ARSENIC AND THE PROVISION OF SAFE AND SUSTAINABLE DRINKING WATER

ASPECTS OF INNOVATION AND KNOWLEDGE TRANSFER

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Abstract

Safe and sustainable drinking water supplies underpin societies at all stages of economic development. Increasing population, increased standards of living and local and global environmental factors will variably play a role in the Asia-Pacific countries in increasing water stress and reliance on finite vulnerable groundwater resources, many of which are prone to contain hazardous concentrations of arsenic. Arsenic in groundwater-derived drinking water supplies is currently impacting the health and economic productivity of millions of people in these regions. Innovative remediation technologies include graphene oxide based filtration, as well as technologies, such as organic and microbial destruction, that make alternative, hitherto avoided, water sources, as more attractive to consumers, regulators and suppliers. Management of drinking water supplies, including appropriate treatment for arsenic, requires a holistic approach, considering (i) strategic and operational priorities, (ii) criteria for selection of the most appropriate, in a local and/or regional context, treatment and management options in the context of formalised water safety plans, and (iii) effective participation in networks to underpin timely knowledge transfer of relevant robust innovations in the management and treatment of water supplies.

Introduction

Arsenic is toxic and a known human carcinogen (IARC, 2012). Detrimental health outcomes arising from chronic exposure to arsenic from drinking water include cancers (especially skin, lung, bladder, kidney), hypertension and cardiovascular diseases, diabetes mellitus, pulmonary disease, peripheral vascular disease, skin lesions and neurological illnesses and sadly for many people ultimately premature death (Smith et al., 2000). The scale of premature mortality and morbidity attributable to arsenic in drinking water is far greater than that of any other known chemical – the devastation caused in Bangladesh alone has been described as the "largest mass poisoning of a population in history" (Smith et al., 2000). Arsenic-attributable premature mortality in Bangladesh, the country most impacted, is estimated to be on the order of 40,000 (after Argos et al., 2010) and given the extensive exposures outside of Bangladesh, the global figure is likely to be several times this value.

A journalist asked me the other day why so little had been done to remedy the high arsenic content of drinking water supplied to hundreds of millions of people around the world and particularly in the Asia-Pacific region. I replied that this possibly reflected one or more of the following:

(i) Most people are not aware that arsenic in drinking water is responsible for the premature deaths of perhaps as many as 100,000 people every year.

(ii) Most consumers cannot detect arsenic in their drinking water as it is colourless, tasteless and odourless.

(iii) Most people are unaware that heart disease, cancer and suppression of the immune system are all risks associated with regular drinking of water with 10 µg arsenic/L.

(iv) Even many water sector professionals have been unaware that there is increasing evidence of harm arising from consumers regularly drinking water with arsenic concentrations lower than the WHO (World Health Organization) provisional guide value of 10 µg arsenic/L.

(v) Most consumers are not aware that even more people than those that are exposed through drinking water are exposed to arsenic through eating rice, including that irrigated by high arsenic groundwater, and that in West Bengal, India, such rice consumption has been associated with elevated genotoxic effects in consumers (Banerjee et al., 2013).

(vi) Many countries have economic and/or health problems that are, or are perceived as, more pressing.

(vii) Where, nevertheless, substantive efforts have been made to remediate water supplies, difficulties in monitoring, particularly in dispersed small sources, together with additional issues of real-world deployment of laboratory-tested technologies, have led to serious challenges in many impacted countries.

The requirement to effectively reduce toxic arsenic from drinking water sources has become an explicitly recognised component of Goal 6 of the Sustainable Development Goals (SDGs) (UNESCAP/ADB/UNDP, 2017). Furthermore, appropriately integrative innovative solutions have the potential to further address interlinked SDGs through all of economic, social and environmental dimensions (cf. UNESCAP, 2017). There is increasing evidence for the detrimental economic impacts of high arsenic in drinking water (Gibson et al., 2017) as well as, particularly given the serious age-dependent (Lindberg et al., 2008) and gender-dependent social (Sultana, 2009) and medical (Vahter et al., 2007) consequences of chronic arsenic poisoning, increasing evidence for householders' willingness to pay for appropriate water treatment (Gibson et al., 2016). With increased education, increased public access to the internet and increasing published and otherwise voiced concerns over arsenic in water supplies, public concerns over arsenic in their water supplies can reasonably be predicted to increase. This likely will result in pressures for tighter, more effective regulation and consequently regulatory and financial drivers, including avoidance of fines and reputational damage, for water suppliers, including both companies and public organisations, to consider and implement more effective arsenic remediation.

