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Groundwater arsenic in Bangladesh: what's new for policy research?

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Abstract

This paper provides an overview of policy responses to arsenic in groundwater in rural Bangladesh to assess their role and potential effectiveness in reducing exposure. With 97% of the country consuming groundwater for drinking, there is a continuing crisis of tens of millions of people exposed to elevated levels of arsenic. An examination of the number of people protected through two major remediation efforts suggests that recent progress may not be sufficient to keep up with the increasing population or to resolve the crisis during this century. Recent developments in remedial options are examined to identify their potential role in an evolving policy and research agenda. There appears to be growing agreement about future research and policy responses that can scale remedial options and make them widely accessible. These include: (1) the need for a reliable and affordable programme of arsenic testing and retesting; (2) attention to risks from other soluble contaminants and pathogens; (3) explicit priority setting across locations, time and to address fairness; and (4) development of value chains to ensure remedial options are supported over time.

Keywords: Arsenic; Bangladesh; Health; Socio-economic aspects; Water supply

Introduction

Bangladesh experiences high levels of naturally occurring arsenic in groundwater, the consumption of which leads to massive morbidity and mortality in the population who ingest the arsenic in their drinking water and food. Flanagan *et al.* (2012), using data from 2009, showed that about 65 million people were exposed to drinking water with arsenic levels in excess of the World Health Organization standard of 10 parts per billion (ppb), and, of these, some 20 million were exposed to levels above 50 ppb (the Bangladesh standard for arsenic). There is considerable uncertainty surrounding these estimates due to uneven population growth, high rates of well replacement and large spatial variability of shallow groundwater arsenic concentrations, even within villages (see supplementary information, Section 1, available with the online version of this paper). The human health effects of groundwater arsenic in

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Bangladesh increased dramatically from the 1990s. This was due to a move away from contaminated surface water sources at a time when tubewell technology (in shallow aquifers) had become affordable and widely accessible, but when groundwater testing for arsenic was not prevalent. Around 97% of the country's population still use groundwater for drinking.

The risks to human health from chronic arsenic exposure are not all reversible once exposure has ended (note that there are many ways to define and analyze risks in water supply; see Sadiq *et al.* (2007), Lindhe *et al.* (2011) and Petkovic *et al.* (2011) for some examples). Latent health effects, many fatal, may take decades to appear. The need for reassessment of national health priorities in the face of scarce resources presents a complex challenge. In the arsenic context, policy makers inevitably trade off between allocating resources for treatment and resources for prevention, including the trade-off between the needs of the historically exposed and of those not yet exposed. The magnitude of this problem is immense, suggesting that the key challenge is to implement effective interventions more quickly at a population scale. Future mitigation actions can benefit from understanding experience with past policy actions and from recent and continuing scientific developments in order to set strategic priorities and revise public policy.

This paper first provides an overview of policy responses in rural Bangladesh to assess their effectiveness using past and recent scientific developments. Next, recent developments such as *in-situ* treatment of water, arsenic removal filters and dietary modifications are examined to understand their role in an evolving policy and research agenda. In this context, effectiveness signifies the ability to reduce exposure of large numbers of people in a reasonable time frame. The initial policy response focused on encouraging households to change their source of groundwater to safe wells or to deeper community tubewells (Ahmed *et al.,* 2006). In later years, the response has moved to introducing piped water from a safe source (World Bank, 2015). An examination of the number of people reached through these efforts suggests that progress may not be sufficient to keep up with an increasing population.

This review suggests that in light of promising technologies and practices that are in development or have already been proven, there may be a large gain from finding the means to scale them up and to make them much more widely accessible in a country with pervasive commercial and logistical challenges. A reliable and affordable program of arsenic testing and retesting, combined with careful and explicit priority setting across locations (e.g. where to act), time (what to do first) and fairness (whose needs are greatest) would help to reach vast numbers of exposed populations in a timely manner.

