.

Human activities create conditions that promote the migration of contaminants. For example the abstraction of groundwater results in the lowering of water table levels. The diversion of water by Farakka, Tista and other dams has resulted in increased use of groundwater, causing a significant lowering of the groundwater table in the Bengal delta. The diversion of surface water for the last 35 years by India, from about 30 rivers that flow into Bangladesh, has produced major environmental changes. In terms of flow, the Ganges river was the eighth largest river in the world. Prior to 1975, the average flow during the dry season at the Hardinge Bridge point in Bangladesh was 2000 Cum/Sec. The present flow, due to India's 35 years of unilateral diversion, is only 400 Cum/sec. During the dry season, the river bed is completely dried out (Fig. 4).

Besides the abstraction of groundwater and the diversion of surface water from the common rivers of Bangladesh and India, no other human or natural cause is known to have occurred in Bangladesh that could have destabilized the arsenic bearing minerals present in the sediments and brought about a significant geochemical change in the sediments and groundwater in the Bengal basin. In addition to Farakka, India has constructed dams/barrages in Feni, Muhuri, Selonia, Gomti, Sonai, Khowai, Dhalai, Manu, Juri, Sonai Bardal, Kushiyara rivers in the east, Piyan, Bhogai, Jinjiram, Dharla, Sangil, Tista, Buri Tista, Deonai-Jamuneshwari, Ghoramara, Talma and Karatoa rivers in the north and Ichamati-Kalindi, Benta-Kodalia, Bhairab-Kabodak, Khukshi, Atrai, Punabhaba and Mahananda rivers in western Bangladesh (Fig. 5).

Prior to 1975, most of the following problems occurring in Bangladesh were not present and the severity of some of the problems that were present prior to 1975 has greatly increased. They include:

- Arsenic poisoning of groundwater.
- Severe floods (1988, 1998 and 2004).
- Depletion of surface water resources.
- Depletion of groundwater resources.
- Desertification.
- Extinction of aquatic species.
- Negative impact on fish industry.
- Drop in organic matter content in the soil.
- Destruction of agriculture and horticulture.
- Inland saline water intrusion.
- Loss of navigable waterways.
- Riverbank erosion.
- Climate change.
- Loss of professions.
- Outbreak of environmental diseases.
- Land subsidence (from water table lowering) and.
- Social instability due to symptoms of arsenic poisoning etc.

The diversion of surface water from rivers and the over-use of groundwater are the human activities largely responsible for the destabilization and destruction of the ecosystem of the Bengal Basin and current environmental problems in Bangladesh. Currently no one has collected hydrological data from the 30 common rivers of Bangladesh and India. We have presented a hydrograph of the Ganges River as evidence that supports the recent oxidation conditions that became present in Bangladesh after 1975.

David Kinniburg further stated that "The groundwater As problem is greatest in the south-east of Bangladesh where the water table is highest and where there is small unsaturated zone (1-3m at Lakshmipur). There is a much thicker unsaturated zone and a greater seasonal fluctuation of the water table in northwestern Bangladesh, although the groundwater arsenic concentrations there are generally low. The greater depth to water table and the greater zone of fluctuation in the north waste reflects hydrologic factors as well as the greater use of groundwater for irrigation. The pyrite oxidation would predict high as groundwater's in this area, not the low concentrations observed. The severely As-affected areas in south-east Bangladesh are too far away from the Farakka barrage to be significantly influenced by it. Many are part of the Meghna catchment, not the Ganges catchment"(Kinniburg,D.G., 2003)[27].

In southeast Bangladesh (Lakshmipur and Noakhali), a significant lowering of the water table took place due to the diversion of surface water from the Ganges by Farakka and other dams and barrages in other common rivers of Bangladesh and India. During 1977 to 1997 in Lakshmipur, the observation well -NA012 and NA018 show water table draw down from 2 to 3 m. In Noakhali, the observation well-NA020 show water levels draw down from 2 to 3 m. Additionally, the water level in well BA013 was drawn down from between 3 to 4 m in Barisal, 2 to 3 m in Pirojpur in well BA015 and 1 to 2 m in Madaripur in well FA36 (Fig. 6).

The distance of the Farakka barrage has nothing to do with the arsenic crisis in Bangladesh. The main problem is the lack of recharge water in the Bangladesh side of the Ganges River due to harvesting of water in upstream areas in India. The significant lowering of the water table due to over pumping of groundwater in the southeast area has caused migration of arsenic into the deep aquifer. The significant lowering of the water table has also caused saline water intrusion and rise of sea level above the groundwater table in coastal areas. As a result, arsenic contaminants are not flushing into the sea. This migration process for the last 35 years has caused higher concentrations of arsenic in the southeast areas. In some areas of the northwestern part of Bangladesh, the low concentrations of arsenic appear to be caused by two main reasons:

- Arsenic has migrated from the northwest area to the south and southeast, along with groundwater flow direction and over pumping of groundwater.
- Low arsenic concentrations may also be the result of the presence of low arsenic bearing minerals in sediments.

Fig. 2: Arsenic lesion on hands and foot and cancer on head(Photo:Wilson 2004)[44] and (Husain 2009)