This article considers some of the recent and current innovations and issues relevant to remedying high arsenic water supplies whilst also considering the wider aspects of knowledge transfer and management helpful to better ensuring safe and sustainable water supplies. Much of what is discussed here may also be applicable to improving water quality with respect to other constituents. A reference list is provided for those interested in more in-depth coverage than is possible here.

Environmental drivers of water quality with respect to arsenic

High concentrations of arsenic in drinking water sources are typically found in groundwaters, although some surface water sources may also have elevated concentrations. High arsenic concentrations in surface waters may derive from natural geothermal inputs (Lord et al., 2012), acid rock drainage, evaporation of saline inland lakes, from upland peats (Rothwell et al., 2009) and more rarely and sporadically from volcanic emissions, as well as from anthropogenic sources, including sulphide-bearing mine and mine treatment sites, industrial waste sites and sites for the manufacture and application of arsenic-bearing pesticides, herbicides and wood preservatives (Polya and Middleton, 2017). High concentrations of arsenic are more widely found in groundwaters, typically derived from (i) microbially mediated reductive dissolution of arsenic-bearing Fe/Mn oxyhydroxide host mineral phases (Islam et al., 2004); (ii) desorption in oxidised groundwaters (Guo et al., 2011); (iii) oxidative dissolution of arsenic bearing sulfides, notably pyrite and arsenopyrite (Smedley and Kinniburgh, 2002); (iv) geothermal inputs (Lord et al., 2012); and less extensively, from (v) anthropogenic inputs. There is also extensive debate (Harvey et al., 2002; van Geen et al., 2003; Polya and Charlet, 2009; Lawson et al., 2016) about whether or not and to what extent massive withdrawals of groundwater for irrigation purposes may be leading to secular increases in groundwater arsenic, particularly in intensively rice-cultivated areas of circum-Himalayan Asia.

High arsenic groundwaters are found in many parts of world. Densely populated deltaic regions of South Asia (e.g. West Bengal, Bangladesh) and South-East Asia (Viet Nam, Myanmar, Cambodia) are areas of particularly pronounced high groundwater arsenic hazard. Global occurrences have been collated by Ravenscroft et al. (2009). Maps of the probability of high arsenic hazard in both reducing and oxidising groundwaters on a global scale have been generated by Amini et al. (2008), whilst similar maps are available for South-East Asia (Winkel et al., 2008), Cambodia (Sovann and Polya, 2014) and China (Rodriguez-Lado et al., 2013) – several of these maps have been collated by Eawag (2017) and geostatistical methodologies discussed by Bretzler et al. (2017).

There are several ways in which environmental factors control drinking water quality with respect to arsenic and consideration of these factors can be useful to inform mitigation options. Notably:

- (i) There are clear patterns in the geological environments that are associated with many (but not all) high arsenic groundwaters, for example the geographic distribution of relatively recent orogenic belts (Mukherjee et al., 2014).
- (ii) The biogeochemical environment within aquifers plays a key role in controlling the rate and extent to which arsenic may be transferred from aquifer solid phases, in which it represents no substantive risk to human health, to groundwater, in which – depending how the groundwater is used and treated – it may contribute to very substantive human health risks (Smedley and Kinniburgh, 2002).
- (iii) Changes in climate, with geographically variable negative or positive impacts on availability of surface waters and on groundwater recharge over the next few decades (Jiménez Cisneros et al., 2014).
- (iv) Extremes of rainfall may, on the one hand, in times of low rainfall lead to a deficiency in surface water supplies, whilst on the other, in time of high rainfall lead to flooding and contamination of surface water supplies rendering them less suitable or unsuitable for human consumption – these events may lead to increased demand for groundwater, with the typically higher potential for high arsenic hazard than surface waters.

