



Invited review

Arsenic in bedrock, soil and groundwater – The first arsenic guidelines for aggregate production established in Finland



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ABSTRACT

Concern over arsenic (As)-rich drinking water has gained worldwide attention since the 1990s, when the problem was discovered in West Bengal in India and in Bangladesh. Since then, authorities and research institutes have focused on risk assessment and management for As in Finland. Nationwide geochemical mapping projects determined background levels and revealed regions with a higher than average As content in bedrock and soil. Approximately 10% of the citizens in Finland use drinking water from private wells. Groundwater, especially from drilled bedrock wells, may contain As concentrations higher than 10 µg/L, the European Union quality guideline for As in drinking water. Here, we present the outcome of two European Union projects, RAMAS and ASROCKS, which based their conclusions on nationwide databases and thousands of samples. Both RAMAS and ASROCKS focused on the Tampere-Häme region of Southern Finland, where bedrock and soil contain more As than in other parts of Finland on average. Over 1000 groundwater samples revealed that drilled bedrock wells may contain As-rich water in certain geological units. Naturally occurring As in bedrock and soil may also cause the mobilization of As during rock aggregate production and construction activities, potentially impacting on groundwater aquifers, surface waters, and biota. Arsenic concentrations in aggregate production and construction exceeded the regional background levels in some bedrock and aggregate product samples, but during leaching tests As concentrations were found to be low. Based on the results, risk management tools were revised and guidelines for the rock aggregate industry were established in cooperation with authorities, companies, and other stakeholders. To our knowledge, the guidelines established were the first in the world. The guidelines for As for the aggregate and construction industries can be applied in other countries and adapted to local conditions.

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1. Introduction

The toxicity of arsenic (As) has long been evident, but only during the 1990s did awareness of human exposure to As through drinking water raise concern, when the problem was discovered in West Bengal in India and in Bangladesh (Smith et al., 2000). Millions of people were affected by the consumption of As-rich groundwater and rice. A considerable amount of research has been carried out to better understand As contamination in drinking water and food supplies (Correll et al., 2006; Fendorf et al., 2010; Ng et al., 2003). It was understood that chronic exposure to As may cause health problems (e.g., Rahman and Naidu, 2009). Recent studies have focused on As in hydrological processes between the geosphere, hydrosphere, and biosphere (e.g., Bhattacharya et al., 2014; Bundschuh et al., 2013; Naidu and Bhattacharya, 2009; and references therein). Likewise, comprehensive investigations have focused on the occurrence, behavior, and remediation of As in mining environments (e.g., Nieto et al., 2013; Nordstrom, 2011; Sarmiento et al., 2009). However, the As risks to humans and ecosystems from the production of rock aggregates and in the construction industry in areas with naturally occurring As had not been recognized before the European Union LIFE Environment projects RAMAS and ASROCKS were carried out in Finland.

The three-year (2004–2007) RAMAS project gathered diverse As information from the Tampere region and identified the risk areas. It also provided certain risk management guidelines, mainly from groundwater and health perspectives. Subsequently, the ASROCKS project (2011–2014) continued the work and focused on guidelines for the rock aggregate and construction industries. The present paper provides a brief review of the main results of these projects. The existing nationwide geochemical databases formed a solid basis for the more detailed investigations.

Especially the ASROCKS project investigated the environmental impact of the rock aggregate and construction industries in a target area with naturally elevated As concentrations in bedrock and soil compared to other parts in Finland. However, even the higher than average As values in Finland are moderate when compared to other locations in Europe (Fig. 1). Therefore, the problem of As contamination during rock aggregate and construction activities may well be worse in many other European countries and in other parts of the world.

The open and confidential cooperation of Finnish authorities, enterprises, and research organizations has been productive, and risk management and guidelines have been established for potential As risk areas. The risk management tools developed in Finland can be applied in other parts of the world where As risks are potentially more severe.

1.1. Natural occurrence of arsenic

Arsenic is a natural constituent in bedrock and soil. It usually occurs at low concentrations (average 1–2 mg/kg in the Earth's crust; Taylor and McLennan, 1985; Bhattacharya et al., 2002), but may be concentrated in certain rock types and especially in gold and sulfide-bearing ore deposits and occurrences. Pyrite [FeS₂; or arsenian pyrite Fe(As,S)₂] and arsenopyrite [FeAsS] are typical sulfide minerals containing As.

These minerals are relatively stable in the bedrock and in deep soil under reducing and near-neutral conditions. However, the mobility of As is largely dependent on changes in the pH and redox conditions resulting from natural processes (e.g. microbial activity) or anthropogenic disturbance of earth materials (e.g. mining) (Smedley and Kinniburgh, 2002). For instance, low pH (<4) and high pH (>9) favor its mobility (Smedley and Kinniburgh, 2002). The behavior of As is also dependent on its oxidation state, As(III) and As(V) being the most commonly occurring inorganic species in the groundwater environment (Smedley and Kinniburgh, 2002).

In areas with elevated As concentrations in the crystalline bedrock, mining and construction may expose As-bearing minerals. Contact with air may cause oxidation and the release of As to groundwater and surface water, with similar mechanisms as in acid mine drainage (Blowes et al., 2003). In oxic water, As commonly precipitates as Fe(III)arsenates or adsorbs onto Fe(III)oxides and Fe(III)oxyhydroxides. However, these minerals are usually metastable and, depending on the pH and redox conditions, can be subject to dissolution (Smedley and Kinniburgh, 2002). Therefore, understanding the consequences of human actions (such as agriculture, drainage, the use of aquifers as a source of potable water or irrigation, or excavating in areas with naturally high concentrations of As) may help to prevent human exposure to this toxic and carcinogenic element.

In the past decades, our knowledge of As in the geosphere, especially in drinking water, and the consequent health impacts has substantially increased (Bhattacharya et al., 2002; Ernst, 2012; Kapaj et al., 2006; Ng et al., 2003; Nordstrom, 2002; Smith et al., 2002). Many areas around the world have been recognized to exhibit naturally elevated subsurface As concentrations, and entire aquifers have been affected by As (Fendorf et al., 2010; Rodríguez-Lado et al., 2013). The long-term use of drinking water containing high concentrations of As poses a risk to human health, and As in surface waters may cause adverse effects on aquatic organisms. Chronic exposure to As may cause health impacts, including arsenic poisoning, cancer, skin lesions, and damage to internal organs, as well as respiratory, digestive, circulatory, neural, and renal systems (Kapaj et al., 2006; Mandal and Suzuki, 2002; Fowler et al., 2015).

1.2. Arsenic in geological deposits worldwide

Holocene fluvial plains and deltas may host As-rich groundwater. For instance, in Bangladesh, As is associated with organic-rich alluvial sediments of the Bengal Basin, where the sediments have been transported from eroded crystalline rocks from the Himalayas. Many studies and hypotheses have been presented concerning the origin of As (Ahmed et al., 2004; Hasan et al., 2007; Mukherjee et al., 2011; Sracek et al., 2004; Zheng et al., 2004). The most frequently presented explanation is that As adsorbs onto ferric oxyhydroxide coatings in the sediments. Microbially mediated degradation of organic matter causes the reduction of pore waters, triggering the dissolution of the oxyhydroxides, and thereby dissolving the iron and the adsorbed As (Ravenscroft, 2011). Human exposure to As in Bangladesh mainly occurs through drinking water and the use of As-rich groundwater in cooking and irrigation. In the latter cases, As is transferred to the food

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