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An analysis of the cost-effectiveness of arsenic mitigation technologies: Implications for public policy

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Abstract

This study presents a cost-effectiveness analysis and mapping requirements for three arsenic mitigation technologies sponsored by the government of India in the state of Bihar, offering recommendations for the technologies most likely to benefit 12 million at-risk people. The three arsenic mitigation technologies investigated in this paper are arsenic treatment (*ATU*) units, new hand pump (*NHP*) units, and new tube wells with stand post (*NTWSP*) units. For 100% coverage of arsenic mitigation in the arsenic-affected districts of Bihar, 314–5111 *ATU* and *NHP* and 16–256 *NTWSP* in Buxar and Jehanabad, respectively, are required. *NHP* and *NTWSP* units were found to be the most cost-effective arsenic mitigation interventions in the state, whereas *ATU* was found to be the dominant intervention. Installation of *NHP* could be the most efficient arsenic mitigation intervention in areas where the population is scarce and illiterate. *NTWSP* could be the most cost-effective arsenic mitigation intervention in regions having higher rates of literacy and of arsenic awareness among their communities. The cost-effectiveness of arsenic mitigation technologies should be carefully evaluated before designing and implementing arsenic mitigation policies.

Keywords: Arsenic; Mitigation; Cost–benefit analysis; Cost-effectiveness analysis; Arsenic treatment units; Hand pumps; Tube wells; Policy; Bihar; India

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1. Introduction

Natural groundwater arsenic contamination is reported in more than 100 countries worldwide, affecting an estimated 202.3 million people's lives (IWA, 2016; Singh, 2017; Singh and Stern, 2017). Arsenic is a naturally occurring metalloid and a group A human carcinogen, widely distributed in Earth's crust (USEPA, 1999; Ravenscroft et al., 2009). Among the arsenic-contaminated countries, half have only recently identified the problem (Ravenscroft et al., 2009; Bundschuh et al., 2010; IWA, 2016). These countries adhere to various standards of arsenic in drinking water, ranging from 5 μg/L in the United States to 50 μg/L in most developing countries (Ahmed, 2003; Ravenscroft et al., 2009; Singh and Stern, 2017). Moreover, more than 57 million people consume water that contains more than 50 μg/L of arsenic, and 137 million inhabitants take in more than 10 μg/L of arsenic worldwide by drinking water (Ravenscroft et al., 2009). Of all arsenic-exposed countries, Bangladesh and India are the most severely affected. In the past decade, hundreds of people

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have died, and more than 100 million individuals are reported to have been potentially exposed to arsenic in these areas (Ravenscroft et al., 2009; IWA, 2016). In India alone, nearly 70 million persons are reported to have been potentially exposed to elevated levels of arsenic through drinking water (Chakraborti et al., 2017). Both these countries use groundwater, extracted through hand pumps, for all domestic and agricultural needs (Nickson et al., 2007; Ravenscroft et al., 2009). To clearly demarcate the arsenic-contaminated drinking water sources, the spouts of hand pumps contaminated with more than 50 μg/L of arsenic were painted red in both Bangladesh and India, and the spouts of the hand pumps contaminated with less than this value were painted green in Bangladesh and blue in India (Milton et al., 2007; Nickson et al., 2007). However, many people still rely on the red-painted handpumps' water because of the unavailability of arsenic-free drinking water sources in their neighborhoods (Singh, 2015a, Singh and Vedwan, 2015; Singh and Brachfeld, 2016).

Prolonged exposure to arsenic may cause several diseases popularly known as arsenicosis. A lifelong risk of skin cancer of 10^{-5} may occur at 17 μg/L of arsenic in drinking water, and 1 in 10 people may die from various cancers such as lung, bladder, and skin cancer if they continue consuming water containing 500 μg/L of arsenic (Das et al., 2009). People regularly exposed to arsenic for 5–10 years may experience cancers of the pulmonary, cardiovascular, hematological, hepatic, renal, neurological, and immunological systems (Mazumder, 2000; Chakraborti et al., 2017). Pregnant women may also experience spontaneous abortion (Chakraborti et al., 2003; Das et al., 2009; Chakraborti et al., 2016a,b, 2017). Infants and children are the age groups most vulnerable to the adverse effects of arsenic (Das et al., 2009). Among all arsenic victims, impoverished communities suffer the most because of the lack of arsenic-free drinking water sources and due to financial constraints (Curry et al., 2000; Singh, 2015a,b; Singh and Vedwan, 2015).