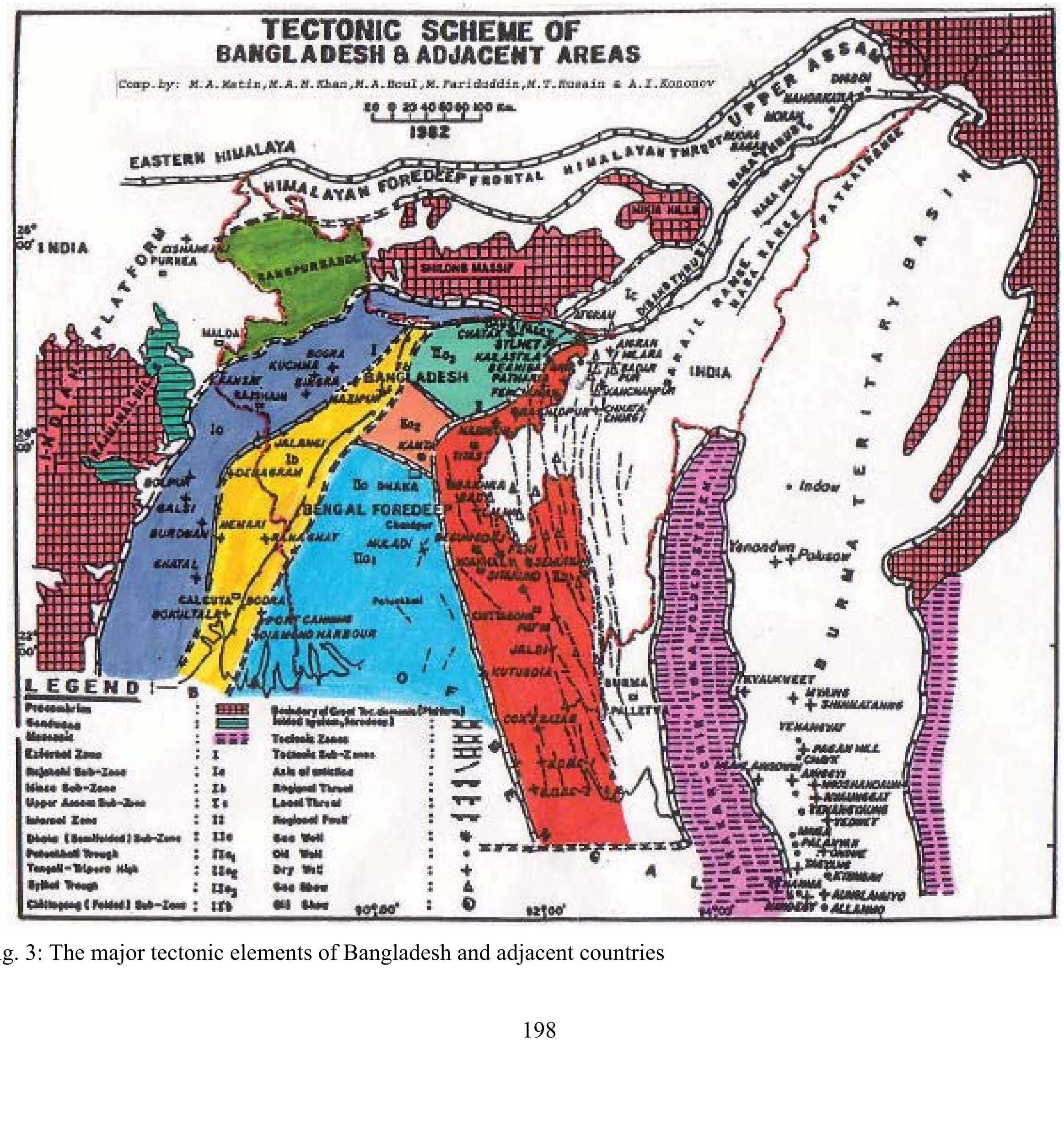


Fig. 3: The major tectonic elements of Bangladesh and adjacent countries

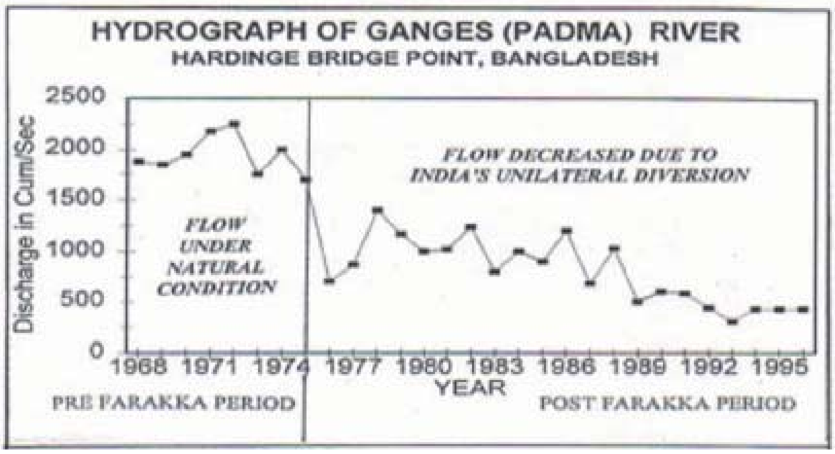


Fig. 4: Illustration of the pre and Post Farakka average annual discharge of the Ganges river at Hardinge Bridge point, Bangladesh (Hebblethwaite, 1997)[45]

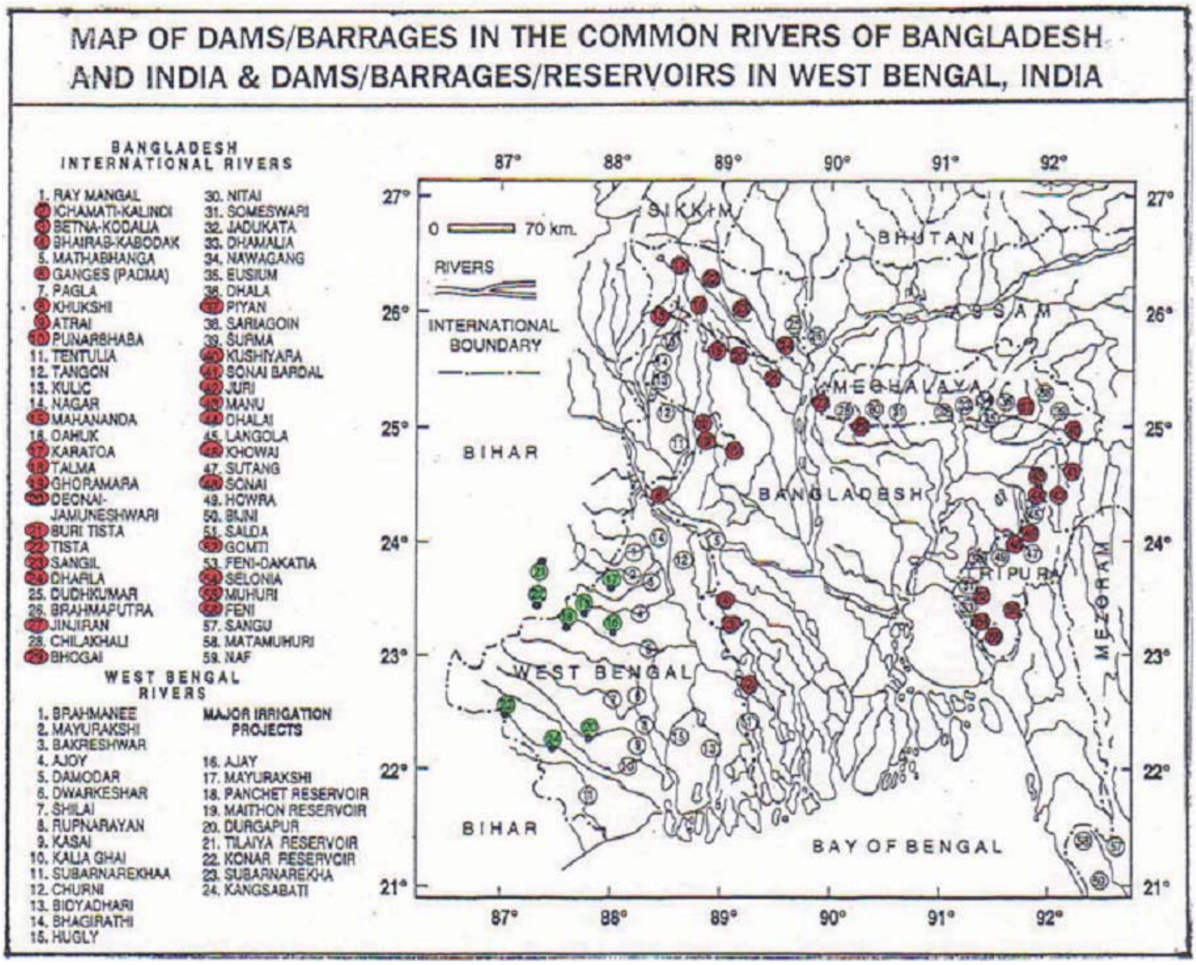


Fig. 5: Illustration of dams/barrages in the common rivers of Bangladesh and India (red circle) and dams/barrages/reservoirs in West Bengal of India (green circle)

