Barriers and Opportunities to Achieving Safe Drinking Water in Bangladesh

A System Dynamics Approach

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Abstract

Although Bangladesh is a nation rich with freshwater resources, many of the country's citizens lack access to safe drinking water. Between 35 and 77 million residents are estimated to have been chronically exposed to unacceptable concentrations of arsenic, a known carcinogen, through their drinking water. Additionally, the presence of bacterial contamination in surface water and shallow aquifers limits the availability of safe source water alternatives. Governmental and non-governmental organizations have attempted to remedy the drinking water crisis for decades with little widespread or long-lasting success. Often the most successful mitigation techniques include digging deep tubewells, which have a lower likelihood of arsenic and microbial contamination, and installing decentralized water treatment technologies designed to remove certain contaminants. However, changing environmental conditions, increasing urbanization, and the presence of strong cultural norms and social preferences are likely to have an effect on the success of many commonly employed mitigation techniques. Therefore, an analysis of the environmental, socioeconomic, and technological factors is needed to identify the current barriers to providing safe water in Bangladesh as well as the opportunities for more effective interventions. Data from previous studies was compiled and analyzed to create a causal loop diagram (CLD) in order to organize important factors, identify exogenous forces, and define causal relationships among different factors. Six driving forces were identified in the current system, and several interventions were purposed, including the integration of community preferences in the decision-making process and technology implementation and increased water testing.

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I. Introduction

Although Bangladesh is a nation rich with freshwater resources, many of the country's citizens lack access to safe drinking water. In the 1970's, the government began to encourage citizens to use groundwater instead of the surface water, which was often contaminated with pathogens, as a means of reducing the incidence of waterborne disease.[1] Governmental and non-governmental organizations (NGOs) worked together to install thousands of shallow tubewells in rural communities.[40] However, in 1993, researchers discovered many of the shallow tubewells were contaminated with high levels of arsenic, a known carcinogen.[1]

Today, the citizens of Bangladesh are still struggling to access safe and reliable drinking water. Although the Bangladeshi government, along with many national and international NGOs, are working to address the wide-spread public health crisis, studies have found that one in five (about 20%) of the country's tubewells have arsenic concentration higher than the Bangladesh safe drinking water standard of 50 parts per billion (ppb) and an estimated 35 to 77 million people have been exposed.[8, 40] The continued harm to the Bangladeshi population has been well researched and widely documented.[8,36,40,42]

Furthermore, groundwater is not necessarily free of harmful bacterial contamination as previously thought. Shallow tubewells often contain fecal coliforms, which can cause diarrheal disease in humans.[24] A recent study indicated an inverse relationship between arsenic and bacterial contamination of shallow tubewells, which means a simple solution to the water quality problems is not likely.[44]

The objective of this paper is to review current literature focused on drinking water in Bangladesh in order to assess the problem through the lens of system dynamics. The state of the system is examined using a Casual Loop Diagram and recommendations concerning future interventions are made in the final section of this paper.

II. Defining Sustainable Development in Rural Bangladesh

In the simplest of terms, sustainable development is defined as freedom from poverty, want, insecurity, and repression for those living today and for future generations.[35] The most basic human needs include consistent availability of adequate food, shelter, and water. Currently, sustainable water resources and treatment technologies are not being provided to thousands of communities in rural Bangladesh.[36,38,42] The Bangladeshi government has not adequately responded to the drinking water crisis, which was uncovered over twenty-five years ago, and efforts by NGOs are often spear-headed by foreign actors with limited resources.[9] It is clear from the continued lack of safe drinking water, the traditional interventions currently employed are not meeting current needs and not sustainable in the long term.

For lasting change to occur, the system must be considered with a broader lens. A sustainable system is defined as one that is environmentally aware, socially acceptable, and economically viable. In Bangladesh, the lack of a socially acceptable and economically feasible safe drinking water source appears to be the main factors affecting long term solutions. While environmental concerns, such as water scarcity or hazardous waste accumulation, are not currently a barrier to the implementation of technology, they will become a greater issue in years to come as climate change continues to progress.

III. Physical Characteristics Affecting Safe Drinking Water Access

A. Mechanisms of Groundwater Contamination by Arsenic and Pathogens

The region of Bangladesh most affected by arsenic contamination lies in the delta of the Ganges, Brahmaputra and Meghna rivers (Figure 1).[1,3,41] The sediment of the Ganges delta and Meghana floodplain is comprised of fine to very fine grained sand and is rich in organic material, which creates a strong reducing environment.[1,3] Results of a previous study indicate three common phases of arsenic deposits: an oxide phase of iron and manganese, an organic matter phase, and sulfide and silicate phases.[7] The process by which the arsenic mobilization occurs from these phases depends on the hydrogeochemical characteristics of the aquifer, the presence of oxidized and/or reduced mineral phases, and the cofactors associated with the arsenic-rich deposit; however, bacteria-mediated mineralization of organic matter and reductive dissolution