Provision of arsenic-free water sources and installation of arsenic treatment systems are the two principal means of arsenic mitigation in severely arsenic-contaminated regions (Bundschuh et al., 2010). The most common arsenic removal technologies are based on the principles of oxidation, coagulation, flocculation, filtration, coprecipitation, and adsorption. Other arsenic removal technologies include ion exchange, activated alumina, reverse osmosis, and electrolysis (Bundschuh et al., 2010). In addition, ALCAN chemicals, ADHICON, APYRON technology, arsenic and iron removal plants (AIRPs), photocatalytic oxidation using TiO_2 under UV light irradiation, iron-coated sand tourmaline minerals, Water Systems International (WSI) installations, solar distillation, Oxide India technology, solar oxidation, combined coagulation/flocculation, electrodialysis reversal (EDR), iron (addition) coagulation with direct filtration, iron-rich laterite, subterranean arsenic removal tech (SAR), conventional iron/manganese (Fe/Mn) removal processes, oxisol, lime softening, nanofiltration, membrane filtration, ion exchange with brine recycle, and passive sedimentation are other available arsenic removal technologies (Bundschuh et al., 2010; Islam et al., 2010; Mosler et al., 2010). Organic materials, such as cellulose, milled bones, sedges, sorghum biomass, lettuce biomass, keratin-rich biomass, and cysteine-rich biomass, are also used for this purpose. Some cost-effective household-level arsenic removal technologies such as pond sand filters and sono filters are also being developed, and advanced technologies such as bioremediation, phytoremediation, and artificially constructed wetlands are also in progress (Bundschuh et al., 2010; Islam et al., 2010; Mosler et al., 2010). Although one or more of these technologies has worked well in some cases, because of the lack of area-specific techniques amid complicated and expensive technologies, the presence of multiple contaminants, the generation of high-volume toxic sludge after treatment, the inefficiency of all these technologies at dealing with high arsenic concentrations, the need for trained manpower, high operation and maintenance costs, and the need for monetary contributions from beneficiaries, none has been fully adopted by the communities affected, and thus none has achieved sustainability (Bundschuh et al., 2010; Singh, 2015a; Singh and Vedwan, 2015; Singh and Brachfeld, 2016). So far, deep tube wells, artificial ground water recharge, rainwater harvesting systems, surface water sources, dug wells, SAF/pitcher filters, and tapping of safe aquifers have all gained a certain degree of success, among other arsenic mitigation technologies (Kabir and Howard, 2007; Shibasaki et al., 2007; Shafiquzzaman et al., 2009; Bundschuh et al., 2010; Islam et al., 2010; Mosler et al., 2010). The success of these arsenic mitigation technologies varies with and indeed depends on the socioeconomic, demographic, and sociobehavioral factors of the arsenic-affected communities (Singh, 2015a). However, only a few studies capture these dimensions of arsenic-affected communities in designing and implementing arsenic mitigation policies. In a recent study conducted in rural India, most arsenic-affected communities preferred arsenic treatment units (filters) and piped water supply systems for their sustainable arsenic mitigation technologies, followed by deep tube wells, dug wells, and rainwater harvesting systems (Singh, 2015a; Singh et al., 2017). Moreover, communities' willingness to pay for arsenic mitigation technologies, awareness of arsenic and associated health risks, trust in local agencies and institutions, and social capital significantly contributed to the priority given the uses and adoption of available arsenic mitigation technologies (Singh, 2015a). What's more, studies are severely lacking of the economic feasibility, in terms of cost–benefit balancing or cost-effectiveness, of the available arsenic mitigation technologies in most of the arsenic-affected areas.

The cost–benefit analysis (*CBA*) and the cost-effectiveness analysis (*CEA*) are two econometric tools commonly applied to evaluate the monetary benefits of a

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