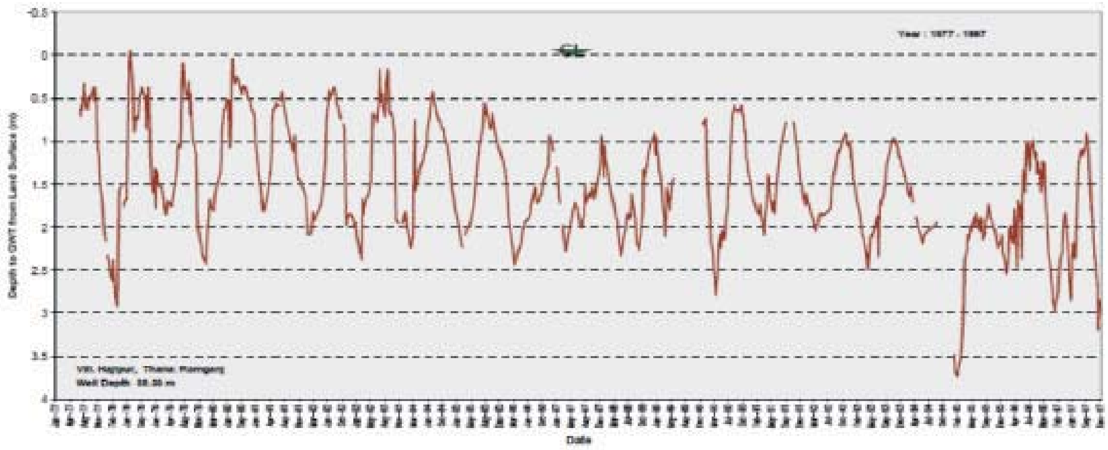


Fig. 6: The hydrograph shows a significant lowering of the water table that occurred after 1975 in south east Bangladesh (arsenic hot spot area), caused by over pumping of groundwater and diversion of river water from the Ganges, Teesta and over twenty-eight other common rivers of Bangladesh and India. This hydrograph was originally misinterpreted by Aggarwal *et al.*

The high concentration of arsenic in southeast Bangladesh is the result of oxidation caused by the lowering of the water table and the presence of arsenic bearing minerals in the "Neo-oxidation zone". In the Neo-oxidation zone, one may or may not find arsenic bearing minerals because of 35 years of increase draw down of the water table. On the other hand, migration of arsenic from the up-gradient, side gradient and cross-gradient sources are common in any contaminated site. The most important factor that caused migration of contaminants into deeper aquifers is pumping of groundwater, which develops a cone of depression. The depths of most of wells in southeast Bangladesh, including Lakshimipur, ranges from 20 to 250 m. The strainer and the pump intake were set much deeper in the wells and as a result contaminants migrated from the shallow Neo-oxidation zone to the deep aquifer. Hundreds of recently installed deep uncontaminated tube wells are now being contaminated due to the same well hydraulic mechanism. Like the Ganges catchments, the Meghna catchment has been severely impacted by abstraction of groundwater and diversion of river water for the last three decades (Fig. 1,5).

Kinninburg *et al* are not aware of the impact of the harvesting of water in the dry season in Indian territory from these common rivers. Consequently, they have failed to understand the recent hydrological, hydro geological and hydrochemical history of the Bengal Basin.

The distance of the Farakka barrage is not very significant in the creation of arsenic poisoning.

The reduction of water in the Ganges river by the Farakka barrage on the Bangladesh side has caused lowering of the water table in a large area, including southeast Bangladesh. This is because prior to 1975 before the construction of the Farakka barrage, there was no shortage of water in the Ganges river in Bangladesh. In the dry season before the construction of the barrages, the Ganges river used to supply large volumes of water in the southeast region (Fig. 4).

DISCUSSION

Recent Oxidation Mechanism for Releasing Arsenic into Groundwater: Dipankar Das and others conducted a geochemical survey in the six districts of west Bengal bordering the western part of Bangladesh. These districts are Mulda, Murshidabad, Bardhaman, Nadia, North 24-Pargana and South-24 pargana. Their subsurface investigation revealed the presence of arsenopyrite minerals in the sediments. They stated that "the source of arsenic in groundwater and in the soil is from pyrite minerals containing arsenic. However, they did not discuss how arsenic is released in groundwater from arsenopyrite. They cited the oxidation of pyrite process presented in the literature from the U.S. However, in their conclusions they state that: The way that arsenic enters the groundwater in these six districts is not well understood. Our borehole analyses show arsenic-rich FeS_2 in sediment layers. Since iron pyrite (FeS_2) is not soluble in water, the question therefore arises as to how arsenic from pyrites enters the water." (Das *et al.*1996)[18].

Although pyrite is not soluble in water, it decomposes when exposed to air or in aerated water and proceeds rapidly in confined environments without the addition of oxygen from external sources as the acid level reaches a pH of 3.5 or lower.

A U.S. government article on acid mine drainage (AMD) describes the process. It stated, “The formation of acid drainage is a complex geochemical and microbially mediated process. The acid load ultimately generated is primarily a function of the following factors: Microbiological Controls; depositional environment; Acid/base balance of the overburden; Lithology; Mineralogy; and hydrologic conditions.

Chemistry of Pyrite Weathering:

”$2\ FeS_2 + 7\ 0_2 + 2H_20 \text{ -> } 2\ Fe_2^{+} + 4\ SO_4 + 4\ H^+$ (1)

$4\ Fe_2^{+} + 0_2 + 4H+ \text{-> } 4Fe_3^{+} + 2\ H_20$ (2)

$4\ Fe_3 + 12\ H_20 \text{-> } 4\ Fe(OH)_3\ \{\ 12\ H^+$ (3)

$FeS_2 + 14\ Fe_3^{\ +} + 8\ H_20 \text{ -> } 15\ Fe_2^{+} + 2\ SO_4^{2-} + 16\ H^+$ (4)

In the initial step, pyrite reacts with oxygen and water to produce ferrous iron, sulfate and acidity. The second step involves the conversion of ferrous iron to ferric iron. This second reaction has been termed the "rate-determining" step for the overall sequence.

The third step involves the hydrolysis of ferric iron with water to form the solid ferric hydroxide (ferrihydrite) and the release of additional acidity. This third reaction is pH dependent. Under very acid conditions of less than about pH 3.5, the solid mineral does not form and ferric iron remains in solution. At higher pH values, a precipitate forms, commonly referred to as "yellow boy."

The fourth step involves the oxidation of additional pyrite by ferric iron. The ferric iron is generated by the initial oxidation reactions in steps one and two. This cyclic propagation of acid generation by iron takes place very rapidly and continues until the supply of ferric iron or pyrite is exhausted. Oxygen is not required for the fourth reaction to occur. The overall pyrite reaction series is among the most acid producing of all weathering processes in nature".

The article goes on to state that the raising and lowering of the water table (wetting and drying) in the reacting environment provides optimal conditions for the weathering of pyrite. The changes in the geochemical environment due to high withdrawal of groundwater resulted in the decomposition of pyrites and the release of arsenic. Similar pyrite reactions have been described by many workers around the world (Schreiber *et al*, 2003)[30].

Dipankar Das *et al.* mineralogical studies by XRD (X-ray diffraction) show the presence of FeSO4. In 1988 Welch *et al.* studied arsenic in the groundwater in western areas of the U.S. and suggested that the "mobilization of arsenic in sedimentary aquifers may be, in part, a result of changes in the geochemical environment due to agricultural irrigation. In the deeper subsurface, elevated arsenic concentrations are associated with compaction caused by groundwater withdrawal" (Bridge and Husain, 2000)[14] and (Bridge and Husain,2001)[19].

If the time of arsenic contamination is after 1975 in Bangladesh, a probable explanation is that the changes in the geochemical environment due to the high withdrawal of ground water resulted in the decomposition of arsenic bearing minerals that were stable in the reducing environment. These arsenic oxides, if introduced to the reducing conditions below the water table, are reduced to poisonous oxide forms.