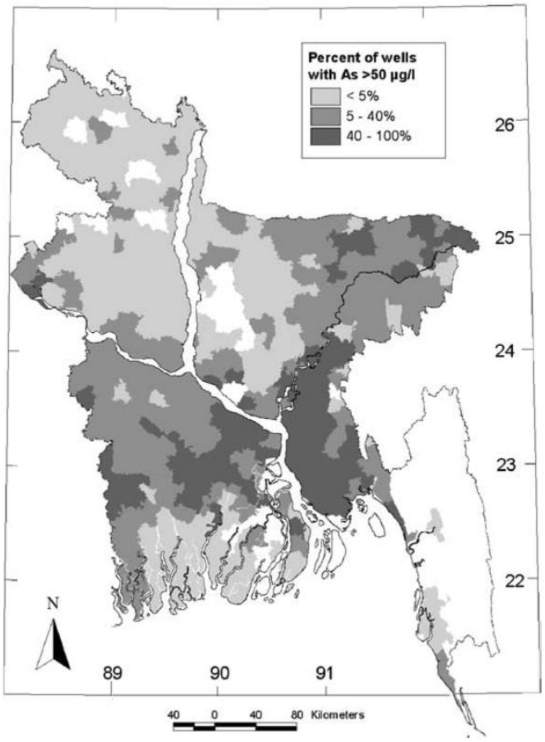

Figure 1. Percentage of wells with >50 µg/l arsenic. The map summarizes >33,000 field and laboratory test data from drinking water samples compiled by the Department of Public Health and Environment in Bangladesh. The map was reproduced from Ravenscroft et al., 2005[41]

of iron and manganese oxyhydroxides are the dominant pathways by which arsenic is released.[1,3,7]

The dissolved arsenic is predominantly found in the shallow aquifers (<100 m deep), while in deeper aquifers (>150 m deep), there is little to no arsenic contamination.[3,41] When aqueous arsenic is present, it is predominantly found in two oxidation states, arsenite (As^{3+}) and arsenate (As^{5+}), though the ratio of arsenite to arsenate present in groundwater is highly unstable due to changes in the redox potential of the aquifer, the activity of microorganisms, and the presence of oxygen.[30] The ratio of arsenic species affects the type of treatment needed to effectively remove the contamination as arsenite is not easily removed through sorption.[1,30,43]

In the northern reaches of Bangladesh, the shallow aquifers are relatively arsenic free due to older, coarser grain sediment that is low in organic matter.[3]

B. Current and Future Climate Characteristics and the Potential Effect on Water Quality

The Global Climate Risk Index ranked Bangladesh among the top 10 countries most vulnerable to climate change.[26] The predominant impacts affecting water resources are changes in rainfall and temperature and sea water rise. Currently, Bangladesh has six seasons with two prominent precipitation stages: monsoon season and dry season.[26] Water source availability and quality vary from monsoon season to dry season.[22] Historically, the monsoon season (April to September) would bring between 1,250 to 3,500 millimeters of rainfall to most regions of Bangladesh with the coastal and eastern regions receiving the highest levels of rainfall (Figure 2).[25] Climate change is beginning to impact the length of the seasons and the frequency of intense rain events with the summer and rainy seasons are prolonging and the winter, autumn, dewy, and spring seasons are shrinking.[26]

Sea water rise due to climate change is also a prominent threat to Bangladesh's water resources. The sea level in Bangladesh is estimated to rise about 40 centimeters by 2080, and a one-meter rise would result in a quarter of the county's land mass underwater.[26] Another impact of rising sea level is increased salt water intrusion in groundwater aquifers, resulting in fewer safe water sources for communities in those areas.[26] Overall, climate change will greatly impact water resources in Bangladesh, and while there is little the country can do to prevent these encroaching threats, changes in rainfall, temperature, and sea level must be included when addressing long-term water access issues.

IV. Cultural and Economic Factors Affecting Safe Drinking Water Access

Social, cultural, and economic factors are as important as treatment effectiveness for the introduction of a new treatment technology and should be considered during the planning and implementation stages of safe water interventions. Individual and community preferences for available water technologies can be assembled from the vast literature on decentralized drinking water technologies employed in Bangladesh and other east Asian countries, including Nepal and India.

A shift in strategy is needed to more successfully and quickly address the lack of safe drinking water in Bangladesh. Local people should be included in the decision-making process as they are often both capable and willing to assume responsibility for the water resources when given the chance. [9,34] Rather than the top-down technology implementation often used, participatory water management, in which local people and organizations work symbiotically, should be implemented. This management strategy is beneficial for two reasons: first, community members often have unique insight into the water quality and health issues and would like to be involved in decisions-making, and second, government micromanagement at the village level is often impossible and undesirable.[12] Currently, research tends to focus on the effectiveness of various treatment technologies and user preferences and experiences are often only a side note, if considered at all.

Treatment methods that require an excessive amount attention, labor or time are unlikely to be successful even if the water source is located in or near the household. In one study, a third of individuals using household treatment options that required daily maintenance switched to piped or deep tubewells when able.[20] Although the new water sources were father away, the individuals viewed these options as more convenient and manageable than the high maintenance household-base technology. However, the same study found that lack of privacy and long distances often discouraged women, the primary water gather in Bangladesh, from seeking out improved water options.[20,37] Therefore, the location and the required maintenance of a water source should both be considered when installing new equipment or encouraging households to switch.

Taste, odor and appearance often play a significant role in use of a particular water source.[37] For example, one study found that participants preferred piped water free of iron, thus lacking a metallic taste, as they felt it was better for their health.[2]

Cost is another factor that can be prohibitive in a community's acceptance of a new technology. For one, most communities in rural Bangladesh are poor, so many of the more effective or convenient treatment methods are not affordable unless highly subsidized by an outside source.[17] Additionally, citizens place a low value on arsenic free water. One study concluded that people living in arsenic-afflicted areas of rural Bangladesh were only willing to pay about 0.2% to 0.3% of their income per month (about 9 – 11 Bangladeshi Taka) to secure safe drinking water.[2] However, low cost does not always appear to be the highest priority, especially if it comes at the expense of other factors, such as convenience.[20]

V. Available Water Sources

There are several types of water sources available in Bangladesh although some are more prevalent than others. The benefits and drawbacks of each are important to consider when recommending sustainable drinking water practices and identifying areas of opportunity within the current water system. Factors, such as seasonal and long-term reliability, potential bacterial and arsenic contamination, potential for other contamination (including salinity), and aesthetics, such as odor, taste, and appearance, are important to consider when evaluating sources. These issues were chosen as focus points of evaluation in this analysis as studies have shown they can have a strong impact on water consumption and health of users.[20,22,41,39]