Regulatory aspects of water quality with respect to arsenic

The regulation of arsenic in drinking water has had a chequered history and, arguably, still is chequered at present. The WHO guideline value for arsenic in drinking water is (and has been since 1993) 10 µg/L (WHO, 2011) and whilst this is widely adopted as a regulatory standard in many countries around the Asia-Pacific region, less protective national regulatory standards of 50 µg/L, equal to the previous (1963) WHO guideline value, are also widespread. In the USA, the 10 µg/L value did not become an enforceable requirement until as recently as 2006. The current WHO guideline value is described (WHO, 2011) as a "provisional value" reflecting (i) uncertainties in adverse health effects associated with chronic exposure to arsenic in drinking water with concentrations much less than 100 µg/L; and (ii) "practical difficulties in removing arsenic from drinking-water, particularly from small supplies, and the practical quantification limit for arsenic" (WHO, 2011, p.317).

Much of the uncertainty in quantifying adverse health effects arises from (i) the commonness otherwise of many of the health effects (e.g. lung cancer, cardiovascular disease), (ii) the presence of multiple confounding factors (e.g. gender, age, diet, smoking status, other lifestyle factors, genetic susceptibility and exposure to arsenic from other sources such as rice and other foodstuffs) and (iii) arguably that the most robust epidemiological studies on the adverse health effects of chronic exposure to arsenic in drinking water have been conducted on populations exposed to relatively high concentrations of more than 100 µg/L. Extrapolating epidemiological data from such high concentrations to lower concentrations has therefore required the adoption of an assumed model for extrapolation. However this is thwart with difficulties particularly as, NRC (2001) have concluded that "the available mode-of-action data on arsenic do not provide a biological basis for using either a linear or nonlinear extrapolation" or indeed for determining whether or not there is a threshold below which there are no effects.

Meharg and Raab (2010) amongst others, point out that, with many analytical methods capable of quantifying arsenic at concentrations as low 0.02 µg/L, 50 times lower than the WHO provisional guideline value, analytical constraints should not, in the interests of protecting public health, be cited as a valid reason for the provisional adoption of the 10 µg/L guide value.

Notwithstanding the difficulty and expense of sufficiently powerful epidemiological studies to accurately determining dose–response relationships at drinking water concentrations around 10 µg/L and the difficulty of accurately extrapolating higher concentration data to these concentrations, there is increasing evidence that there are substantial adverse health effects associated with consumption of drinking water with arsenic concentration both at and lower than the WHO 10 µg/L provisional guideline value. WHO (2011) cite NRC (2001) modelled likelihood estimates for just lung and bladder cancer alone for USA residents drinking water with arsenic concentrations 10 µg/L to be between 120 and 230 per 100,000 – far higher than the 10 in 100,000 often muted as the upper limit of acceptable cancer risks from drinking water. Smith et al. (1992) estimate the lifetime risk of dying of lung, liver, bladder or kidney cancer from the same 10 µg/L exposure to be 1300 per 100,000 people. Leonardi et al. (2012) estimated adjusted relative risks of acquiring basal cell carcinomas in populations exposed to 7.0–19.43 µg/L arsenic in drinking water relative to a control population to be 1.73 (confidence interval 0.97, 3.11) i.e. 73% more likely to acquire this form of skin cancer. Medrano et al. (2008) report fully adjusted cardiovascular and coronary heart disease mortality rates in Spain were 2.2% (–0.9 %, 5.5%) and 5.2% (0.8%, 9.8%) higher in the population supplied with drinking water with arsenic concentrations of 1–10 µg/L than in that supplied with less than 1 µg/L.

Drivers and barriers for improving water quality with respect to arsenic

There are multiple drivers for water suppliers to improve water quality, in general, and with respect to arsenic, in particular. These include: (i) regulatory compliance and fulfilment of statutory obligations; (ii) avoidance of financial or reputational penalties; (iii) improved customer satisfaction; (iv) improved profits; and (v) the moral imperative underpinning multiple SDGs (UNESCAP/ADB/UNDP, 2017).