BGS/DPHE report states that "the greatest arsenic concentrations are mainly found in the fine-grained sediments especially the gray clays. A large number of other elements are also enriched in the clays including iron, phosphorus and sulfur. In Nawabganj, the clays near the surface are not enriched with arsenic to any greater extent than the clays below 150 m. There is no evidence for the weathering and deposition of a discrete set of arsenic-rich sediments at some particular time in the past. It is not yet clear how important these relatively arsenic-rich sediments are for providing arsenic to the adjacent, more permeable sandy aquifer horizons. There is unlikely to be a simple relationship between the arsenic content of the sediment and that of the water passing through it"(BGS/DPHE, 1999)[7].

The arsenic is associated with low energy sediments and organic matter would also tend to be associated with the lower energy environments. Organic matter is present in the sediments below the water table in Bangladesh. Arsenic along with other trace elements, when present in the environment, is enriched in organic rich sediments. Sulfur from the decay of organic matter combines with iron to form sulfides in reducing environments and these sulfides will incorporate arsenic if arsenic is present. When the groundwater table was lowered by increased irrigation during the dry season and the sediments were exposed to the oxygen from the atmosphere in a moist environment, arsenic rich sulfides associated with organic matter and other reduced arsenic bearing minerals would oxidize in this moist environment and release arsenic. Bacterial decay of the organic matter would produce

H_2CO_3, HCO_3^- and CO_3^-. The kind of sulfates present are dependent on pH, hydrogen sulfide below an Eh of 3, or H2 SO_4 above an Eh of 3. With the appropriate concentrations below an Eh of 3 and between a pH of 3 to 9, these carbonate and sulfur species would react with the ferrous iron in solution to produce siderite and pyrite. (Figure 1. After Robert M Garrels, Solutions, Minerals and Equilibera).

In order to validate the Recent Oxidation Mechanism as the main mechanism for releasing arsenic into groundwater aquifers in Bangladesh, scientists must find evidence of the following four conditions:

- Evidence of the presence of arsenic bearing minerals in aquifer sediments.
- Evidence of the lowering of the water level in groundwater aquifers after1975 in Bangladesh.
- Evidence of the penetration of atmospheric oxygen into the subsurface neo oxidation zone.
- Evidence of yearly recharge of the newly created de-water zone, i.e., neo oxidation zone.

If any of the above conditions is absent then the recent oxidation mechanism is invalid for releasing arsenic into groundwater.

Evidence for the Presence of Arsenic Bearing Minerals in Bengal Delta Aquifers: Breit *et al.* Ahmed *et al* and Mandal *et al.* study clearly reveal that arsenic bearing minerals are present in aquifer sediments in the Bengal basin. Ahmed *et al.* and other proponents of the natural disaster hypothesis collected samples in the highly contaminated areas where 35 years of increase draw down and recharge oxidized the arsenic bearing mineral during dry season. The surface area of reaction of the clay and sand particles like arsenic minerals in the aquifer sediments is very high. The minerals were oxidized very quickly and remained in solution under reducing conditions and/or adsorbed in clay, sediments and iron oxides. Therefore, these investigators could not find arsenic bearing minerals in their study areas. Thirty five years of oxidation is an adequate time to break down arsenic bearing minerals in the aquifer sediments in Bangladesh. If these investigators look for the arsenic bearing minerals in an undisturbed area where arsenic bearing mineral is present and no significant lowering of the water table occurred, they will definitely find arsenic bearing minerals in the aquifer sediments in Bangladesh and West Bengal of India.

The other conditions are the lowering of the water table after 1975, yearly recharge of the post 1975 de-water zone, the presence of dissolved arsenic in groundwater and adsorbed arsenic in sediments. This suggests that arsenic bearing minerals were present in the aquifer sediments prior to 1975 before the harvesting of river water and over pumping of ground water.

Evidence of the Lowering of the Water Level in the Groundwater Aquifer after 1975 in Bangladesh: The unilateral harvesting of river water from the Ganges, Tista and 28 other common rivers of Bangladesh and India in the upstream territory of India (Fig. 5) for the last 35 years has triggered the drying up of rivers and tributaries, ponds, lakes, canal and other water bodies in Bangladesh. The area which was under water for thousands of years prior to 1975, is now dry land during the dry season. Soil moisture deficiency is a common phenomenon both in upland areas as well as low land areas. The tube wells in the entire country for drinking water have been inactive and non-functioning due to the reduction of water level in the rivers.

BGS/DPHE investigators reported that “Irrigation wells (STWs and DTWs) are typically shallow (<100 m) with multiple screen in an unconfined aquifer. The water level is commonly near the surface and within the limit of suction pumps (7 m). The pump intake is set above the screen level, but the screens are set lower (typically 30 m bgl for STW and 100 m bgl for DTW), depending on where the appropriate coarse litho logy is encountered. Pumping of this type of well causes vertical gradients to be developed as the well induces flow from the water table to the well screen. This depletion of the water table is replenished during the wet season as long as total abstraction does not exceed the available resources” (BGS/DPHE 2001)[8].

Fig. 7: These hydrographs show significant lowering of the groundwater level occurred in Bangladesh after 1975, due to harvesting of water from the Ganges river.

In Bangladesh, over pumping of groundwater was required due to the lack of recharge water in rivers. The groundwater hydrograph and the river water discharge data show a strong pre and post Farakka surface and groundwater relationship (Fig. 7 and Fig. 4)

BGS /DPHE also reported that ”The decline in water levels due to abstraction for irrigation during the dry season through the use of shallow and deep sidewalls can be significant, especially in areas of thick near-surface silt and very fine sand layers with low specific yields.

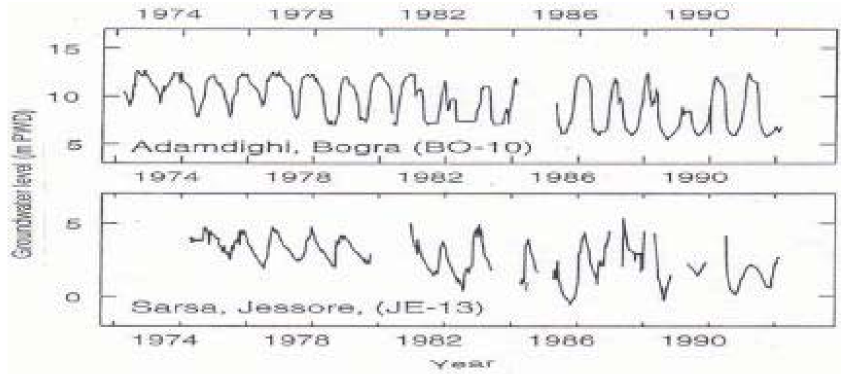


Fig. 7: These hydrographs show significant lowering of the groundwater level occurred in Bangladesh after 1975, due to harvesting of water from the Ganges river. In Bangladesh, over pumping of groundwater was required due to the lack of recharge water in rivers. The groundwater hydrograph and the river water discharge data show a strong pre and post Farakka surface and groundwater relationship (Fig. 7 and Fig. 4)

In low-lying areas of increased annual abstraction for irrigation, as in the Jamuna and Ganges delta floodplains, shallow tube well use may be halted due to decline of water levels below the suction level before the end of the dry season. In such areas, crop irrigation has to be completed using water from deep tube wells. Such a regional decline in water level renders many hand-operated suction pumps inoperative towards the end of the dry season" (BGS/DPHE1999)[7].