A. Rainwater

Rainwater may be collected and used for drinking purposes, both seasonally and year-round. For optimal use, a rainwater harvesting system, which typically composed of a storage tank and a catchment area, should be sized based on the amount of rainfall received, the frequency of rainfall, and the water demand.[5] During monsoon season (April to September), 1,250 to 3,500 mm of rainfall can occur in most regions of Bangladesh with the coastal and eastern regions receiving the highest levels of rainfall (Figure 2).[25] If excess rain is stored, a household may have sufficient supplies to last through the dry months (November to February); however, the stored water can become contaminated if not properly stored.[18] Rainwater harvesting is especially beneficial to coastal communities, where saltwater intrusion is making groundwater unsuitable for consumption.[18] In some coastal villages dealing with high levels of saltwater intrusion, around 36% of households used rain water as a main source of drinking water during the rainy season.[5]

While rainwater is free of bacteria and arsenic before it comes in contact with the catchment area, bacterial contamination can occur depending on the catchment surface and the method of storage (Figure 3).[22] For example, one study found the average total coliform in collected water is higher for thatched roofs than corrugated iron roofs.[18] Inefficient storage practices and longer storage times can also contribute to increased bacterial count as well.[22,25,31] Depending on the local air pollutants and the material on which the rain is collected, the water may pick up chemicals as it falls and lands on the catchment area.[25] Additionally, rainwater lacks minerals so may have an off-putting taste to some people.[5,18]

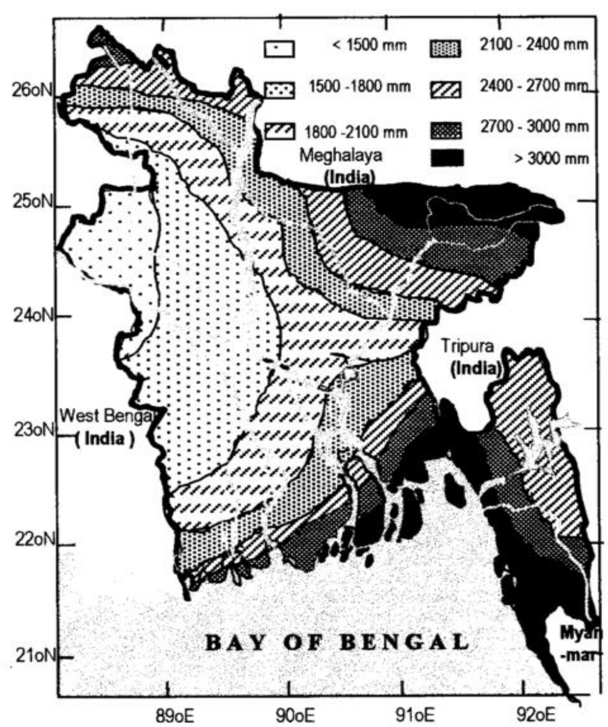

Figure 2. Distribution of rainfall in Bangladesh. The map was reproduced from Ahmed, 1999.[5]

There are both positive and negative features of rainwater harvesting when considering the long-term sustainability of this option. Rainwater harvesters are relatively easy to build and maintain, and they can be installed at a household level, which means that even isolated individuals can have access.[5] However, poorer households often do not have a roof or other catchment area suitable for rain water collection.[5] Therefore, rainwater harvesting is only economically feasible choice in higher income areas or in communities receiving outside support.

B. Surface Water

Bangladesh has ample surface water resources. About 10% of the country's area (or 5,559 square miles) is covered by freshwater and there are an estimated 1.2 million ponds.[16,23] In addition to the standing water, over 795 billion cubic meters is estimated to flow through the Ganges-Brahmaputra river system every year.[16] However, the high quantity of water does not guarantee safe water access. In fact, excess water can add to the disintegration of water quality. During the monsoon season, between one-third and two-thirds of the country may be under water, leading to contamination of the surface waters by human and animal waste and industrial and agricultural pollutants.[16]

Until the 1970's, surface water was the primary source of drinking water for Bangladeshi households.[30] However, microbial contamination of surface water sources resulted in high incidence of diarrheal disease, which led to a national, government-sponsored campaign encouraging citizens to switch to groundwater.[30] Since then, the ponds and lakes of Bangladesh have further declined in quality. Ponds frequently receive human waste and are often used for aquaculture, which results in higher levels of bacterial contamination.[6,20] Algal blooms, caused by high nutrient concentrations, increases the chance of cyanotoxin contamination.[22] Increasing quantities of industrial waste and agricultural runoff, including pesticides and herbicides, are also rising concerns.[6,39] Therefore, in its current state, untreated surface water is not a safe option for individuals in rural Bangladesh.

C. Dugwells

A dugwell is one of the most easily accessible water sources in Bangladesh. The wells are manually constructed and tap into the shallowest aquifer.[6,22] The opening is usually lined with concrete, covered with a concrete slab or metal sheet to prevent direct contamination, and contains a hand pump through which water is drawn.[22] The high availability and low cost of building material and the lack of specialized construction equipment make dug wells relatively simple to build.[27]

Although dugwells are a common water source in rural Bangladesh, there is low demand for the installation of new dug wells as the water often has undesirable taste and odor and is of low quality.[6,20] A study conducted by Howard et al. found that nearly 90% of samples contained thermotolerant coliforms, an indicator of fecal contamination (Figure 3).[22] The monsoon season further exacerbates the microbial water quality degradation resulting in water unfit for consumption.[22] Therefore, although dugwells are ubiquitous in Bangladesh, they should not be used as a source of drinking water unless further treatment, specifically disinfection, is applied and regular arsenic testing should take place to ensure the well is not contaminated.