However, there are also multiple barriers for water suppliers to improve water quality, including with respect to arsenic. These include: (i) costs in relation to benefits; (ii) lack of desire or awareness of the need to improve water quality; (iii) competing challenges and projects; (iv) lack of awareness of relevant innovations, including in treatment technologies; (v) lack of communication of robustly tested innovative treatment technologies; and (vi) conservative attitudes to change.

An often used description of the water sector in many countries is that it operates in a very conservative risk-averse manner (Alegre et al., 2015). This might be taken to be criticism of a sector generally less likely to adopt disruptive technologies or other innovations than some other sectors, but equally water suppliers typically have substantive responsibilities and obligations to a wide range of stakeholders and the costs of selecting and implementing innovative remediation technologies or procedural/management that do not fully fulfil their predicted operational benefits can be very substantive indeed. Careful consideration of approaches therefore seems prudent.

Criteria for selection of approaches to improve water quality with respect to arsenic

Selection of water remediation approaches can benefit from being done in the context of water safety plans (Davison et al., 2005; see also Richards, 2017). There is a generally not a "one-size-fits-all" best solution, but rather selection criteria need to be used to assess the differing requirements depending upon (i) whether the treatment required is for wastewater or point of entry (POE), centralised points of supply or more dispersed point of end use (POU); (ii) the nature of existing water treatment infrastructure; (iii) the chemical and physical nature of the water being treated and including the nature and extent of other chemical hazards requiring treatment; (iv) stakeholder perceptions; and (iv) budgetary and logistic constraints.

The Committee of Innovation Remediation Technologies, National Research Council (CIRT-NRC, 1997) identified 3 major categories of criteria for selection of remediation approaches, viz. (i) technological performance; (ii) commercial characteristics and (iii) stakeholder acceptability.

Technological performance criteria (CIRT-NRC, 1997) include: (i) improvement in water quality against the relevant regulatory or otherwise selected target value; (ii) robustness – effectiveness of technology over a range of environmental conditions including water composition and flow rates; (iii) forgiveness – effectiveness of the technology over a range of operating conditions; (iv) ease of implementation; (v) ease of maintenance including required down-time; (vi) ease of scale-up; (vii) compatibility with existing treatment plant and, if appropriate, ease of retro-fitting; (viii) predictability of performance; (ix) minimal production of secondary harmful components, including CO2; and (x) operational lifetime of plant or key components.

Commercial criteria (after CIRT-NRC, 1997) include: (i) capital costs; (ii) operating costs; (iii) replacement costs of whole plant or plant components with respect to anticipated component lifetimes; (iv) availability of technology with respect to licensing or patent restrictions; (v) availability of materials and appropriate trained/expert human resources; (vi) reduction of risk of regulatory non-compliance with respect to anticipated regulatory targets; (vii) overall profitability with respect to the availability of capital and organisational financial performance and targets otherwise.

The relevant major stakeholders include (i) consumers (i.e. public); (ii) regulators; (iii) innovation users (e.g. water supply organizations); (iv) innovation providers (e.g. research organizations) and facilitators (e.g. knowledge transfer networks, industry associations); (v) investors; (vi) insurance companies; and (vii) personnel implementing innovation (e.g. treatment plant workers). Recognising diversity (e.g. related to class and/or gender) of opinions and priorities within stakeholder classes is highly relevant (cf. Crow and Sultana, 2002). Stakeholder acceptability criteria include: (i) compliance with regulatory requirements; (ii) disruption to consumers and local communities; (iii) impacts on environmental and economic amenity; (iv) impacts on taste; and (v) safety of operations.