Prior to 1975, during the dry season, there was no shortage of river water and no significant draw down of water level occurred below the thousands of years old historical oxidation zone. After 1975, significant draw down of water level started due to river water harvesting in the upstream territory of India from more than 30 common rivers of Bangladesh and India and over pumping of ground water, which created a neo oxidation zone. DPHE/BGS's study clearly revealed that significant lowering of the water table occurred after 1975 (Fig. 6 &7).

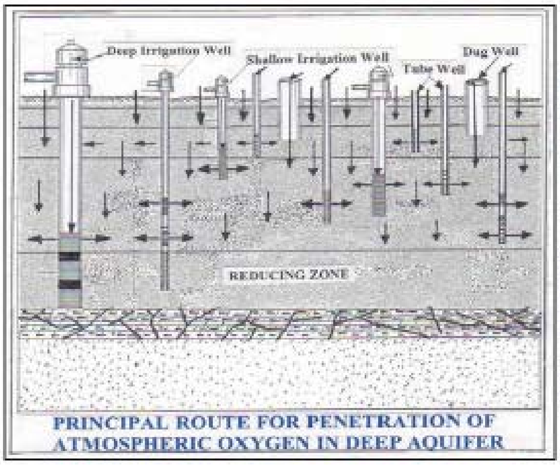
During the dry season, atmospheric oxygen enters into the neo oxidation zone, causing break down of arsenic bearing minerals. During the wet season the neo oxidation zone is replenished, thus releasing arsenic into groundwater. The arsenic remains in solution under the reducing conditions.

BGS/DPHE has found a zone of maximum concentration of arsenic that ranges from 15 to 30 m depth. On the other hand, Harvey and others reported a zone of dissolved arsenic (>90%) As (III) that ranges from 30 to 40 m(Harvey *et al.*2002)[31] and (2003)[32] . The thirty five years of increased draw down and recharge have caused migration of poison arsenic from the neo oxidation zone into deep aquifers (reducing zone), thus contaminating the thousands of years old uncontaminated water.

Evidence for the Penetration of Atmospheric Oxygen into Subsurface Neo-oxidation Zone: Proponents of the reduction hypothesis have difficulty understanding how oxygen enters into the Neo-oxidation zone or into the deep aquifer. Oxygen entered into the deep aquifer in the de-water zone along with the lowering of the water table. Schreiber *et al.* describe the following processes in the state of Wisconsin for the source of oxygen, all of which are applicable in the context of Bangladesh and the West Bengal of India:

"(1). Oxygen-rich water infiltrates to the SCH in the recharge area; (2) vertical leakage of oxygen-rich water through the Sinnipee confining unit initiates a regional oxidation of sulfides in the SCH; (3) partial de-watering of the St, Peter aquifer due to extensive groundwater withdrawal exposes the SCH to oxygen; and (4) boreholes provide a direct conduit for atmospheric oxygen to reach the SCH in areas where the static water level is coincident with, or below, the SCH"(Schreiber *et al.* 2003)[30].

The vertical and areal extent of the neo oxidation zone during the dry season in Bangladesh has been greatly increased due to abstraction of groundwater from 8 to12 million shallow tube wells, 0.5 million shallow irrigation wells and 55, 000 deep irrigation wells. The harvesting of river water in the upstream territory of India from more than 30 common rivers of Bangladesh and India has greatly increased in the last three decades. Prior to 1975, the area, which was under water for thousands of years, is now dry land. After 1975, due to the diversion of river water and abstraction of groundwater, millions of



Figs. 8,9: Illustration of how atmospheric oxygen penetrates into subsurface formations through tube wells, irrigation wells, faults and fractures present in the land surface along with the lowering of the water table (Husain and Bridge, 2006)[10]

shallow tube wells during the dry season have become inoperable due to the significant lowering of the water table. These wells supply atmospheric oxygen (direct conduit) to the de-water zone (cone of depression) caused by pumping of groundwater by shallow and deep irrigation wells (<100 m) during the dry season, thus oxidizing the arsenic bearing minerals present in the sediment (Fig. 6-9).

Breit *et al.* discovered that "Exposure of some grey Holocene sediment to humid air for one week oxidized 50% of the extractable iron and arsenic emphasizing the sensitivity of these elements to redox environment" (Breit *et al.*2001)[20]. The Breit *et al.* findings further reveal that atmospheric oxygen reacts with arsenic bearing minerals in the cone of depression/de-water zone/Neo-oxidation zone in the subsurface aquifer sediments in the Bengal Delta.

Oxygen also enters into the subsurface through fractures, faults, fissures and tree root systems in soil along with the lowering of the water table. In Bangladesh, 8 to10 million water wells serve as a direct conduit for supplying atmosphere oxygen into subsurface formations, thus distributing atmospheric oxygen along with the lowering of the water table. The supply of oxygen occupies the pore spaces once saturated with water and oxidized arsenic bearing minerals present in the aquifer sediments.

Like BGS/DPHE, Aggarwal *et al.* have failed to understand the recent hydrgeological and geochemical situation in Bangladesh, because they have failed to collect pre and post 1975 hydrological data of the common rivers of Bangladesh and India. They did not even collect adequate pre and post 1975 groundwater hydrological data. Moreover, they misinterpreted the groundwater level data in their study area and have failed to understand the relationship between surface water and groundwater, three decades of diversion of river water and the abstraction of groundwater in Bangladesh.

Charles Harvey and his group also did not collect pre 1975 and post 1975 river water discharge data in Bangladesh. They collected groundwater level data between 1988 and 1997 from 183 hydrographs in their study area. They reported a significant lowering of the water table in their study area in Munshigonj, Bangladesh.

Evidence for Yearly Recharge of the Recently Created De-water Zone: There are 230 rivers in Bangladesh. Out of those 230, 57 are trans boundary rivers flowing from India to Bangladesh. Although many rivers are now drying up during the dry season due to India's unilateral diversion of river water from the 30 common rivers, the entire country receives large amount of water from these rivers during the wet season. In addition to the cross boundary inflow, huge rain fall caused floods to occur as well as saturation of the unsaturated zone including the neo oxidation zone created in Bangladesh after 1975.

The increased draw down of the water table in the dry season and recharge in the wet season, for the last 35 years, has caused migration of arsenic contaminants (AS-V) from the Neo oxidation zone to the reducing zone where (AS-V) remain in solution as (AS-III).

Fig. 10: This illustrates how flood and rain water replenish the natural de-water and man-made neo oxidation zones in the wet season in Bangladesh. Unfortunately the recharge water is rapidly lost during the dry season due to recent man made changes in the hydrogeologic regime. People standing on land are submerged by water during the wet season

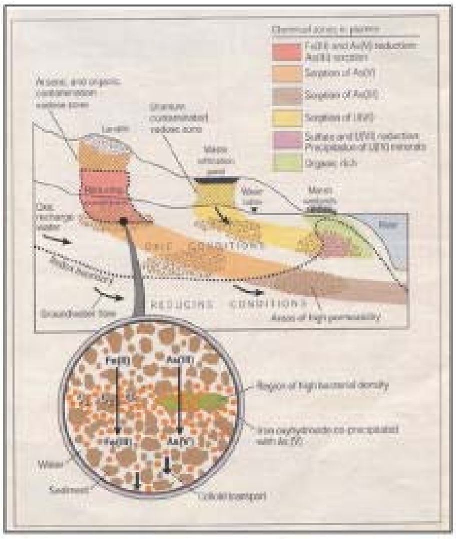
It is important to note that during the wet season, the neo oxidation zone is changed into the reducing zone due to high stand of water. The cyclic wetting and de-watering process has caused generations of arsenic contamination in Bangladesh(Bridge and Husain,2000)[48] . Prior to 1975, the thousands of years old oxidation zone that lies above the recently created neo oxidation zone was free of arsenic contamination and this zone is still free of arsenic contamination. But the problem is that during the dry season, the zone is now devoid of water due to harvesting of river water in the up stream regions in India.