Past actions

When arsenic was discovered in the groundwater in Bangladesh, significant effort was invested in learning the distribution of arsenic across the country. Early testing efforts by the British Geological Survey revealed that around one-third of the wells did not meet the country standard of 50 ppb; and two-thirds exceeded the guideline value of 10 ppb set by the World Health Organization (BGS-DPHE, 2001). That research also revealed that arsenic concentration in shallow groundwater, especially at depths of less than 30 m, is highly determined by local geology and is variable even within a village (van Geen *et al*., 2006). This made well testing and arsenic labeling a viable strategy for encouraging switching to safe wells to reduce exposure to arsenic. Research also demonstrated that concentrations of arsenic in tubewells were fairly stable over time, and that deep tubewells (deeper than 150 m) are likely to contain lower levels of arsenic.

Screening tubewells for arsenic and installing deep wells

Between 1999 and 2005, the Government of Bangladesh implemented a program called the Bangladesh Arsenic Mitigation Water Supply Program (BAMWSP), which was financed by the World Bank. Under BAMWSP, about 5 million household tubewells were tested free of charge, and the spouts of hand pumps were painted red to indicate arsenic above 50 ppb ('unsafe') and green for below 50 ppb ('safe'). Households were advised to drink only from green wells and to share safe wells with others. Initial testing by the British Geological Survey in 2001 revealed that 95% of 335 samples collected from wells deeper than 150 m had less than 10 ppb of arsenic. Tens of thousands of deep public tubewells were installed to provide arsenic-safe alternatives.

While the efficacy of well testing in encouraging source switching was initially questioned (Hanchett *et al.*, 2002), subsequent research suggests that voluntary well switching follows well testing, and switching from unsafe to safe wells causes reductions in urinary arsenic levels (Chen *et al.*, 2007). A number of research studies examining short-term responses within 6 months to 2 years of well testing in Bangladesh showed that one-third to one-half of households switched upon learning their source was unsafe, despite having to walk further and thus incur costs of effort, time and perhaps income (Madajewicz *et al.,* 2007). Medium-term behavioral responses – between 3 and 5 years after the countrywide testing – demonstrate that most households that switched within 2 years of testing have not returned to the unsafe well they discontinued using (Balasubramanya *et al.,* 2014).

However, recent research has also shown that a significant share of households continues to use wells that they know are unsafe up to 2 years after testing, in part because alternatives are difficult to find or are considered too far away to access. In addition, well switching depends on the availability and retention of arsenic information. BAMWSP painted cast-iron pump spouts; in almost all cases, by 2 years after well testing, the paint had washed away, meaning that arsenic information was lost. This may have lowered the ability of well testing to reduce exposure to arsenic (Balasubramanya *et al.,* 2014). Moreover, households often install new shallow tubewells and replace existing ones. With well-testing programs since discontinued, around 50% of households in Bangladesh consume untested water (George *et al.*, 2017; see supplementary information, Section 2, available with the online version of this paper).

Recent research on arsenic in deep wells suggests that elevated levels can be found in them as well, with only 84% (and not 95% as initially estimated) of tubewells deeper than 100 m having arsenic concentrations less than 50 ppb (Chakraborti *et al.,* 2010; Radloff *et al.,* 2011). More importantly, deep aquifers can be contaminated from drawdown of high-arsenic shallow groundwater if large volumes are extracted (Radloff *et al.,* 2011). This is especially problematic if deeper wells are also used for irrigation purposes (McArthur *et al.,* 2016). Several other challenges have been identified with the continued and more widespread use of deep tubewells. For example, regulating the number of deep wells is likely to be challenging in a context where households are used to installing private wells. Opar *et al.* (2005) noted that some households extended their private wells to greater depths after deep wells were introduced in Bangladesh. Regulating the abstraction of water and restricting its use to drinking water are likely to be challenging because tubewell water has come to be used for many purposes, including washing and bathing. Access to tubewells has reduced the time and effort women need to spend in collecting water (World Bank, 2005). This suggests that a household's use of a deep community well as their primary source of drinking water is likely to be dependent on the proximity of the household to the deep well. The need to carry water from community wells is likely to compromise the gains in convenience that private tubewells initially offered.