Amongst other factors, both (i) the maturity of technologies and approaches and (ii) the readiness of communities to aspect remediation options (Kot et al., 2014) may both be critical criteria, which may change over time, particularly if efforts are made to facilitate this. The technology readiness level (TRL) (Mankins, 1995) is a useful metric with 9 stages, ranging from TRL 1 (least mature), where basic principles are observed and reported, up to TRL 9 (most mature) where an actual system has been implemented successfully in the intended operational environment. Such a metric may be useful in risk management and/or decision making in the selection of an appropriate remediation technology as well as identifying technologies that might be useful in the future and which might warrant investment to develop and/or commercialise – such activities represent a potential particularly fruitful area for collaboration between research organisations, manufacturers and suppliers of relevant technologies and water supply companies, and which can be facilitated by all of government, water sector companies and relevant professional organisations.

Decision-making

If nothing else, the lists above reflect the complexity of decision-making where there are (i) multiple selection criteria, many of which are inter-dependent; (ii) multiple stakeholders, who, in turn, may be involved in complex dependencies and relationships; and (iii) notwithstanding the particular importance of arsenic, a multiplicity of other water quality components, inorganic, organic and microbiological, satisfactory control of which is required. Given these circumstances, decision-support systems (DSSs) become increasingly important and represent a major area for innovation and opportunity.

DSSs in the water sector have, to date, largely focussed on the management of water supply, i.e. volume of supply and, to that end, integration with river basin management (IRBM) or groundwater basin scale management. Such approaches include drought modelling (Mishra and Singh, 2011), watershed management (Reddy et al., 2017) and variably utilise approaches including regression analysis, time series analysis, artificial neutral networks, fuzzy expert systems and data mining. Perhaps, in part, because of the complexity and the integration of scales sometimes sensibly required, many of these models have focussed on physical-geographical variables, for example spatio-temporal distribution of rainfall, evapotranspiration, land-use, vegetation types and integration of processes and models over various scales.

There is increasing recognition, however, as to the importance of human activities in modifying water supply, including at the basin-scale, and this has led to innovative and more complex modelling permitting the integration of physical-geographic parameters and processes with socio-economic parameters as well as processes involving various types of stakeholders or agents. Kelly et al. (2017) review five such modelling approaches including the use of System Dynamics, Bayesian Networks, Coupled Component Models, Knowledge Based Models and Agent-Based Modelling. These models are of variable relative utility depending upon the nature and availability of input data, the degree of understanding of relevant processes, the importance of feedback loops and whether or not aggregated affects or interactions between individual stakeholders is preferred (Kelly et al., 2017). How effective these approaches are depends upon the motivation and abilities of stakeholders (cf. Phi et al., 2015). Additionally, the effectiveness of these approaches may also depend upon how they are utilised – for example, agent-based modelling (cf. Harou et al., 2009) might best be utilised by narrowing down the number of broadly equivalent options to be considered and which may then be selected by expert experiential judgement of relevant professionals – thus providing a synergistic balance between highly technical modelling expertise and commercial expertise in circumstances where it is impractical to robustly quantify the relevant weighting of disparate selection criteria (after J. Harou, pers. comm.).

Whilst the purpose of various modelling approaches may primarily be for decision-making, the involvement of stakeholders and the nature of the modelling process may also contribute to one or more of: (i) greater capability to deal with uncertainty in key parameters, both in the present and in the future; (ii) increased understanding of the relevant environmental/operational/ socio-economic systems; and (iii) increased social learning, that is "the capacity of a social network to communicate, learn from past behaviour, and perform collective action" (Kelly et al., 2017 after Fraternali et al., 2012 and Haapasaari et al., 2012). The latter is particularly relevant to decision-making in the management of complex water supplies and infrastructure involving inputs from and impacts on multiple stakeholders with diverse interests and views. Additionally, such social learning may impact positively on the effectiveness of participatory approaches to decision-making and to acceptance by consumers (cf. Leventon et al., 2017a; 2017b).

Arsenic remediation approaches

Human exposure to arsenic in drinking water may be reduced in one or more of two ways, notably:

(i) Removal of arsenic from water supplies (cf. Ravenscroft et al., 2009; Hering et al., 2017).
(ii) Switching to alternative lower arsenic concentration water supplies (cf. van Geen et al., 2003).

