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Groundwater arsenic contamination in Burkina Faso, West Africa: Predicting and verifying regions at risk

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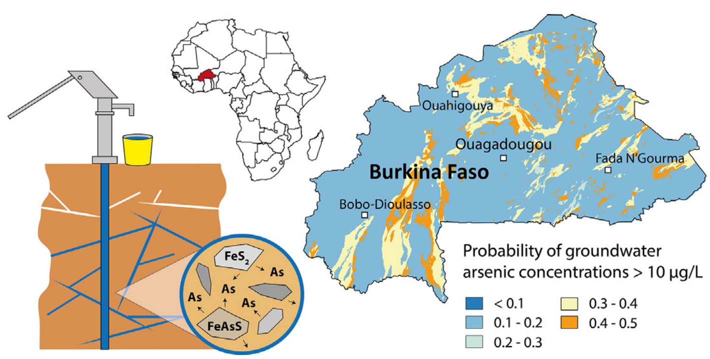
HIGHLIGHTS

- 14.6% of rural drinking water boreholes in Burkina Faso are affected by arsenic >10 μg/L.
- Geogenic arsenic is related to sulphide minerals from volcanic rocks and schists.
- Hazard maps pinpoint areas vulnerable to groundwater arsenic contamination.
- ~800,000 people are potentially exposed to drinking water arsenic >10 μg/L in Burkina.
- Awareness of a transboundary water quality problem affecting the whole region

GRAPHICAL ABSTRACT



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ABSTRACT

Arsenic contamination in groundwater from crystalline basement rocks in West Africa has only been documented in isolated areas and presents a serious health threat in a region already facing multiple challenges related to water quality and scarcity. We present a comprehensive dataset of arsenic concentrations from drinking water wells in rural Burkina Faso ($n = 1498$), of which 14.6% are above 10 μg/L. Included in this dataset are 269 new samples from regions where no published water quality data existed. We used multivariate logistic regression with arsenic measurements as calibration data and maps of geology and mineral deposits as independent predictor variables to create arsenic prediction models at concentration thresholds of 5, 10 and 50 μg/L. These hazard maps delineate areas vulnerable to groundwater arsenic contamination in Burkina Faso. Bedrock composed of schists and volcanic rocks of the Birimian formation, potentially harbouring arsenic-containing sulphide minerals, has the highest probability of yielding groundwater arsenic concentrations >10 μg/L. Combined with population density estimates, the arsenic prediction models indicate that ~560,000 people are potentially exposed to arsenic-contaminated groundwater in Burkina Faso. The same arsenic-bearing geological formations that are positive predictors for elevated arsenic concentrations in Burkina Faso also exist in neighbouring

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countries such as Mali, Ghana and Ivory Coast. This study's results are thus of transboundary relevance and can act as a trigger for targeted water quality surveys and mitigation efforts.

1. Introduction

Despite the increased construction and development of centralised water distribution systems and piped water supplies in sub-Saharan Africa during the last decades, small-scale groundwater abstraction via hand-dug wells or village hand pumps is often the sole source of drinking water for rural populations (MacDonald et al., 2009; Martin and Van De Giesen, 2005). Especially in the arid and semi-arid regions of the Sahel belt, where surface water resources can dry out completely in the long dry season, rural areas rely on groundwater for their drinking water supply (Edmunds, 2008). In general, groundwater is regarded as having good drinking water quality and to be predominantly free of pathogens, but chemical constituents may present a hazard that is often discovered late or not at all due to insufficient testing and surveying of water quality (MacDonald and Calow, 2009; UNICEF, 2008).

This is the case for arsenic, which can occur naturally in groundwater in concentrations that can lead to serious and chronic health effects after prolonged consumption (Naujokas et al., 2013). Arsenic exposure has not only been linked to the development of a variety of cancers, but also to developmental, neurological, respiratory and cardiovascular effects (Argos et al., 2010; Naujokas et al., 2013; Yuan et al., 2010; Yuan et al., 2007). The World Health Organization (WHO) has imposed a drinking water guideline concentration for arsenic of 10 μg/L, which has also been adopted by Burkina Faso (MAHRH/MS, 2005; WHO, 2011). Large-scale geogenic contamination of groundwater with arsenic in South and Southeast Asia (e.g. Bangladesh, India, Cambodia, Vietnam) has received a lot of attention in the last two decades (e.g. Bhattacharya et al., 1997; Flanagan et al., 2012; Smith et al., 2000; Berg et al., 2007). The phenomenon is still relatively unknown and little studied in West Africa though (Ahoulé et al., 2015), where fractured aquifers composed of weathered crystalline bedrock predominate. This is a totally different system to the young sedimentary aquifers of arsenic-affected regions in Asia, where arsenic is predominantly released by reductive dissolution (Ahmed et al., 2004). Studies in Ghana and Burkina Faso have shown that the oxidation of arsenic-containing sulphide minerals found in rocks of the Birimian formation is the primary process responsible for high arsenic levels found in some groundwater (Asante et al., 2007; Barro-Traoré et al., 2008; Buamah et al., 2008; Sako et al., 2016; Smedley, 1996; Smedley et al., 2007; Somé et al., 2012). However, an understanding of the extent of the problem and a detailed investigation of the sources and geological conditions leading to arsenic contamination is currently lacking.