Ahmed *et al*. (2006) estimate that initial tubewell switching and the installation of deep tubewells reduced exposures to arsenic by 29% and 12% (respectively) of the arsenic-exposed population by 2006, the largest contributions by any of the early remedial options. However, lack of well testing in the presence of continued installations of new wells keeps populations at risk. Private well testing is relatively inexpensive (variable cost of $0.16 per test) and potentially easy to deliver on a large scale. Trials showed that households willingly purchased tests that were offered as part of a community-level awareness-raising program, thus helping governments recover the costs of comprehensive testing programs (George *et al*., 2017). Extending access to deep tubewells at scale may be more problematic: geological factors place natural restrictions on the ability to extend water from deep aquifers to large populations without contaminating these deep waters.

Providing piped water and expanding deep wells

Recent efforts in providing arsenic-safe drinking water have focused on providing piped water, using a deep tubewell as the water source. Treating surface water for bacterial contamination is particularly difficult, given the high levels of pollution, the lack of space for filters and the use of treatment ponds for fishing and aquaculture (World Bank, 2005). Desk studies by the World Bank indicated that the capital costs plus operations and maintenance costs of piped water were lower than for other ways of providing arsenic-safe drinking water, such as dug wells, rainwater-harvesting options, arsenic filters for shallow groundwater and river pumping, especially for villages that have more than 500 households (World Bank, 2005). From the demand side, research into preferences of rural communities for water sources indicates a strong preference for piped water from deep tubewells, in part due to the convenience and ease of having a tap on the premises (Ahmed *et al.,* 2006). A study by Hoque *et al.* (2004) shows that groundwater sources were preferred over rainwater and surface water; and piped water from deep tubewells was preferred over both household and community-based arsenic filters. However, the experience of actually implementing piped schemes has been far from encouraging.

The Government of Bangladesh implemented the Bangladesh Water Supply Program Project (BWSPP) between 2004 and 2010. The objectives of the project were: (1) promoting rural piped water supply with private-sector participation; (2) promoting private-sector participation in water supply in municipalities; (3) implementing arsenic-mitigation measures in arsenic-affected villages; (4) supporting development of adequate regulations, monitoring, capacity building and training; and (5) supporting the development of a local credit market for village piped water supply. As targets, 300 villages were to be provided with functioning piped water supply schemes; at least three municipalities were to be provided with improved and functioning water supply schemes operated through private-sector participation; and approximately 200 villages (approximately 2,000 point-sources) were to be provided with sustainable alternative water supply options at sufficiently high service. At the end of this project, only 21 villages had been provided with piped water supply schemes; 13,159 non-piped water sources consisting primarily of deep wells, dug wells and pond sand filters had been provided, and 10,615 tubewells had been tested for arsenic. Over a 7-year period, the BWSPP reached 996,514 people in villages and towns with safe water – 50,000 served through rural piped supply (5%); 109,872 through municipal schemes (11%); 175,000 through rural non-piped supply in arsenic-affected areas (18%); and 661,642 through rural non-piped supply in cyclone-affected areas (66%) (World Bank, 2011; also see supplementary information, Section 3, available with the online version of this paper).

The Bangladesh Rural Water Supply and Sanitation Project, a continuation of the BWSPP, was introduced in 2012 and due to run until 2017. The project targets were set at the following: rural piped water schemes in 125 locations, each serving 600–1,200 domestic connections; increase 14,000 non-piped water points in arsenic hotspots, with additional non-piped points in disaster-prone areas; provide technical assistance and support in a number of areas to improve implementation activities; provide support to the Department of Public Health and Engineering for the management, administration and technical assistance required for project implementation; support preparedness and rapid response to disaster, emergency and/or catastrophic events, as needed. A mid-project appraisal, conducted in 2015, has adjusted the targets (see supplementary information, Section 4, available with the online version of this paper). The number of piped water schemes has been reduced from 125 to 35, with target beneficiaries reduced from 550,000 to 154,000. The number of non-piped water points has been retained at 14,000 in arsenic hotspots, while the creation of additional water points in disaster-prone areas has been dropped; the target number of beneficiaries is estimated at 770,000 people. Overall, the project is expected to reach 924,000 people – 154,000 through piped water (17%), and 770,000 through non-piped water points (83%) (World Bank, 2015).

