Arsenic contamination in water resources: mitigation and policy options

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Abstract

Risk of arsenic contamination in water supplies continues to increase in many countries, especially in developing nations. Its sources and effects are multiple and diffused in nature and it requires detailed assessment and policy. This paper discusses the global extent of the problem, its sources and effects and explores different policy options. Sources and pathways of interaction require comprehensive assessment and policy. Innovation in low cost technologies offers possibilities for reducing abatement cost and for economic efficiency. To reduce arsenic in water resources, incentive policies such as taxing and subsidizing can be used to reduce arsenic levels in point sources through creation of appropriate incentives. The paper also identifies opportunities for enhancing self-protection efforts through education and information sharing. Under a self-protection policy, though the damages decline to a greater extent, there is a possibility of an increase in arsenic emission. We propose a combination of policies that involve low cost technology, education and awareness to mitigate the damage from arsenic contamination at a watershed scale. It is also necessary to enforce these policies through appropriate institutional changes that involve coordination and cooperative efforts to mitigate arsenic contamination.

Keywords: Arsenic; Education policy; Incentives; Self-protection; Taxing and subsidizing policy; Technology; Water resources

1. Introduction

The continuing growth in global population is increasing demand for fresh water and placing a severe strain on water supplies. One of the reasons for the increase in water scarcity is the reduction in usable supplies through water quality degradation, which reduces the amount of fresh water available for residential, agricultural and industrial uses. Despite recent efforts to mitigate this problem, human populations continue to face a substantial risk from water quality problems in many parts of the world.

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A continued degradation of land and water resources that are a consequence of deteriorating 
water quality can result in “hydrocide” of future populations (Lundqvist, 1998). Water quality in aquifers 
is also deteriorating at a rapid pace, resulting in enormous long-term costs to society (Ahmed et al., 2004). 
It is estimated that two out of every three persons on the planet will live in water stressed conditions by 
2025 (UNEP, 2000). UNEP (2000) identifies water quantity and quality as dominant issues in the 
environment and development agenda of the coming century. This paper focuses on reviewing sources, 
transfer, impacts and options to mitigate arsenic contamination of water supplies, which is a critical issue 
in many regions of the world.

Water degradation resulting from toxic and cumulative pollutants such as arsenic is a major water 
quality issue that is receiving increased attention. Arsenic contamination has recently received 
worldwide attention because of the nature of its health effects. The problem is severe in South Asia, 
particularly in Bangladesh and eastern parts of India, where the impacts on water quality and public 
health are seen in disastrous proportions. Arsenic enters water supplies through various pathways that 
are both natural and anthropogenic in origin and is often cumulative in nature. This makes it difficult to 
develop appropriate policies. One issue that is often debated is the level of standard to enforce. While the 
World Health Organization (WHO) suggest a standard of 50 micrograms per litre ($\mu g l^{-1}$) (WHO, 
1993), scientific studies advise a much lower value of 10 ppb (WHO, 1999). The Environmental 
Protection Agency (USEPA) enforced a limit of 50 $\mu g l^{-1}$ for arsenic in drinking water (Viessman & 
Hammer, 1998) but changed it to 10 $\mu g l^{-1}$ in 2001. In the Hetao region of China, the average content of 
arsenic in drinking water is as high as four times the WHO environmental standard (Zhang et al., 2002).

Given the public health concern and water quality impacts, the study of arsenic contamination and 
evaluation of this problem globally can be useful in studying comparative mitigation opportunities and 
developing policy options.

This study aims to explore the extent of the problem at a global scale, to review potential pathways of 
contamination, and to evaluate technological, incentive-based and self-protection policies to mitigate this 
problem. Specifically, (i) to review the transfer and fate of arsenic contamination; (ii) to identify potential 
abatement technologies; (iii) to assess the impact of tax policy on arsenic mitigation and damages; and 
(iv) to identify opportunities for self-protection using education and information access. We hypothesize 
that: (i) arsenic contamination has implications for global water quality and public health; (ii) reduction in 
arsonic impacts requires innovation to achieve low cost, abatement technologies; and (iii) taxing and self-
protection policies have an influence on arsenic abatement efforts and damage costs.