The evidence of the mentioned four conditions clearly reveal that groundwater arsenic poisoning in Bangladesh is a recent man-made disaster which started in Bangladesh after 1975. The recent oxidation mechanism is the principal cause for the mobilization of arsenic into groundwater. The subsequent migration of arsenic oxides from the neo oxidation zone into the reducing zone aused recharge of the unsaturated zone during the wet season. As a result (AS-V) is converted into AS(III) and remains in solution under the reducing condition (Fig. 10, 11).

Permanent Solution to the Arsenic Disaster in Bangladesh: The permanent solution to the arsenic disaster in Bangladesh depends on the source and cause of groundwater arsenic poisoning. According to our research findings, it appears that ground water arsenic poisoning in Bangladesh is a recent man made disaster. The harvesting of river water from the common rivers of Bangladesh and India and over pumping of groundwater are responsible for releasing arsenic into groundwater through the recent oxidation mechanism. Arsenic is remaining in solution under reducing conditions through migration from the neo oxidation zone to the reducing zone due to the lowering of the water table.

Therefore, the best solution to the problem appears to be restoration of the thousands of years old natural environment by restoring the river flow and groundwater level that existed prior to the 1975 commission of Farakka, Tista and other dams/barrages that India constructed in the common rivers of Bangladesh and India (Fig. 11,12).

The river water should be filtered, treated, continually tested and delivered through a closed system to provide a safe water supply for the nation. The abundance of arsenic free groundwater above the arsenic free contaminated zone will be able to supply plenty of arsenic free water for agricultural irrigation and industry in the dry season. In other words, restoration of natural flow in the common rivers of Bangladesh and India will help maintain the natural environment and protect the public health, ecosystem and environment of Bangladesh. There is no other better solution to the arsenic crisis and other environmental problems created after 1975 than the restoration of natural flow in the common rivers of Bangladesh and India that existed prior to 1975.



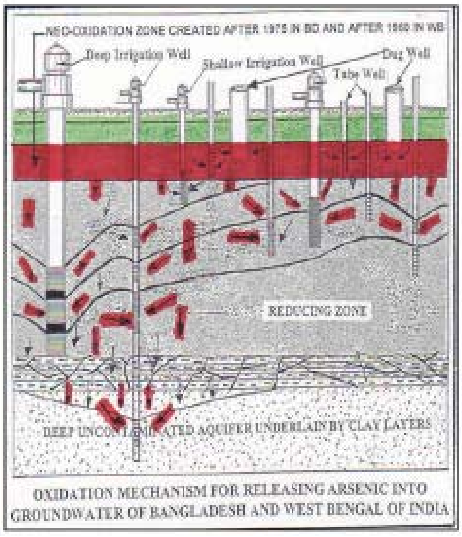


Fig. 11,12: These diagrams show how the state of arsenic changes under oxidation and reducing conditions (Davis, J.A., *et al.* 2004)[33] and Husain and Bridge, 2006) [10] and migrates into deeper aquifers due to over pumping of groundwater along with development of the cone of depression

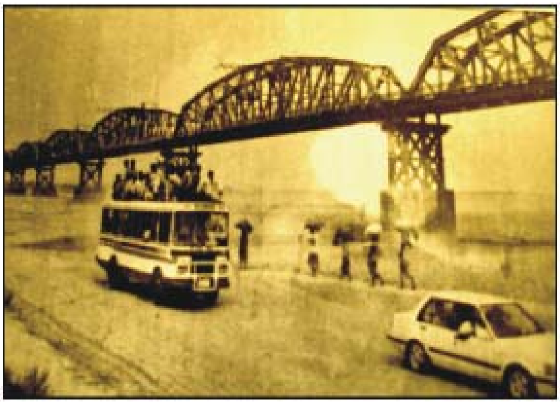


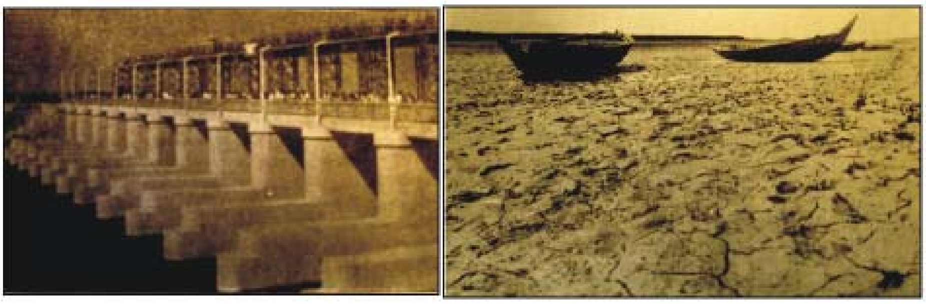
Fig. 13,14: These pictures show the Farakka barrage and drying up of the Ganges river on the Bangladesh part (Photo:Anwar, J.2000)[21] and (Sattar, 1996)[34]. Prior to 1975, during the dry season, this area was under water for thousands of years and now is dry land. People used to use steamers and boats for transportation. Today, they use buses and cars on the river bed. The entire ecosystem has been destroyed for the last 35 years

The natural ground water level that existed prior to 1975 should be restored by removing all dams/barrages that India constructed in the common rivers of Bangladesh and India. The removal of dams/barrages and dredging of rivers will decrease the number of disasters in both Bangladesh and the upstream region of India.

The over pumping of ground water must be stopped because arsenic is migrating from shallow contaminated aquifers to deep, uncontaminated water through thousands of deep tube wells recently installed. The deep uncontaminated aquifers should be monitored properly and may be used on a safe yield basis.

The flushing of arsenic contaminants may take a long time, but the removal of dams/barrages affecting Bangladesh will provide plenty of water during the dry season for drinking, irrigation and industry. The restoration of ground water levels in Bangladesh that existed prior to 1975 will prevent migration of arsenic contaminants from the adjoining states of India.

Solution to the Arsenic and Pathogens Contaminated Drinking Water: In Bangladesh, prior to the 1960's, people extensively used surface water from ponds, rivers, canals and lakes. They also used dug well



Figs. 15,16: These images show India's Teesta barrage in the Teesta river and drying up of the river on the Bangladesh side

water for thousands of years. The waters from these sources were not free from pathogenic bacteria. As a result, thousands of infants, and young people used to die from cholera, diarrhea, typhoid and other waterborne diseases.

In order to avoid waterborne diseases, numerous agencies started to install shallow tube wells in the late 1960's. It is important to note that in 1948, there were 50,000 tube wells in use in Bangladesh. At that time, well water users were unharmed from waterborne diseases because water from tube wells was fairly free from pathogenic bacteria. Since the 1960's to the late 1980's, about 8 to 10 million tube have been installed in Bangladesh.

In the mid 90's, another severe water crisis emerged in Bangladesh. Tube well water in many areas were found to be contaminated with deadly arsenic. Out of 64 districts, 61 districts have been contaminated with groundwater arsenic. Many NGO's have been using arsenic removal filters, but they are recontaminating the public health, ecosystem and environment by indiscriminate disposal of arsenic waste.