The revised numbers of people these two flagship programs will benefit (actual and expected) are close to one million under each program. Ignoring new demands that arise from population growth, at this average annual rate of progress it would take more than 100 years to reach even another 20 million people, the number of people estimated to be exposed to arsenic $>$50 ppb. Complex cost-sharing arrangements between the community, local service providers and the government, and lack of adequate capacity were cited as reasons for the gap between the targets and actual performance of piped water schemes. Community deep wells and well-testing programs have been easier to deliver at scale but, with new evidence on the geological risks of tapping into deep aquifers, it is not clear to what extent deep wells can ensure a safe water supply.

Recent developments

New research has demonstrated that significant arsenic exposure also comes from dietary sources, and not just through ingesting contaminated drinking water. Across Bangladesh, people grow rice and vegetables in areas with high levels of arsenic in the soil and water. This arsenic is bioavailable when people consume these staple foods (Joseph *et al.,* 2015a). Providing arsenic-free drinking water will not be sufficient to reduce harmful exposure.

Other recent scientific developments have explored treating groundwater for arsenic, either through the use of household or community filters, or through *in situ* treatment prior to abstraction. An emerging area of research examines dietary modifications with selenium to counter arsenic toxicity.

Household filters for removing arsenic

Household filters offer the advantages of allowing people to continue to use their own most convenient tubewells as a water supply, and to avoid the need to access and transport water from more distant sources. In some cases, the filters also remove other harmful elements such as high concentrations of iron and manganese. Filters such as the SONO have a long operational life without the need to purchase additional absorbent materials (Hussam *et al.*, 2008). Filter failure rates are modest. For example, about 10% of 7,500 filters examined in use were not effective in removing arsenic

(Johnston *et al*., 2010); and some SONO filters were providing water that meets a 10 ppb standard for arsenic even after 8 years of use (Neumann *et al.,* 2013).

However, a filter's efficacy in removing arsenic depends on hydrogeological conditions, which are not uniform across Bangladesh. For instance, a sand filter's efficacy in removing iron and arsenic relies upon having a sufficiently high concentration of dissolved iron in the source groundwater and a sufficiently low presence of phosphate (Luzi *et al.,* 2004). In addition, some filters require more maintenance such as replacing the sand periodically; taking steps to prevent bacterial activity; and disposing of accumulated arsenic safely (Luzi *et al.,* 2004).

The use of filters has been rather limited in Bangladesh; an important reason for low uptake is cost. A review by Hanchett *et al.* (2011) suggests that while the SONO filter is one of the most affordable options ($40), without a subsidy it remains unaffordable to many of the rural poor in Bangladesh. Most filters have been distributed either free of charge or at a highly subsidized price. Even then, replacement rates are very low (Johnston *et al*., 2010). Consistency in use of household filters seems to vary; within 2 years of the initial distribution of 10,000 highly subsidized filters, 25% of recipient households had abandoned use of the filters (Johnston *et al*., 2010). Neumann *et al*. (2013) found that operational filters had trapped far less arsenic than could be consistent with the reported levels of use, suggesting that some filter owners have over-reported their household water use or, contrary to their claims, chosen to filter only some portion of it.

Community filters for removing arsenic

Devices that treat larger volumes of water are best suited to community supplies, such as shallow or deep tubewells with capacity to serve 50–100 households. Typically, a small monthly fee is levied to cover operating expenses such as electricity, replacement filters and having a designated caretaker.

Low rates of fee collection and well appropriation by local elites can be common problems. Hanchett *et al.* (2011) examined the SIDKO model of community filtration plant with an installed cost of about $4,300. They found that of 37 units in use, about 14% (49%) delivered water in excess of the 50 (10) ppb standard. While the ability to serve the water needs of up to 50 households can lower the average cost per household, most of these community filtration units were serving only 20–35 households (and almost 10% were not operational at all), pushing the cost per household out of reach for many.