In the following section, the extent of arsenic contamination is presented with discussions related to 
both developed and developing countries. This also provides a background for the problem under study.

2. Global distribution of arsenic contamination

Arsenic contamination is severe in several developing countries. For example, the distribution of 
arsonic contamination in Bangladesh is presented in Figure 1(a). In the worst case of arsenic 
contamination, about 35 million people in this country are exposed to arsenic levels that are above the 
US Environmental Protection Agency standards. The problem of arsenic contamination of the 
groundwater in Bangladesh was identified in 1993, but it did not get proper attention until very recently. 
By this time more than 30 million people were impacted and as many as 70–80 million people are 
threatened by arsenic contamination. Exploitation of groundwater from deeper aquifers has resulted in
mobilization of the arsenic and led to mass poisoning, which is defined by the generic term arsenicosis (Rahman et al., 2001). A higher concentration of arsenic contamination is observed within the deltaic and floodplain region of Bangladesh (Islam & Uddin, 2002). A 1998 estimate showed high arsenic concentrations in shallow tube wells in 61 out of 64 districts of Bangladesh; 46% of the samples were above 0.010 mg l\(^{-1}\) and 27% were above 0.050 mg l\(^{-1}\) (BGS & DPHE, 2001). In the Pabna district of northern Bangladesh, the pumped groundwater had an exceptionally high arsenic concentration of 14,000 µg l\(^{-1}\) (Rott & Friedle, 1999). The problem is also prevalent in other developing countries such as India, China, Vietnam and Laos. The arsenic-rich groundwater is mostly restricted to the alluvial aquifers of the Ganges basin (Bihar, Uttar Pradesh and West Bengal) in India (Nickson et al., 1998).

In the state of West Bengal in India, the groundwater in 9 out of 18 districts has high levels of arsenic contamination. The tube wells in West Bengal contained arsenic concentrations ranging from 60 µg l\(^{-1}\) to 3,700 µg l\(^{-1}\). Various types of adverse health effect including cancer which are often associated with prolonged exposure to arsenic have been reported in these districts (Acharyya, 1999). The pandemic of arsenic poisoning (arsenicosis) due to contaminated groundwater in West Bengal, India, has been thought to be limited to the deltaic region of the Ganges River. A recent study conducted in the Middle Gangetic Plain showed that 56.8% of this area exceeded arsenic concentrations of 50 µg l\(^{-1}\) and 19.9% of the area exceeded 300 µg l\(^{-1}\), the concentration producing the overt arsenical skin lesions observed in the state of Bihar (Chakraborti et al., 2003).

In large parts of rural Argentina, where people depend on groundwater for water supplies, the arsenic concentration exceeds the Argentine drinking water standards of 50 µg l\(^{-1}\). In the shallow aquifers, more than 48% of the 63 studied wells showed arsenic at toxic levels (maximum 4,800 µg l\(^{-1}\)), while in the deep groundwater the concentration was below 50 µg l\(^{-1}\) (Bundschuh et al., 2004). In Mexico, high concentrations of arsenic were detected in the aquifer system of Zimapán valley and arsenic variations were detected in more polluted urban deep wells (Rodríguez et al., 2004).

In general, the contamination is not severe in most developed countries compared with that of developing countries. In the US, experts are of the view that only a few water supplies have levels of

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**Fig. 1. Arsenic contamination in developing and developed nations.**


Source: Ryker (2001)
arsenic above 50 ppb and even the number with levels above the standard of 10 ppb are easily manageable (Focazio et al., 1999). A study has demonstrated that less than 1% of water systems exceed an arsenic concentration of 50 ppb (Foust et al., 2004). Concentrations of arsenic in Atlantic Canada are generally low, and have a maximum allowable limit of 25 ppb.

Arsenic contamination occurs from a variety of point and non-point sources. An understanding of the sources and transfer of arsenic at a watershed scale is useful in order to identify appropriate abatement technologies and policies. The next section presents a brief discussion of various sources and pathways of arsenic contamination.