In order to supply arsenic free groundwater and pathogen free water to affected communities, the WATC research team developed the following solutions:

- During wet season, the people of Bangladesh and other arsenic affected countries can abstract arsenic free water from 3 to 5 feet above the "arsenic contaminated zone." They can abstract and enjoy arsenic free water for about 6 to 7 months by using tube wells. During the wet season, people will not have to deal with ground water arsenic contamination at all. During the wet season, people should not use arsenic removal filters because water above the arsenic contaminated zone is free of arsenic poisoning. Municipal water supply units also generate large volumes of arsenic sludge. Abstracting arsenic free water from above the contaminated zone reduces the amount of arsenic toxic sludge by 50 to 60 percent more than past years.

The government of Bangladesh can save millions of dollars each year by implementing this project. Prior to the generation of ground water arsenic poisoning in Bangladesh in 1975, people of Bangladesh used arsenic free water from above the neo oxidation zone. The water above this zone was free of arsenic poisoning prior to 1975, is free of arsenic poisoning now, and will be free of arsenic poisoning in the future. We think this is the best solution for 6 to 7 months out of the year in arsenic contaminated areas.

- During the dry season, people can use river water. The low turbidity river water can be filtered through the “Freedom Water Filtration System” and disinfected by a chlorination process. This method has been successfully used in all water treatment units and emergency water supply projects throughout the world. This method is safe in all respects. In most underdeveloped countries, an individual may find this method inconvenient due to a lack of knowledge of the method. If they follow the Freedom Water Filter's community based arsenic removal and disinfection method used with pathogen contaminated water, they will find it more convenient, inexpensive and environment friendly than any other water treatment system currently available. The disinfection of water by chlorine is very convenient, fast and inexpensive.
- During the wet and dry seasons, people can also abstract arsenic free water from dug wells, even in arsenic contaminated areas. It is important to note

that dug wells are not free of arsenic contamination where tube wells are found to be highly contaminated at the same depth. Dug well water is low in arsenic concentration due to the well's bigger diameter and atmospheric oxidation which helps precipitate arsenic with iron. In tube wells, the oxidation process is very slow due to its small diameter. As a result, tube wells are found to be highly contaminated. If large volumes of water are abstracted on a daily basis from dug wells without any proper protection, dug well water will show high concentrations of arsenic. This is because the water source of dug wells and tube wells is ground water. With proper protection, however, arsenic free water can be abstracted from dug wells in arsenic contaminated areas. In this process, arsenic waste will remain at the bottom of dug wells. Therefore, it will reduce and stop the risk of re-contamination of air, soil and sediments, surface and ground water resources, and agricultural resources. In developed countries, pathogenic organisms in surface water and dug well water which cause various types of diseases are no longer a problem due to proper water protection, treatment and monitoring. The government of Bangladesh, West Bengal, Nepal, Cambodia, Laos, Vietnam and Pakistan can effectively abstract arsenic free water from dug wells year round. We are conducting research to find a better way of abstracting bacteria and arsenic free water from dug wells in arsenic contaminated areas.

- The use of arsenic removal filters is the last option in dealing with the arsenic crisis because disposal of arsenic waster is very expensive. Improper disposal causes air pollution, contamination of soil and sediments, surface and ground water, aquatic organisms and agricultural resources. Current geological, hydrological, hydrogeological, hydro-meteorological and socio-economic conditions are not suitable for the construction and maintenance of a large, modern sanitary landfill for properly disposing of arsenic sludge from the arsenic removal filters and treatment units. Most or all of the arsenic removal systems in operation in Bangladesh are indiscriminately disposing arsenic waste in the open and thus creating huge environmental problems. In order to address the arsenic problem in Bangladesh and other underdeveloped countries, the WATC Water & Environmental Research Center, Wichita, Kansas, USA developed the Freedom Water Filtration System.

Freedom Water Filter: The Freedom Water Filtration System was developed by Meer Husain, at WATC International Arsenic, Water, Ecosystem & Environmental Research Center in Wichita, Kansas, USA. It is based on the principles of water treatment plants for removing organic and inorganic contaminants, pathogenic bacteria, groundwater geochemistry of trace metals, remediation of arsenic, uranium, nitrate, chromium, TCE, PCE, volatile organic compounds and other organic and inorganic pollutants by Permeable Reactive Barriers as well as the disposal of arsenic and other harmful waste as per U.S. EPA waste disposal regulations (EPA 2000)[35].

The System Consists of Two Units:

- A reaction unit which contains ferric oxide and Zero Valiant Iron (ZVI). Arsenic and many other metals have a great affinity to be absorbed by ferric oxide and ferrous oxide produced from the Zero Valent Iron in contact with water. The Zero Valent Iron has been effectively used for the last few decades for removing hydrocarbon and other organic and inorganic pollutants present in water. The reaction unit removes about 98 to 99 percent of arsenic, both As (III) and As (V), from the water.
- The filtration unit removes rest of the arsenic and supplies clean and healthy water. The unit consists of ferric oxide, manganese-dioxide, activated alumina and activated carbon.

The Zero Valiant Iron(ZVI) and ferric oxide have been effectively used for removing arsenic in many municipal water supply systems throughout the U.S. These iron based media have been extensively used for the remediation of many metal (As, Mn, Mo, Se, U, V, Cr, Zn, HC, TCE, PCE) contaminated sites in the U.S. and many other countries (EPA, 2006)[36],(Chwirka *et al.* 2000)[37], (USEPA 2002)[38], (Stan *et al.*2002)[39],(Metz, *et al.* 2006)[40],(USEPA, 1998)[41], (Edwards,1994)[42] and (USEPA, 2000)[47].

Over two dozens of three different models of filters (US07, BD08 and BD09) are currently operating in Bangladesh both in urban and rural areas. The Freedom Water Filter (US07) can supply water to 40 to 50 families per day. The Freedom Water Filter (BD08) can supply water to 60 to70 families per day. The Freedom Water Filter (BD09) can supply water to 90 to100 families per day with a daily requirement of 25 liters of water per family per day.

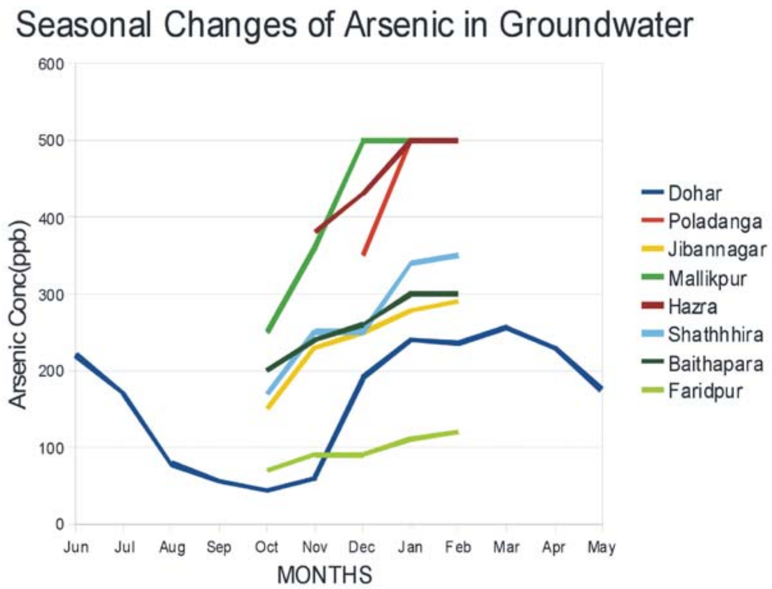


Fig. 17: The monitoring of seasonal changes of arsenic in groundwater in seven districts in Bangladesh show that during the wet season, (June to October) concentration of arsenic is significantly reduced and increased in the dry season (November to May)