Methods for the removal of arsenic from water supplies have been reviewed by many authors including by Ravenscroft et al. (2009) and more recently by Hering et al. (2017), who also list NGOs who have further usefully reviewed information on drinking water treatments. Conventional treatments typically make use of one of more of (cf. Ahmad et al., 2017) (i) precipitation/coagulation/filtration; (ii) adsorption/ ion exchange; (iii) membrane filtration; (iv) oxidation; and/or (v) bioremediation, including microbial treatments (Hayat et al., 2017). Advances are currently being made or have the potential to be made in the areas, amongst others, of (a) the use of nano-particles, such as nano zero valent iron (NZVI) to sorb arsenic (Habuda-Stanić and Nujić 2015); (b) graphene oxide for arsenic removal by sorption (Kumar et al., 2014) or potentially through ion-specific tunable nano-filtration (Abraham et al., 2017); and (c) novel metal-organic frameworks (Sarker et al., 2017). Hristovski and Markvoski (2017) highlight the potential benefits of better understanding the thermodynamics and kinetics of contaminant-sorbent interactions to enable the engineering of most appropriate sorbents, including nanocomposites, for particular target chemicals and matrices.

Notwithstanding all these technological solutions, increasing the supply of low arsenic water could be as much about putting in place practices to encourage switching water supplies as it could remove arsenic from an existing (typically groundwater) supply – such practices could include: (i) reducing per capita water demand through education programmes, household practices or agricultural practices (e.g. reducing over-irrigation of rice and other crops); (ii) effective monitoring (cf. Polya and Watts, 2017), evaluation of populations at risk (cf. Crabbe et al., 2017), biomonitoring (Middleton et al., 2016) and communication of arsenic-attributable risks to stakeholders (cf. Polya et al., 2017) (iii) removing microbiological pathogens and organics, such as pesticides and emerging pharmaceutical and other contaminants, from low arsenic waters (cf. organics destruction technology reported by Brown et al., 2004; Nabeerasool et al., 2015), making them more attractive and suitable as alternative water supplies; (iii) development of further alternative water sources, e.g. through rainwater harvesting or managed aquifer recharge. At a time when there are increasing concerns voiced over the "emerging water gap" between demand and supply (2030 Water Resources Group, 2009), reducing the pressure to use arsenic-bearing groundwater for drinking water by reducing the overall demand for water is an attractive win-win option for both addressing water supply and, indirectly, arsenic water quality issues.

Final word – Promoting innovation and knowledge transfer

The water sector across the Asia-Pacific region face increased population, lifestyle and climate-related challenges of both water supply and water quality (WWAP, 2015). Rapid development of communication technologies and social media platforms and the massive increase in open access scientific publications, together with the increased recognition of detrimental health impacts of drinking water arsenic even at what were once considered "low" concentrations is likely to drive tighter regulation of arsenic in water supplies. Such regulation may, to a large extent, be driven by consumer and other stakeholder perceptions and attitudes.

Science, technological and social science innovation will play a key role in the water sector meeting the demands of a changing world. Increased effective communication and partnership working between water sector stakeholders, including innovators (in research organisations or departments in both the public and private sector) and knowledge transfer professionals and organisations (such as knowledge transfer offices, technology innovation centres, Catapults) will create opportunities to meet these challenges. Despite the obvious commercial constraints, there are strong proponents of building upon knowledge transfer initiatives to "Open Innovation 1.0" (i.e. facilitating innovation along value chains through enhanced interactions between innovators and stakeholders) to "Open Innovation 2.0" (i.e. integration of activities beyond bilateral transactions to multi-lateral collaborations involving co-creation by consortia) (EC, 2014). Entrepreneur-driven SMEs may play a pivotal role, both as innovators and as innovation intermediaries. Given the commercial risks, initiatives such as risk sharing instruments and public-private finance are argued by some (EC, 2014) to be key support to facilitate the supply of appropriate venture capital to promote both effective knowledge transfer and open innovation. Lastly, in a sector in which investment is substantially driven by regulatory regimes (IAM, 2013), national governments have a critical role in setting standards and drawing up policy, including in relation to the basis and nature of water pricing.

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