3. Sources and effects

Arsenic in drinking water is related to multiple sources that include both natural and anthropogenic origins. These sources include leaks from industrial waste dumps and mines, use of old arsenic-containing pesticides and indirect effects from indiscriminate groundwater pumping. The pathways of arsenic contamination and transfer depend on locational characteristics. For example, high arsenic residues are found in some soils in the Maritimes in Atlantic Canada: a result of using sodium arsenite as a pesticide in potato fields. The highest concentration of arsenic release in Atlantic Canada comes from wood preservation operations that use chromated copper arsenate (CCA) and ammoniacal copper arsenate. In some areas, arsenic contamination occurs naturally, through arsenic bearing rocks. In the Shubenacadie River lakes area of Nova Scotia, arsenic contamination of well water has resulted from runoff and seepage from tailings piles of gold mines used between the 1860s and 1930s. A survey of the groundwater and drinking water carried out by the Province of Nova Scotia in the mid-1970s identified a higher incidence of arsenic contamination in wells near gold districts than in those in other areas. In some other areas, such as the delta of the Ganges and Irrawaddy, and the bend of the Yellow River, arsenic has been transferred through natural geological processes in the watershed over millennia, often attached to iron.

There are different pathways through which arsenic enters human systems: drinking water, inhalation and dermal uptake (Aswathanarayana, 2001). Uptake through water is a major source and is observed in Bangladesh, West Bengal, Inner Mongolia, Xinjiang in China, southwest and northeast coasts of Taiwan and western USA. Inhalation of arsenic-containing aerosols through coal burning is observed in Guizhou, China. Dermal uptake of arsenic is observed in Taiwan, where rice farming is practised. The dermal pathway explains the prevalence of “blackfoot disease”, which is more common among rice farmers, fisherman and salt workers whose feet and legs are exposed to arsenical waters for prolonged periods.

The effect of arsenic contamination has both economic and ecological consequences. Short-term exposure to very high levels of arsenic in drinking water can result in muscular pain, skin rash, and numbness, burning sensation or pain in hands and feet, and deterioration of motor and sensory responses. Long-term exposure to higher levels of arsenic in drinking water may cause thickening and discoloration of the skin, nausea, decreased production of blood cells, abnormal heart rhythm and blood vessel damage and numbness in the hands and feet. Ingesting high levels of inorganic arsenic can even result in death. Lasky et al. (2004) identified possible arsenic dose exposures acquired through consumption of contaminated chicken and potential risks associated with it.

The World Health Organization, the US Department of Health and Human Services (DHHS) and the US EPA have determined that inorganic arsenic is a human carcinogen. Several studies have also shown
that inorganic arsenic can increase the risk of lung, skin, bladder, liver, kidney and prostate cancers. Arsenic can cause cancer, blindness and fetal malformations in other mammals and amphibians. Various adverse health effects including cancer have been reported from the districts in West Bengal which are associated with prolonged arsenic exposure. Blackfoot disease is more prevalent in developing countries, particularly among the poor, because the process of detoxification of arsenic may not take place in their bodies as a result of nutritional inadequacies.

These health damages can amount to millions of dollars in increased health costs, lost income, disability and lost employment. Although these are indirect economic effects through health impairment, there is a direct economic implication of lessening marketability due to arsenic tainted products. Nasar et al. (2003) found that rice irrigated with arsenic-laden groundwater contained biomagnified amounts of the toxic heavy metal in root, stem, leaf and grain in that order. This contamination alone can limit or even negate the comparative advantage of marketable productivity and quality. In addition to its effect on quality, it can reduce photosynthesis and crop yields in plants.

A number of gaps in the scientific knowledge still exist, particularly on routes of arsenic ingestion and health impacts of arsenic (Adeel, 2001). While arsenic contamination could occur through a variety of pathways, its damages are quite substantial. A combination of strategies that include prevention and abatement (sources) can be used in mitigating the effect of arsenic contamination. The next section explores various policy options that could be used for varying background conditions.