The shallowest aquifer from which the dugwells obtain water often have little to no arsenic contamination due to the seasonal water table fluctuations that flush away or immobilize the contaminant.[6,27] However, Howard et al. found a small, but significant, portion of dugwells do contain arsenic above the WHO limit of 10 ppb (Figure 3).[22]

D. Deep Tubewells

While surface water and rainwater are consumed by some Bangladeshi households, groundwater is by far the most common source drinking water. Groundwater, which includes shallow and deep tubewells, provides over 90% of drinking water and much of the water for irrigation in Bangladeshi communities.[41] A baseline survey of 200 households in rural Bangladesh found that about 3% of respondents drank water from deep tubewells.[20]

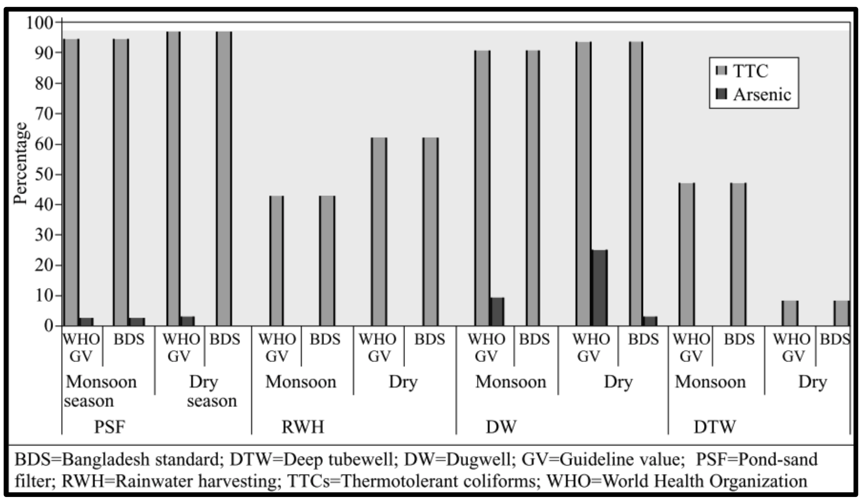

Figure 3. Percentage of samples in monsoon and dry season that exceeded the Bangladesh and WHO standards for thermotolerant coliforms and arsenic. The graph was reproduced from Howard et al., 2006.[22]

The installation and maintenance of a deep tubewell is simpler than the sources previously described. Deep tubewells are community-scale devices installed by NGOs and the government using specialized drilling equipment.[6] Typically, a small cement apron surrounding the wellhead prevents against short-circuiting contaminants.[22] A hand pump is used to draw the water from the aquifer and it is consumed without further treatment.[22] Although the community deep tubewells are often located further from a household than home-based devices, residents will use the wells if they are constructed in a safe location.[6]

Deep tubewells are generally viewed as the safest source of drinking water in Bangladesh. The wells draw from older aquifers at least 150 meters in depth.[22,41] The deeper aquifers naturally contain little to no arsenic (Figure 3); however, long term leakage of arsenic contaminated water from shallow aquifers may occur over time.[41] A relationship between excessive groundwater extraction for irrigation and deep aquifer arsenic contamination has been modeled, but the extent to which the two are linked is not clear. The relationship likely depends on local geology, specifically the presence of a clay layer, the depth of the wellhead below the oxidized sediment, and the arsenic concentration of the shallow aquifer.[1,41,43] A model proposed by Stollenwerk et al. demonstrates the risk of arsenic contamination in a deep aquifer is highly dependent on these local characteristics (Table 1).[43] Therefore, while deep tubewells are currently one of the best options for reliable, safe drinking water, changes in use practices must be made if they are to remain an arsenic-free option in the long term.

Other water quality concerns include salt water intrusion and microbial contamination during monsoon season.[22,41] Salt water intrusion is only a concern for coastal and island-based communities. Microbial contamination of deep tube wells is likely caused by contaminated priming water and is therefore a result inadequate training and maintenance.[22]

Table 1. Modeled attenuation of arsenic by oxidized sediments assuming no impermeable clay barrier is present. The table was reproduced from Stollenwerk et al., 2007.[43]

Depth below top of oxidized sediment (m)	Years until simulated breakthrough of >10 μg/L As for specified concentrations			
	50 μg/L	100 μg/L	300 μg/L	900 μg/L
2	31	25	16	9
10	209	189	145	95

E. Shallow Tubewells

There are an estimated 6 to 11 million shallow tubewells in Bangladesh making them the most common drinking water source.[14,32] Shallow tubewells are generally defined as wells with a depth less than 100 meters, but the majority of those installed are between 10 and 50 meters deep.[14,32,39] As stated previously, groundwater provides over 90% of drinking water in Bangladesh with up to 97% of households using shallow tubewells as their main drinking water source.[20] The widespread prevalence of the shallow tubewell makes it a highly important component of the current drinking water system.

For decades, the high occurrence of arsenic contamination has been the primary health concern for shallow tubewells in Bangladesh.[11,27,32,39] Arsenic is most commonly found in aquifers between 10 and 30 meters, which falls within the drilling depth of most shallow tubewells and results in the great number of contaminated wells (Table 2).[32,41] A comprehensive study conducted by the British Geological Survey and the Bangladesh Department of Public Health and Engineering (DPHE) in 1998 found that 46% of shallow wells exceeded the WHO limit of 10 pbb and 27% exceeded the Bangladesh limit of 50 ppb.[11] In addition, older tubewells tend to have higher concentrations of arsenic concentrations likely due to a lateral migration of arsenic within the aquifer or a change in redox reactions during pumping (Figure 4).[39,41] Thus, overall arsenic concentrations have likely increased since the initial 1998 survey. A consistent testing regimen is needed to track the magnitude of these changes in a specific locale overtime.