Sarkar *et al.* (2010) have tested an alternative system for community-level treatment with several hundred units in operation in West Bengal, India. Among its innovative features is the use of a highly adsorbent resin that can be regenerated periodically at a centralized facility operated specifically for that purpose. The protocols developed for this treatment system place an emphasis on safe containment and storage of accumulated arsenic, where some other systems have allowed re-contamination of host communities due to inadequate arsenic-disposal practices.

Various authors note that where filters fail to meet a specified arsenic standard such as 10 or 50 ppb, they might still be providing substantial benefit by removing hundreds of ppb of arsenic that might otherwise be consumed. Johnston *et al.* (2010) argue that greater access by local users to affordable arsenic testing of both the raw and filtered water, and greater affordability of the filtration units themselves could boost the role for arsenic filters in rural Bangladesh.

In situ oxidation processes for removing arsenic

A new approach for removing arsenic from groundwater at the community level does not involve filtration at all, but modifies the groundwater *in situ*, prior to abstraction. This approach is referred to as '*in situ* arsenic removal by iron oxides and microorganisms' or 'adsorptive-catalytic oxidation' and it avoids issues of chemical additives or sludge disposal. Variations on this approach are operational in West Bengal in India (Sen Gupta *et al.,* 2009) and have been piloted in Bangladesh (van Halem *et al.,* 2010).

A volume of shallow groundwater is periodically pumped to the surface where it is aerated then re-injected back into the same tubewell. The introduction of calibrated amounts of the oxygenated groundwater to the aquifer creates an oxidation zone that: boosts the growth of bacteria that oxidize both iron and arsenic; suppresses the growth of anaerobic bacteria that reduce arsenic from an insoluble form to a soluble form; and promotes the continuous precipitation of iron (as Fe(III)) to ensure adsorption and further oxidation of soluble arsenic (Hashim *et al.,* 2011). The process initially takes about 7 weeks to stabilize within the aquifer and can reduce the amounts of iron, manganese and arsenic in pumped groundwater, in the latter case to below 10 ppb.

Prerequisite conditions seem to include a sufficient background concentration of (soluble ferrous) iron in the aquifer and limits on the background concentration of phosphate. These conditions are common but not uniform across Bangladesh. The equipment and maintenance requirements seem simple enough, yet not much is known about the cost-effectiveness of the process, or about whether this option may be subject to capture by the elite or face other common pool-resource issues.

Modifying diets

A new category of approaches to address arsenicosis involves modifying people's diets by supplementation with selenium, a known antagonist to arsenic that can reduce or eliminate arsenic's harmful effects in humans, even when it continues to be ingested from diverse food and water sources. Studies in selenium-deficient regions have employed dietary supplementation with: (i) oral dosages (pills) of selenium and vitamin E; and (ii) selenium-fortified staple foods (lentils (*Lens culinaris*) served as dhal). Animal studies with dietary selenium (fed as lentils) show a significant clinical response in key health indicators aggravated by arsenic (Sah & Smits, 2012; Sah *et al.,* 2013) and have led to clinical trials with human subjects in the Chandpur District of Bangladesh (Krohn *et al.,* 2016).

The expected advantage of selenium supplementation, if shown to be effective in clinical trials, is that, unlike approaches that restrict ingestion of water-borne arsenic alone, dietary supplementation might be able to counteract some or all of the effects of arsenic ingested from all sources (i.e. from food *and* water), potentially at relatively low cost. People may rely upon multiple water sources in the course of a day. Even if households drink from safe wells, people may continue to ingest significant amounts of dietary arsenic from cooking and eating locally grown rice and vegetables (Mondal & Polya, 2008; Chatterjee *et al.,* 2010; Rahman *et al.,* 2013a; Sharma *et al.,* 2014; Joseph *et al.,* 2015a, 2015b).

Lentils (*Lens culinaris*, served as dhal) are a dietary staple in Bangladesh yet when domestically cultivated, these lentils may be low in selenium. Subject to further agronomic field trials of micronutrient supplementation and uptake, domestically grown lentils in Bangladesh could become 'fortified' with selenium (Thavarajah *et al.,* 2011) by using agronomic approaches such as soaking the seeds or fertilizing the soil or foliage (Rahman *et al.,* 2013b). Locally grown rice, which is typically low in selenium and high in arsenic content, could be fortified with selenium using a foliar spray or by adding it as a fertilizer to the soil (Boldrin *et al.,* 2013; Fernandes *et al.,* 2014). Aromatic rice, controlling for season and location, has significantly less arsenic and more selenium than non-aromatic rice, so that a switch in households' rice-consumption patterns could provide health benefits (Al-Rmalli *et al*., 2012).