4. Policy options

The discrepancy between observed levels of arsenic in water and the optimal level is distinct in several countries, particularly in developing countries such as Bangladesh. The damages are also considerable as is evident from a clear correlation between contamination and arsenic-related diseases in humans. The standard marginal abatement cost (MAC) – marginal damages (MD) framework is used in this paper to evaluate alternative policies. Optimal conditions and the relationship between marginal abatement and marginal damage curves are presented in Figure 2. The triangular area $m$ (bounded by points $e^t$, $e^*$ and the marginal damage function) depicts the total damages existing when emissions are at level $e^*$, while the triangular area $n$ shows the total abatement costs at this level of arsenic emissions. The sum of the two areas ($m + n$) is a measure of the total social costs resulting from $e^*$ level of emission of arsenic pollutant.

The point $e^*$ is an optimal point at which marginal damages equal marginal abatement cost. Marginal damages have a threshold at emission level $e^t$, while the uncontrolled emission level is $e^u$. The marginal damages increase with an increase in arsenic emission while marginal abatement costs increase with the removal of arsenic exposure. In the following sections, we explore various policy options to achieve efficient levels of arsenic abatement within the MAC–MD framework as shown in Figure 2.

4.1. Innovation in technology

Centralized treatment is not always a feasible treatment option in most locations. Instead of this, point-of-entry (POE) or point-of-use (POU) treatment options may be acceptable treatment alternatives, which offer ease of installation, simplify operation and maintenance, and generally have lower capital
costs (Fox, 1989). The Safe Drinking Water Act in the USA also identifies POE and POU treatment units as potentially affordable technologies. Research has shown that POE and POU devices can be effective means of removing arsenic from potable water (Fox & Sorg, 1987; Fox, 1989). Among potential treatment techniques, cost effectiveness is an important criterion that needs to be considered in addition to technical efficiency.

The technologies that have comparative (economic and technical) advantages are considered for the discussion in this paper. Current technologies that are able to reduce the levels of arsenic include ion exchange, membrane filtration, reverse osmosis and various precipitation processes. An economic study done for the EPA has shown that the acquisition cost of individual reverse osmosis units is lower when compared with a centrally located treatment system (Kubr, 2002). Annual abatement costs per ppb of arsenic for reducing from 50 ppb to the new standard of 10 ppb in a community water system of size 100 and a community water system of size 500 are presented in Table 1 (USEPA, 2000a, b). On the consumer side, per capita cost for the removal of arsenic per annum is around US$18.17 and $8.25 for small and large communities.

Table 1. Abatement cost of arsenic treatment technologies.

<table>
<thead>
<tr>
<th>Abatement technology</th>
<th>Removal efficiency (%)</th>
<th>Community size</th>
<th>Abatement cost/ppb (US$)</th>
<th>Community size</th>
<th>Abatement cost per capita (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified lime softening technology</td>
<td>90</td>
<td></td>
<td>45.43</td>
<td>103.10</td>
<td>18.17</td>
</tr>
<tr>
<td>POU reverse osmosis technology</td>
<td>&gt;95</td>
<td></td>
<td>270.13</td>
<td>1,608.33</td>
<td>108.05</td>
</tr>
<tr>
<td>Anion exchange</td>
<td>95</td>
<td></td>
<td>535.05</td>
<td>879.18</td>
<td>214.02</td>
</tr>
<tr>
<td>Coagulation</td>
<td>95</td>
<td></td>
<td>1,728.08</td>
<td>3,339.33</td>
<td>691.23</td>
</tr>
<tr>
<td>Oxidation filtration</td>
<td>80</td>
<td></td>
<td>467.25</td>
<td>748.93</td>
<td>186.90</td>
</tr>
<tr>
<td>Activated alumina (pH 7)</td>
<td>95</td>
<td></td>
<td>300.88</td>
<td>647.45</td>
<td>120.35</td>
</tr>
<tr>
<td>Activated alumina (pH 6)</td>
<td>95</td>
<td></td>
<td>491.83</td>
<td>867.65</td>
<td>196.73</td>
</tr>
</tbody>
</table>

Source: estimates based on USEPA (2000a, b).

*Abatement cost is the cost based on reduction in arsenic concentration from 50 ppb to 10 ppb. The abatement cost includes annual capital cost and operation and maintenance cost.
† Abatement cost per capita is the consumer cost for arsenic removal per annum.
medium community water systems, respectively, where lime soft technology is adopted. The cost is higher using reverse osmosis technology, to the tune of US$108.05 and $128.67 for small and medium community water systems, respectively. The cost is higher in other technologies such as coagulation, anion exchange, filtration and activated alumina. It is apparent that the additional household cost, particularly for low-income groups, to meet the new arsenic standard in drinking water by adopting these technologies would be high. For people on very low incomes, the cost could be partly shared by the community governing body or by the state government.