Table 2. Arsenic distribution in groundwater by well depth. The initial source of data was the GSACB Regional Survey, Phase. [11] *The table was reproduced by Ravenscroft et al., 2005.*[41]

Well depth	No. of wells	Arsenic concentration (µg/l)			
		Mean[1]	Max.	>50	>10
<10 m	36	20	260	33%	69%
10–30 m	576	34	1,090	52%	78%
30–100 m	1,033	4.9	1,670	32%	49%
100–200 m	92	5.6	250	20%	54%
>200 m	283	0.7	110	0.7%	3%
All	2,023	6.7	1,670	35%	51%

Although groundwater was previously thought to be relatively free of microbial contamination, recent studies have indicated fecal contamination is a concern for shallow tubewells.[14,24,44] The concentration of bacteria in a given well is influenced by several short-term and long-term factors. Aquifer depth and season have a significant effect on the presence of *Escherichia coli*, an indicator of fecal contamination, with deep aquifer and dry season samples containing the least contamination (Figure 3).[33] Urbanization, which is occurring throughout Bangladesh, is linked to a rise in fecal contamination likely caused by the increase in population and unsanitary latrines and ponds in the area surrounding the tubewell.[46] Similarly, land development often leads to greater amounts of surface water, as the soil is often dug out for construction, and increased risk of fecal contamination in groundwater.[46] Intense rain events are associated with increased *E. coli* as heavy rain may flush contaminants from unsanitary latrines into surface water.[46] With continued climate change, these intense rainfalls are likely to become more prevalent.[26]

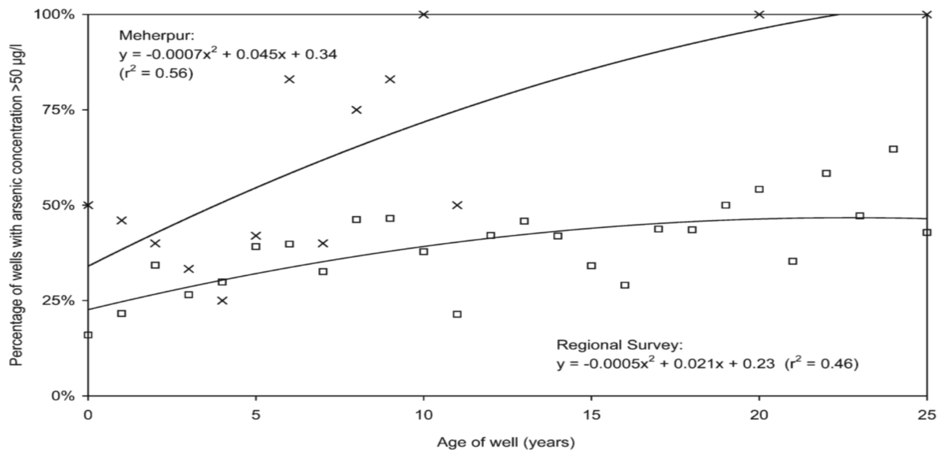

Figure 4. Percentage of wells with arsenic concentration above the Bangladesh safe drinking water standard of 50 ppb. The squares are based on the Regional Survey and the crosses are based on the Meherput survey (detailed in Ravenscroft et al., 2005). The table was reproduced by Ravenscroft et al., 2005.[41]

VI. Decentralized Water Treatment Methods with A Focus on Arsenic and Pathogen Contamination

Although many water treatment technologies have been employed in Bangladesh, most of the technology is based on a few treatment mechanisms, which includes oxidation, co-precipitation, sorption, filtration, and ion exchange.[4,30] Most of the treatment technologies use several of these mechanisms to remove arsenic and treat bacterial contamination.

An overview of the common treatment technologies is provided here.

A. Pond-Sand Filter

Pond-sand filters are the most prevalent treatment strategy for surface water, but the removal efficiency of the filters is under question. About 38% of villagers in southwest coastal region of Bangladesh use pond-sand filters as a source of drinking water.[19] However, a survey considering the demand-based water options found there is no demand for further pond-sand filter installation due to the high levels of pollution present in the source water.[20]

Table 3. Comparison of water quality parameters from twelve pond-sand filters in the Southwest coastal region of Bangladesh to the World Health Organization (WHO) limits. The table was reproduced from Harun and Kabir, 2013.[19]

Water quality parameters	WHO (1993)		Samples exceeding allowable limits	Percentage of samples exceeding allowable limits
	Desirable limit	Maximum allowable limit		
Colour (hazen)	–	15	Nil	Nil
TDS (ppm)	500	1,500	Nil	Nil
pH	7.0–8.5	9.2	Nil	Nil
Cl^- (ppm)	200	600	5, 6, 9	25
K^+ (ppm)	–	12	1, 2, 6, 10	33
Ca^{2+} (ppm)	75	200	Nil	Nil
Mg^{2+} (ppm)	50	150	Nil	Nil
NO_3^- (ppm)	45	–	Nil	Nil
SO_4^{2-} (ppm)	200	400	Nil	Nil
As (total)	0.01	0.01	Nil	Nil
F. coliform (no./ml)	0/ml	0/ml	2, 3, 5–11	75

Pond-sand filters are community-based slow sand filters that remove bacteria by filtering the water through sand and gravel.[27] Bacteria and turbidity is removed through several mechanisms. Physical straining occurs when bacteria and cysts are too large to pass between the pores of sand.[37] Attraction of bacteria to sand grains due to hydrophobicity and surface charge also removes some of the pathogenic organisms.[37]

While pond-sand filters adequately address turbidity and color issues, microbial contamination, cyanobacterial toxins and agricultural and industrial chemicals are still a concern for some sources (Table 3, Figure 3).[22,27] Arsenic contamination is usually not a concern for pond-sand filters although surface water recharged with arsenic contaminated wells may have arsenic concentrations above the WHO standard (Figure 3).[22] Current treatment strategies must improve removal efficiency dramatically before surface water can be considered a safe option. Additionally, the growing contamination of surface waters caused by present sanitation, industrial, and farming practices should be curtailed.