A 6-year study in rural Bangladesh examining whether tablets containing selenium, vitamin E or both together (versus a placebo) can have a causal impact is yet to be reported (Argos *et al.,* 2013, 2014). An earlier short-term study by one of those authors, La Porte (2011), did not detect a response to selenium supplementation in subjects' levels of blood and urinary arsenic.

Subject to confirming that selenium supplementation can reduce arsenic's harmful effects in human beings, important factors that need to be examined include understanding demand-side factors such as households' preferences for the forms of supplementation that are likely to have greater uptake, and their willingness to pay for such foods. On the supply side, research into the costs of supplementation and into the trade-offs between domestic production and imports would be relevant for policy formulation.

Research needs for policy

Despite the tremendous amount of scientific investigation and innovation that have been targeted at the issues of groundwater arsenic in Bangladesh, millions of people continue to ingest arsenic from water and food. With health risks not completely reversible after exposure has been eliminated, continued consumption steadily increases risk of experiencing numerous cancers and non-cancer illnesses.

A number of critics argue for a public policy response, supported by targeted research that is clearer and stronger (Adams, 2013; Bose & De, 2013; Khan & Yang, 2014; Chakraborti *et al.,* 2015). In a review of lessons learned about arsenic mitigation, Milton *et al*. (2012) point to a number of operational concerns including inadequate coordination among stakeholders, differences in attitudes, poor quality of some of the interventions that were funded and inadequate information sharing.

The present review of the voluminous research being published on many fronts points to a number of issues for the next phases of research and policy implementation. These include the following.

Arsenic testing

There is an apparent need for reliable and affordable arsenic-testing materials and for a concerted campaign to use them regularly. Millions of wells have already been tested. Nevertheless, numerous studies show cases where earlier test results have been forgotten due to paint washing off; where filtration and treatment processes supply 'safe' water that exceeds recommended arsenic limits; and where shallow or deep tubewells that were once believed to be safe are no longer safe. Regular and effective testing and retesting, accompanied by enhanced public accessibility to test results, can play an important role in informing people's actions (Argos *et al.,* 2012; Flanagan *et al.,* 2012). Well testing has also been implemented with relative success: both government programs were able to serve the targeted number of households within the program period of 6 years, and were able to reach large populations across socio-economic groups and geological conditions.

A holistic approach to water contaminants

The historical popularity of shallow tubewells since the 1980s was in large part due to fewer problems with harmful pathogens and other contaminants that were present in the available surface water supplies at that time. Field *et al*. (2011) point to the need to address more carefully the effects of microbial contamination in alternative sources as part of households' move away from shallow tubewells as their primary source of drinking water supply. In terms of soluble contaminants, numerous researchers have identified that manganese, lead, nickel and chromium may be present in household water supplies in Bangladesh at levels that may be posing harm to human health. Fortunately, many of the treatment methods to remove arsenic can also attenuate manganese and iron concentrations. A holistic approach would ensure that all interventions are sensitive to the opportunity to address multiple contaminants when these are present.

Explicit priority setting

Given the magnitude of the problem and given the limits on available resources at the household, national and international levels, a careful and explicit program of prioritizing actions, expenditures and responses requires coordinated and consistent support from people, governments, donors and others. Consider how a process could explicitly consider the roles of space (where to act), time (what to do first) and fairness (whose needs are greatest) in setting these priorities:

(a) *Spatial priorities*: Much is already known about locations where the severity of the arsenic problem is greatest in terms of groundwater arsenic concentrations and about the magnitude of the exposed and vulnerable population. However, numerous studies point to remedial approaches that have been installed where the threat from groundwater arsenic is low, or where the number of available users for communal water supplies is far below the installed capacity. These situations call for more careful targeting of scarce budgetary funds.