The Freedom Water Filter (US07) costs $200.00, the BD08 model costs $275.00, and the BD09 model costs $375.00. Two tube wells, which will supply water to the filters, cost $ 800.00. Each filter will last about 20 to 25 years. The filter media must be regenerated and refilled once a year or when the flow is significantly reduced. Residue must be collected and disposed of as per EPA regulation. These systems are operating properly and successfully and have been successful in reducing arsenic levels greater than 500 ppb to less than 5.0 ppb, which is less than *WHO* and *USEPA* drinking water standards of 10 ppb. The system was designed to reduce arsenic levels greater than 3000 to 4000 ppb to less than 10 ppb. The drinking water standard for arsenic in Bangladesh is 50 ppb. The system requires maintenance and regeneration whenever water flow is significantly reduced. The filter media is regenerated by washing it with water. The residue is collected in a bucket and transferred to a community residue collection center for proper disposal.

Disinfection of Bacteria and Virus Contaminated Waters: Many disinfection methods of water are known today. Of these, chlorination appears to be the most inexpensive, convenient to use and effective disinfectant for pathogenic bacteria in Bangladesh and other underdeveloped nations(Gerald,F.C.,996)[46] . In Bangladesh, an average family, consisting of 5 members, requires less than $1.00 for chlorination 25 liters/day/family for a full year. The Freedom Water Filter can be effectively used anywhere in the world for removing and purifying arsenic and pathogenic contaminated water as well as other metals and organic compounds present in water. The system can also be effectively used in flood affected areas and other water crisis areas.

Freedom Water Filter Operation And Arsenic Waste Management: The developer of the Freedom Water Filter has been working on the arsenic problem for about a decade to find a sustainable solution for the people of Bangladesh and other countries. In 2008, he started a pilot project in Bangladesh for removing arsenic from groundwater and treating pathogen contaminated water in urban and rural areas in Bangladesh. He developed a cost effective and environmentally friendly water treatment system that can be replicated in any underdeveloped nations. This is a community based water treatment, water supply and arsenic waste management system. The management of water supply and waste disposal was developed based on the proven and established example of Prophet Mohammad which was cited in the 1955 Year Book of Agriculture and the US EPA arsenic waste disposal regulations.

Fig. 18: Freedom Water Filtration System. Over two dozen systems are currently operating in Bangladesh's rural and urban areas

Frank, B., stated that "Mohammad saw water as an object of religious charity. He declared that free access to water was the right of every Muslim community and that no Muslim should want for it. The percept of Holy Koran, "No one can refuse surplus water without sinning against Allah and against Man" was the cornerstone of a whole body of social traditions and of regulations governing the ownership, use and protection of water supplies. All people who shared rights to a watercourse were held responsible for the care of large water courses. Cleaning was to start at the head of the stream or canal, descending in order to each waterside family. All users shared the cost in proportion to their irrigation rights."(Frank, 1955)[43.]

The implementation of this system will ultimately educate the entire nation about the harmful effects of the indiscriminate disposal of arsenic waste from arsenic removal filters and treatment units. It will also help protect the public health, ecosystem and environment of Bangladesh and other countries. It is important to note that currently many organizations are working in Bangladesh, but no one has been able to present an environment friendly, cost effective and well organized community based water supply and arsenic waste management system thus far. This management system will work properly because of the involvement of the water users, community leaders, grass roots level govern officials, the government regulatory body and local religious and educational institutions.

Filter Operation and Maintenance Team:

- Community leader- a leader of a community who is responsible for operating and managing the water treatment system and supplying water to the community members/family properly.
- Ward member- the smallest elected units of Bangladesh. A ward consists of several villages.
- Representatives from the local educational institutions (such as schools/M adrasa/ Mosque/ Church/ Mandir/Pagoda etc.)Z

The team members will work together for the operation and maintenance of the water filtration system and adequate supply of water to community members. The team will also collect arsenic waste/residue from the filtration units and store it in a community collection center for proper disposal. The team will also maintain a record of operating systems, maintenance, costs, etc. The team will work directly under the supervision of the Team of Freedom Filter Operation and Arsenic Waste Management.

Filter Operation and Arsenic Waste Management Team:

- Upazila Chairman- the elected official of that Upazila. An Upazila consists of several Union Councils and the Upazila Chairman is the chief of the Upazila.
- Union Council Chairman- A Chairman is the elected official of the Union Council. A Union council consists of several Wards. The Union Council Chairman is the Chief of the Union Council.
- Upazila Nirbahi Officer- a government official who is the chief regulatory body of an Upazila.
- Upazila Health Engineer- a key member of the regulatory body of the Upazila who works directly under the supervision of the Upazila Nirbahi Officer.

The Upazila Chairman, Union Council Chairman, Upazila Nirbahi Officer and the Upazila Health Engineer will thoroughly examine the advantages and disadvantages of all water treatment systems and then will select the best system for operation. They will also examine the characteristics of arsenic waste, select the disposal site and approve the disposal method in each Upazila. They will work with the central regulatory body as well as with the NGO's. The NGO's must provide them with correct information regarding the water filtration system and arsenic waste disposal method.

CONCLUSION

The ground water arsenic disaster in Bangladesh is a recent man-made disaster which began in Bangladesh after 1975. The harvesting of river water from the Ganges, Teesta and 28 other common rivers of Bangladesh and India in the upstream territory of India as well as over pumping of ground water are the root causes of the recent oxidation mechanism for releasing arsenic into ground water. Hydrogeological, geochemical, arsenic toxicity, historical medical, and historical groundwater use data, fully support the recent oxidation mechanism for releasing arsenic into ground water. This data also disproves the natural disaster hypothesis of the arsenic crisis in Bangladesh.

The permanent solution to the arsenic disaster in Bangladesh depends on the source and cause of the problem. The removal of the Farakka, Teesta and other dams/barrages in the common rivers of Bangladesh and India, in addition to the maintenance of the natural river flow that existed prior to 1975, are the best solutions to the arsenic disaster in Bangladesh.

The Freedom Water Filtration System is a small community based, cost effective and environment friendly water supply system that can be used for treating arsenic and pathogen contaminated water in Bangladesh and other underdeveloped nations. The arsenic waste generated by the system can be economically disposed as per United States EPA arsenic waste regulations or similar conditions. These measures will ensure the protection of the public health, ecosystem and environment.

In Bangladesh and other countries, indiscriminate disposal of arsenic waste from the Sono Filter and other treatment units should be abandoned immediately. At the same time, arsenic waste disposal regulations must be developed as soon as possible. Improperly disposed arsenic waste from any filter and treatment unit must be collected and disposed of as per EPA regulations. The Freedom Water Filtration System is the only water treatment system which addresses the sever environmental concerns of improper arsenic waste disposal while being able to effectively filter harmful pathogens and arsenic contamination.

As the arsenic crisis escalates and the effects of arsenic related diseases continue, scientists and people in Bangladesh and around the world can rely on the Freedom Water Filtration System to deliver safe, clean drinking water to millions of families each and every day.

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