Economically, the pond-sand filter is a viable option. One study investigating the willingness-to-pay for several drinking water options found that almost all (about 99%) of households stated they would pay the amount needed to build and maintain a pond-sand filter serving 60 to 100 families.[19] The material used to build these filters, including brick, cement, sand, and PVC pipe, are easily available to rural communities.[19] However, ponds are often used for aquaculture, a common source of income, which must end if a pond-sand filter installed.[27]

Therefore, while these filters are cheaper than some other options, they could result in a loss of income for some households.

B. *Biosand filter*

The biosand filter is the household version of a slow sand filter modified to treat arsenic contaminated groundwater. The modified slow sand filter consists of a concrete container filled with several layers of media, including brick chips, iron nails or filings, sand, and gravel (Figure 5).[37] A lid covering the filter prevents direct contamination of the water contained within.[37]

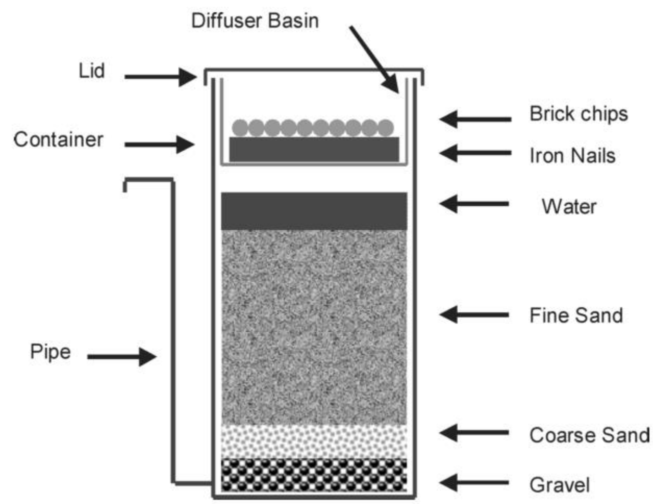

Figure 5. Schematic of a typical biosand filter, which treats for arsenic and pathogen contamination. The figure was reproduced from Harun and Ngai et al., 2007.[37]

Arsenic is removed via adsorption of the contaminant onto the rusty iron nails, which contain iron hydroxide on their surface.[37] As the arsenic-iron complexes are flushed into the sand layer, new parts of the nail are exposed, providing further capacity for arsenic adsorption.[37] The arsenic-iron complexes are physically removed from the water stream as it passes through the sand.[37]

Bacteria are removed from the water through several mechanisms, similar to the slow sand filter described above. Large pathogens are removed via physical straining by the sand.[37] Some of the smaller pathogens attach to sand particles by hydrophobic attraction.[37] Biosand filters also have a biologically active layer within the first few centimeters of the sand, which further removes pathogens.[37]

The ability of biosand filters to remove viral pathogens is currently uncertain. There is evidence some viruses die or are inactivated as the water sits stagnant in the filter, becoming anaerobic.[37] Studies have also shown the biologically active layer may inactivate viruses through absorption or the production of microbial exoproducts, and the iron layer may lead to a reduction in the viable viral community as well.[10,13] However, another study found viral shedding from biosand filters to be a clear concern.[29]

Overall, biosand filters are easy to build and maintain. They can be built using locally available materials, especially if rusty nails are used as the source of iron hydroxides, and the filters can be built by trained community members using simple tools.[37] Additionally, no electricity is needed for filter use or maintenance.[37]

C. Arsenic-Iron Removal Plants

Arsenic-Iron Removal Plants (AIRP) are community-based filters used to treat groundwater with high levels of arsenic contamination.[4] The simplest version of the AIRP treatment train includes aeration, sedimentation, and rapid sand filtration.[4] However, other media, such as activated alum or ferric hydroxides, may be used in place of sand to increase arsenic adsorbtion.[21]

The mechanism by which AIRPs remove arsenic relies on adsorption to iron precipitates and co-precipitation.[4] AIRPs can be effective because groundwater sources with high concentrations of arsenic also tend to have high concentrations of iron.[4] The iron is oxidized as the water flows through the aerator.[45] The aqueous arsenic species adsorb to the iron oxide particles, and the resulting complexes settle and filtered out by the sand filter.[45]

One drawback of the AIRP is the regular maintenance it requires. A large amount of clean water is needed to wash the filter beds and consistent backwashing is necessary to achieve optimal arsenic removal.[4] Unless a regular maintenance schedule is established, removal efficiency of an AIRP is likely to decrease soon after it is installed.

A. Solar Oxidation and Removal of Arsenic

Solar Oxidation and Removal of Arsenic (SORAS), a relatively novel decentralized treatment strategy, attempts to remove high concentrations of arsenic from ground and surface waters using easily obtainable and affordable materials. Dr. Stephan Hug first proposed the SORAS technique as a sustainable arsenic removal option for resource limited communities in 2001 (16). In its simplest form, the SORAS reactor requires only ample sunshine, a PET bottle, a few drops of lemon juice, and possibly a bit of steel wool (5). However, a number of studies have since expanded on this simple design with the goal of identifying challenges in treatment, optimizing reaction kinetics, and increasing treatment efficiency (3,5,8,10,11,16,19,25,26,27,31).