    Groundwater arsenic has become a national tragedy that has prompted national policy action. To be effective, a policy response must acknowledge that, from the householder's perspective, it is a *local* problem that requires local solutions. Among others, Bangladesh has variable geography and hydrogeology, variable densities of wells and of people, and variable market conditions by which people could gain access to technology and information, including government financial and technical support, especially health care (Khan, 2012). Some authors are promoting an approach that targets people exposed to water with an arsenic concentration greater than 200 ppb (Flanagan *et al.,* 2012). Even though switching to a new shallow tubewell is an effective solution in one village, in others the most effective approach might be a deep tubewell or water treatment. Abedin & Shaw (2014) argue that communities themselves should play a greater role in developing and leading mitigation strategies.
(b) *Temporal priorities*: In many cases, the intervention preferred by the community is piped water sourced from deep tubewells but the progress made with extending piped water through the two government programs has been very slow. Piped water may have to become a long-term solution that is possible only after institutional capacity has been built to implement such a solution. Careful thought and analysis can guide how to apportion some of the budget earmarked for piped schemes to more easily scalable solutions. Establishing temporal priorities is important especially when the health risks are not reversible even upon cessation of exposure; there is an urgent need to reduce exposures of large populations as quickly as possible.
(c) *Equity*: Social cost-effectiveness analysis (CEA) is a tool for allocating scarce resources (from all sources, public, private and charitable) so that they achieve the intended targets at least cost. The

'social' part refers to the idea that all of society's costs should be considered, including, for example, the non-monetized value of women's time and effort carrying water from distant sources. The intended targets could be expressed as some health outcomes, such as Disability Adjusted Life Years saved, so that instead of deciding which method delivers a cubic meter of safe drinking water at least cost, the question asked could be which method results in the least pain, suffering and premature mortality. Analysis of this type can guide spatial and temporal priority setting.

An important feature of decision-support criteria such as CEA is that they can be 'equity-adjusted' to bring into explicit consideration any of society's views about whose needs are greatest. For example, within a comparison across alternatives, a unit of expenditure to serve a disadvantaged member of society can be made to count for less (and thus be seen as more preferred) than if that same unit of expenditure were to be targeted toward some other group that is already in a position of relative advantage. Such methods have been used by Mahmood & Halder (2011) for an examination of the differential effects of arsenic toxicity on the poor in Bangladesh.

Argos *et al.* (2010, 2012) survey a number of studies that show that once individuals have had chronic exposure to high levels of arsenic, the subsequent provision of safe drinking water may not lower mortality risk or the risk of skin lesions. These authors encourage allocation of research resources aimed at 'secondary prevention' – i.e. delaying or preventing long-term effects in cases where primary prevention has been ineffective. Allocation of scarce public resources to health research and health care is part of the complex priority-setting process made necessary by these levels of arsenic exposure.

Development of supply chains

A significant number of technologies and programmatic approaches to addressing arsenic contamination are documented in the literature examined here. Some have been operated on a limited scale, often only as part of the research enterprise. Through combined actions by the private and public sectors along with civil society, a number of these might be scaled up and made much more widely accessible than at present. To guide those investments, knowledge gaps need to be addressed. These include understanding community preferences; the ability and willingness to pay for remedial options; and the size of the financing gap that might be covered from other sources. Similarly, an examination of financial, regulatory or other obstacles that may be restricting the widespread introduction of socially valuable interventions in water supply and treatment could also be highly instructive.

Summary

Past experience with the provision of piped drinking water by expanding deep wells suggests that this strategy alone may not scale fast enough to reduce the risks faced by millions of people, especially in rural areas. Recent developments have expanded the set of potential solutions available to policy makers. It is likely that preferred actions to reduce exposure to arsenic will vary over space and time, and according to the income, age and gender of the at-risk populations. Targeted research that quickly fills in knowledge gaps around effectiveness, equity, convenience and affordability would be important for designing a public program that can reach larger populations faster. With health effects from consuming arsenic not completely irreversible, a renewed program of arsenic screening of private wells, combined with effective delivery of a range of interventions to target diverse sub-groups, should guide public action in Bangladesh.

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