A technology policy that is oriented towards reducing marginal abatement cost through appropriate technology (for example reverse-osmosis) to mitigate arsenic contamination could be adopted. Figure 3 depicts the role of innovation in technology for arsenic emission abatement. For instance, POU reverse-osmosis arsenic reduction technology shifts the marginal abatement cost function from MAC₁ to MAC₂. This leads to a reduction in arsenic exposure from $a₁^*$ to $a₂^*$. It could also lead to a decrease in the total abatement cost of arsenic exposures. The presence of additional contaminants can raise additional treatment concerns and result in decreased process performance. For example, pathogenic contaminants such as Giardia can result in a need for disinfection of finished water. Hence selection of treatments that reduce additional contaminants would generate additional benefits from the treatment technology.

4.2. Incentive-based policies

Taxing and subsidizing polluting firms are other policy instruments that could be used to mitigate arsenic contamination. Young & Karkoski (2000) observed that economic incentives are practical in controlling non-point source pollution in California. These policies penalize (reward) non-compliance (compliance) with environmental standards. For instance, a polluting firm is used for discussion in this section. A tax policy provides appropriate incentive for the polluters to comply with desirable arsenic levels. Suppose the firm is initially emitting 50 ppb and if it were to cut emissions to 10 ppb, it would face higher abatement costs. It could continue reducing arsenic emissions through inventing new techniques as
long as the tax rate is above marginal abatement cost. In such cases, the marginal cost would increase from a lower level of $C^1$ (see Figure 4). Since the total cost of the firm includes not only abatement cost but also tax payments, it would be prudent for the firm to enhance the abatement cost to the desired level till it is equivalent to the tax rate ($t^*$). Otherwise total cost would escalate through tax payments. For the firm, the tax rate ($t^*$) would be a better signal to make a decision on whether to comply with the tax or disregard it by continuing to emit arsenic. The benefit would be the improvement of water quality through reduction in marginal damages. The marginal damages reduce from a higher level of $D^h$ to the level of the tax rate ($t^*$). As is apparent from Figure 4, the total damages are reduced. At the undesired level of emission, the damages are represented by triangle, $acd$, while at the new acceptable level of emission, the damages are represented by $abe^*$. If the point source of arsenic emission is distinctly known, taxing policy could play a pivotal role in mitigating the arsenic exposure to the most efficient level.

The tax rate ($t^*$) could be set to achieve $e^*$ (efficient level of arsenic emission) where marginal damages equal marginal abatement costs. Instead of having a “flat tax” which allows more tax payment than other costs, a two-part emission tax on arsenic could be instituted to allow a certain degree of leverage by firms. Up to 5 ppb emission of arsenic could go untaxed; the firm could be taxed for emissions in excess of this threshold. In this two-part emission tax policy, tax payment would be reduced while the firm continues to have an incentive to reduce emissions to $e^*$.

A subsidizing policy can be used to reward reduction in emissions (Field, 1994). This policy is similar to taxation but the transfers are to polluters to help mitigate emission levels. While a subsidy policy tool can be implemented to reduce arsenic emissions, it provides an opportunity cost for the polluters. There are various subsidy schemes that could be used in pollution reduction. Those include cost-sharing technological investments, direct payments for abatement, and tax benefits through reduced property taxes. While tax and subsidy policy instruments are effective in abating point sources of arsenic contamination, these are also applicable to other non-point sources of arsenic pollution.

4.3. Self-protection as a policy

In developing nations such as Bangladesh and India where population growth is high and the arsenic contamination in groundwater is greater, lack of awareness of pollution or lack of self-protection efforts...
could enhance the problem through higher exposure and higher damages. For example, self-protection efforts could include avoiding consumption of water from contaminated wells, small-scale community treatment, and locating wells away from endemic arsenic deposits or industrial sites.