SORAS applies the conventional water treatment strategies of oxidation and adsorption to remove both forms of inorganic arsenic at the household or community scale. Additionally, although increased iron concentrations did slightly decrease bacterial concentrations, the treatment of water by SORAS appears to result in little to no deactivation of bacteria (26). However, further study is needed to understand and corroborate these results.

V. Water Quality Monitoring Infrastructure

Monitoring groundwater sources for arsenic contamination is an essential step in ensuring safe drinking water access in Bangladesh. It has been estimated that testing alone has resulted in the largest drop in the number of individuals consuming arsenic contaminated water than any other intervention so far.[6] In one study, approximately 29% of villagers informed of unsafe arsenic concentrations switched their water source.[6]

Arsenic testing can be performed both in the lab and in the field. While laboratory testing is more accurate and reliable than field test kits, it is expensive and available only in a few locations.[27] Field test kits, on the other hand, are widely available, low cost, and provide rapid results, making them more accessible to communities and individuals.[27]

Most of the arsenic test kits employed in Bangladesh are semi-quantitative, colorimetric field kits.[15] The dominant method used by these kits is the Gutzeit reaction, which involves the production arsine gas (Figure 6).[15] A paper strip impregnated with mercury (II) bromide reacts with the arsine gas, resulting in a color change.[15] The intensity of the color depends on the amount of arsine produced, and the concentration of arsenic in the water can be estimated through comparison of the test strip to a reference color chart.[15] The Gutzeit method is capable of detecting arsenic concentrations as low as 1 ppb.[15]

$$\mathrm{As(OH)_3 + 3Zn + 6HCl \rightarrow AsH_3 + 3ZnCl_2 + 3H_2O}$$

$$\mathrm{H_3AsO_4 + 4Zn + 8HCl \rightarrow AsH_3 + 4ZnCl_2 + 4H_2O}$$

Figure 6. Gutzeit reactions for arsenite (top) and arsenate (bottom, which the primary mechanism used by arsenic test kits. The equations were originally published in Feldmann et al., 2008.[15]

Although a common testing method, the field kits currently available in Bangladesh often produce highly variable results, especially in the concentration ranges around the WHO and Bangladesh drinking water limit.[15,28] One source of inaccuracy is interference by other elements dissolved in the water such as antimony and sulfur, which can also change the color of the test paper.[15] Another potential source of error stems from the water quality testers. The majority of people trained to use the field kits have only the most basic educational qualifications.[9] Therefore, regular technician trainings and periodic verification of field kits by laboratory tests could improve the accuracy of field kit testing.

VI. Causal Loop Diagram – The Technology, Environment, and Socioeconomic Nexus

The preceding information examines the barriers and opportunities to achieving safe drinking water in Bangladesh. From this data, a Causal Loop Diagram (CLD) was created and allows for exploration of the interactions between key factors and driving forces (Figure 5). Based on this relationship map, several recommendations are provided.

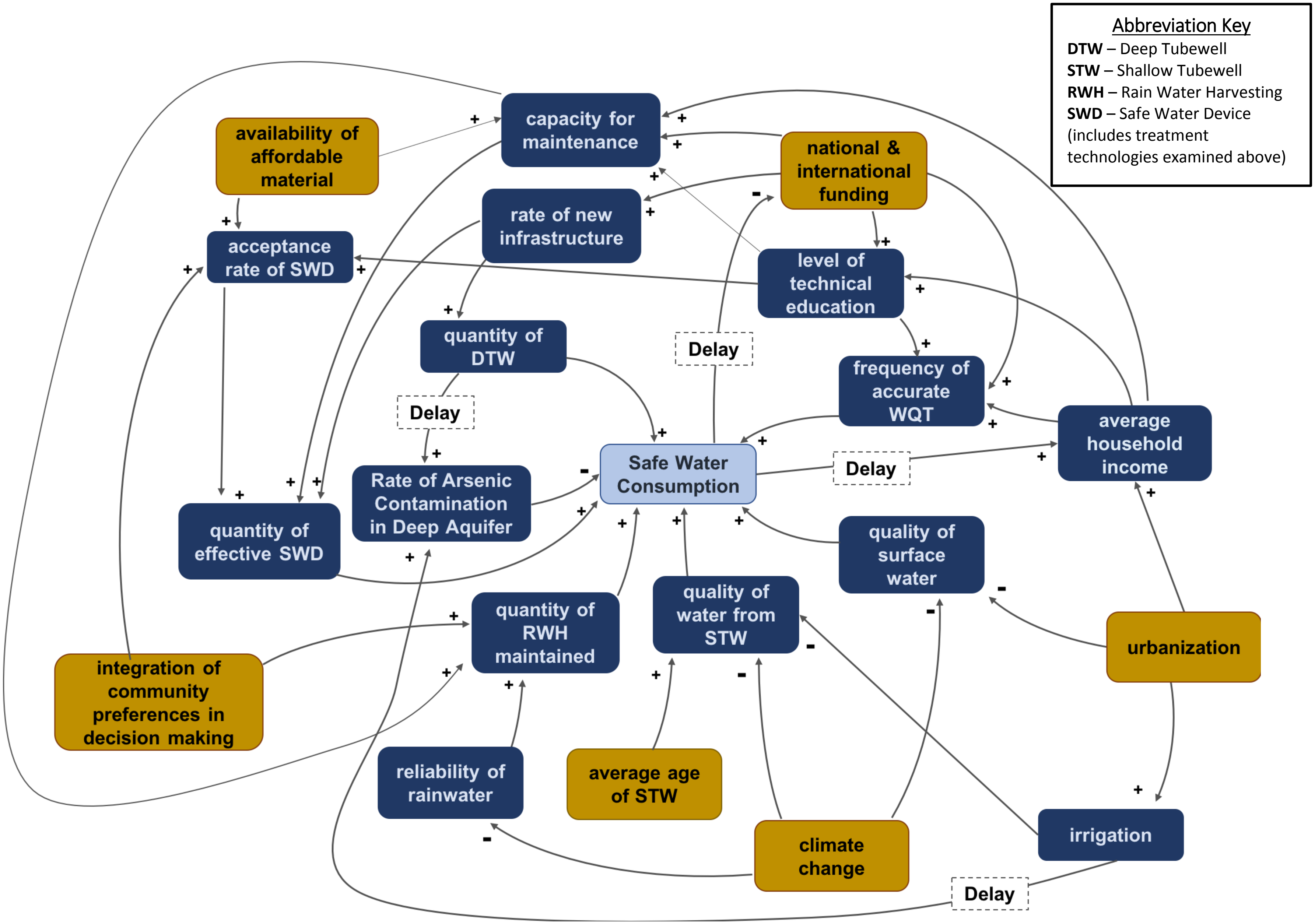
Abbreviation Key
DTW – Deep Tubewell
STW – Shallow Tubewell
RWH – Rain Water Harvesting
SWD – Safe Water Device (includes treatment technologies examined above)
availability of affordable material
capacity for maintenance
national & international funding
rate of new infrastructure
acceptance rate of SWD
level of technical education
quantity of DTW
Delay
frequency of accurate WQT
average household income
Delay
Rate of Arsenic Contamination in Deep Aquifer
Safe Water Consumption
Delay
quantity of effective SWD
quality of surface water
quality of water from STW
quantity of RWH maintained
urbanization
integration of community preferences in decision making
reliability of rainwater
average age of STW
climate change
irrigation
Delay