Since testing wells for arsenic contamination is expensive and time consuming, maps identifying areas that are especially vulnerable to this kind of pollution are largely missing. However, they would be a useful tool for decision makers by helping to focus efforts where they are most needed. Such groundwater vulnerability assessment and mapping is a growing field, with more and more studies focussing on finding methods to assess the vulnerability of aquifers to contaminants such as nitrate or pesticides (Nolan and Hitt, 2006; Nolan et al., 2002; Ouedraogo et al., 2016; Sorichetta et al., 2013).

Specifically concerning arsenic, statistical modelling to predict the spatial occurrence of arsenic and highlight areas where safe drinking water predominates has been performed successfully at different scales, from global to regional, and in a range of different geological terrains (Ahn and Cho, 2013; Amini et al., 2008; Ayotte et al., 2016; Ayotte et al., 2006; Dummer et al., 2015; Rodríguez-Lado et al., 2013; Shamsudduha et al., 2015; Winkel et al., 2008; Winkel et al., 2011; Yang et al., 2012). Fundamental to the development of such models is knowledge of the geochemical processes leading to the occurrence of high arsenic in groundwater, as well as finding the predictor variables (proxies) to explain these. Since geogenic arsenic is by definition of geological origin, such proxies are usually geological variables, but various environmental parameters, such as temperature or precipitation, that influence geochemical processes in groundwater may also be relevant (Amini et al., 2008).

The concentration of arsenic in groundwater is not only related to the abundance of arsenic found in minerals in the aquifer matrix, it is also a function of solubility, which is governed predominantly by pH and redox conditions (Dixit and Hering, 2003; Hug and Leupin, 2003). In China, for example, Rodríguez-Lado et al. (2013) found elevated groundwater arsenic concentrations in sedimentary basins and river valleys to be strongly associated with Holocene sediments, soil salinity, fine subsoil texture and an elevated Topographic Wetness Index, which functioned as proxies for chemically reducing environments with high arsenic solubility. In the case of arsenic release due to sulphide mineral oxidation in crystalline basement rocks, different proxies must be taken into account, as has been shown by Ayotte et al. (2006), Yang et al. (2012), Ahn and Cho (2013) and Dummer et al. (2015) who modelled a positive correlation between arsenic occurrence and certain mineral-bearing geological formations.

The goal of this study is to investigate the distribution and magnitude of geogenic groundwater arsenic concentrations in Burkina Faso in order to better identify affected areas and populations. We carried out a country-wide arsenic survey and created arsenic prediction models based on three different concentration thresholds (5, 10 and 50 μg/L) taking into account the geochemical processes and conditions responsible for elevated arsenic in groundwater in West Africa. The models were calibrated using a spatially limited arsenic measurement dataset and then validated with measurements from other regions in Burkina Faso to ensure country-wide validity. As is often the case in developing countries, datasets of physical parameters such as geology, hydrogeology, mineral resources and climate were not available to the same extent or resolution as in industrialised nations. For this study, only surface parameters were available. The depth of individual boreholes and lithological logs were not available. Therefore, another goal of this study was to investigate whether a reliable hazard model for arsenic can be produced in light of data scarcity. Due to the large number of countries in the West African region and the difficulty in collecting the necessary data for each individual country, we chose a single "model" country for which to create arsenic prediction models. Burkina Faso was selected because some existing studies already show elevated groundwater arsenic but are limited in their spatial extent (Barro-Traoré et al., 2008; COWI, 2004; Nzihou et al., 2013; Ouédraogo and Amyot, 2013; Sako et al., 2016; Smedley et al., 2007; Somé et al., 2012). The same geological formations that harbour arsenic-containing sulphide minerals in Burkina Faso are also found in neighbouring countries such as Mali, Niger, Ivory Coast, Ghana and Benin (Schlüter, 2008). Therefore, this study is relevant to the greater West African region and should spur increased discussion and mitigation efforts concerning arsenic contamination and its health effects.

2. Hydrological and geological setting and its relevance to elevated arsenic concentrations

Burkina Faso has a hot and dry semi-arid climate, with rainfall restricted to one rainy season per year from June to September. Rainfall is higher in the south-west than in the more arid north and east. Groundwater recharge occurs during the rainy season with smaller total amounts in the north than in the south-west, but can be spatially

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