The impact of self-protection efforts can be observed in Figure 5, where marginal damage at $e_1$ is $v_1$ and the total damages are the area enclosed by $abe$. While marginal damages can decrease to $v_2$ under self-protection, emission levels can increase to $e_2$. The total damages (area enclosed by $cdf$) could be reduced, if an educational policy is in place to make consumers aware of the damages and adverse effects of arsenic contamination. Such a policy could be oriented towards abandonment (avoid drinking arsenic contaminated water), curbing excessive withdrawal of water from arsenic safe aquifers and cooperation in periodic testing of groundwater. The policy on education could be a kind of “moral suasion”, a decentralized policy that appeals to a person’s moral values or civic duty, to voluntarily refrain from doing things that degrade the environment through arsenic contamination. Chakraborti et al. (2003) observed a poor response to combating the level of arsenic in groundwater, especially in areas with low-income groups and poor education levels.

In sum, policy priorities to reduce the risk of arsenic contamination in water are necessary to achieve efficiency. Education policy coupled with technology policy would be the first priority for enforcement at the point of entry or point of use level. While considering monetized and qualitative benefits and the enforcement costs, the incentive policy of taxing and subsidizing would be the last option to abate arsenic emissions at source.

5. Conclusion

This study discusses the pandemic effects of arsenic in several countries, particularly in developing nations such as India and Bangladesh. With varying sources of arsenic contamination, accumulation of contaminants follows different pathways and has severe health and economic effects on humans. Since its environmental and economic impacts are cumulative, damages are long term in scope and have the
potential for tremendous economic loss. The severity of the arsenic problem is higher in developing
countries, where a clear correlation exists between water supplies and arsenic-related diseases. To offset
this contamination before it reaches worse levels, location-specific policy design should be adopted by
keeping in view its causes and suitable alternative policies. Several economic policies could be used to
mitigate this problem at both preventive and restorative stages.

This paper analyses some of the economic policy instruments such as technology options, tax and
subsidy, and education policy for their applicability to the arsenic problem. Low cost technologies that
can achieve efficient abatement levels have scope in developing countries. The choice of the most
economical treatment technology can be based on an efficient level of arsenic abatement. When
command-and-control policies are not successful, taxes or subsidies associated with arsenic emission
could be used to create positive incentives for arsenic abatement. The discussion in this paper shows that
education policy and informed self-protection measures can be used as effective means of achieving
reduction of damages from arsenic contamination. Proper education and awareness-raising can serve the
role of moral persuasion to improve awareness of the threat of arsenic to groundwater. Although
marginal damages to society decline through education and information on self-protection, arsenic
emissions could continue to increase. To mitigate this, integrating education policy with low cost
technology can be more effective.

Policy instruments need to be enforced through appropriate institutional reforms. Narain (1998)
argued for a greater interface between policy and technical communities, and coordination among the
institutions engaged in managing natural resources, especially groundwater. Secondly, there still exists
uncertainty and lack of complete research on arsenic contamination. Information dissemination and
transparency in management among the stakeholders is very important to address this problem
effectively. New information on technologies and success stories can be shared through the Internet and
multimedia. Education is a better tool to alert and make people aware of the risks of arsenic. There
continues to be a need for systematic research into the sources of arsenic emission, its release into
groundwater, the effect of arsenic-contaminated irrigation water on crops, the risk of arsenic in the food
chain in relation to livestock/humans, and the impact of arsenic-contaminated water on soil quality. A
watershed approach could be appropriate in analysing pathways and the nature of accumulation. The
processes of screening all the tube wells and aquifer mapping, testing tube well water for people at
reasonable cost and setting up laboratories at regional level for validation could be carried out at a
watershed scale. Location-specific research, combined with a combination of technology, incentive and
self-protection policies could be used to address the problem of arsenic contamination worldwide.

References

Acharyya, S. K. (1999). Ganges delta development during the Quaternary in the Bengal Basin and its relation to arsenic toxicity
in ground water. Proceedings of the International Seminar on Quaternary Development and Coastal Hydrodynamics of the
Ganges Delta, Bangladesh 17.

Workshop on Technologies for Arsenic Removal from Drinking Water organized by Bangladesh University of Engineering
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