Figure 5. Causal Loop Diagram examining the relationship between seven driving forces (*orange boxes)* on unsafe water consumption in Bangladesh with a focus on technological, environmental, and socioeconomic factors. The arrows indicate the direction of causality. *Positive signs* (+) indicate a direct relationship between linked factors and *negative signs* (-) indicate an inverse relationship between linked factors. Temporal delays important to the function of the system are shown.

Six driving forces were identified by the Causal Loop Diagram. Although these forces are not necessarily entirely independent of other feedback mechanisms, they are relatively constant pressures within the Bangladesh drinking water system. The six forces are *National and International Funding*, *Availability of Affordable Material, Integration of Community Preferences in Decision Making, Urbanization, Climate Change*, and the *Age of Shallow Tubewell.*

Currently, each of these forces are acting on the system at various strengths, resulting in a system that is failing to meet the needs of Bangladesh's communities. Therefore, interventions focused on changing the dominance of some of these forces over others can successfully address unsafe water consumption in Bangladesh. Several potential areas of intervention are discussed below:

- *Urbanization* and *Climate Change* will both continue to increase over time, and there is little the government and NGOs can do to prevent or influence the intensity of these forces. However, the acknowledgement and inclusion of both factors in long-term planning should help to mitigate the negative impacts.
- The amount of *National and International Funding* available in Bangladesh is influenced by the amount of unsafe water consumption occurring in the country. However, there is a significant delay in the relationship between the drinking water crisis and the funds available as demonstrated in the decades of minimally successful governmental and NGO campaigns to provide citizens with safe drinking water. A quicker route to change is the proportioning of funds to various interventions, including *Level of Technical Training, Capacity for Maintenance,* and *Frequency of Accurate Water Quality Testing.* Currently, the majority of funds are directed towards deep tubewell drilling and safe water device installations. However, the data presented supports increased water quality monitoring and education focused on maintenance and repair of currently available technologies as a means of increasing access to safe water.

- The *Age of Shallow Tubewell* is another factor that concerned parties have no ability to influence. However, increasing the frequency of water quality testing can alert government and non-profit employees to changing conditions within an appropriate time frame. Shallowtube wells that are no longer producing water safe for human consumption can either be closed or a safe water device can be installed. A database of water quality parameters should be maintained to document and track test kit results over time. Long-term data could be useful in identifying trends and mitigating future issues, such as those caused by *Climate Change* and *Urbanization.*
- The *Cost* and *Availability of Material* used to build, repair, and maintain safe water devices and rain water harvesters influences the acceptance of the technology within communities and the long-term success of treatment. Although the government and NGOs do not have direct control over these forces, coordinated decision-making and forward-looking planning strategies can influence the strength of these factors. If concerned organizations can agree on a treatment plan, rather than acting independently of one another, overall costs could be lowered and the materials needed for the safe water devices would be more ubiquitous. Overall, these changes would lead to a larger number of devices as well as greater acceptance by the communities.
- The *Integration of Community Preferences in Decision-Making* is one of the most impactful forces in the system as well as one of the easiest for decision-makers to incorporate; therefore, it should be the primary target for intervention. As described above, individuals have strong preferences when it comes to the source water and treatment technology employed in their communities. Many factors can influence the rate of use, frequency of maintenance and repair, and ultimate success of water treatment strategies, including treated water aesthetics, distance from household, daily maintenance requirements, and reliability. If these preferences are integrated into the decision-making process at both local and national levels, the success rate of technologies is likely to rise and ultimately, the consumption of unsafe water is decline.

VII. Conclusion

Decades after arsenic contamination was discovered in the country's shallow aquifers, many Bangladeshi citizens still lack access to unsafe drinking water due to economic barriers, environmental changes, and the lack of community voice in the decision-making process. While the quantity of water is sufficient, the quality of most available water sources is dangerously low and continues to degrade. However, while the current system is not working for the people in Bangladesh, there are several interventions through which the system can be improved. Increased communication and coordination between all organization and agencies involved in safe water access has the potential to lower treatment cost and increase the availability of material, and the integration of community preferences will strengthen the acceptance of treatment technology.

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