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The problem of identifying arsenic anomalies in the basin of Sahand dam through risk-based 'soft modelling'

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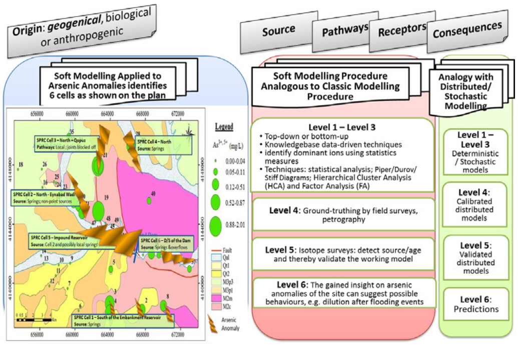
HIGHLIGHTS

- Arsenic levels at a 10 year old dam system exceed its allowed limit by 28 times.
- Arsenic hotspots at Sahand Dam impact human health and its ecology
- Studied Origins, Sources, Pathways, Receptors and Consequences (OSPRC)
- Assembled 6 levels of techniques and gained insights into six OSPRC cells
- Some of these OSPRC cells have local but mostly have system-wide impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

An investigation is undertaken to identify arsenic anomalies at the complex of Sahand dam, East Azerbaijan, northwest Iran. The complex acts as a system, in which the impounding reservoir catalyses system components related to Origin-Source-Pathways-Receptor-Consequence (OSPRC) viewed as a risk system. This 'conceptual framework' overlays a 'perceptual model' of the physical system, in which arsenic with geogenic origins diffused into the formations through extensive fractures swept through the region during the Miocene era. Impacts of arsenic anomalies were local until the provision of the impounding reservoir in the last 10 years, which transformed it into active system-wide risk exposures. The paper uses existing technique of: statistical, graphical, multivariate analysis, geological survey and isotopic study, but these often seem ad hoc and without common knowledgebase. Risk analysis approaches are sought to treat existing fragmentation in practices of identifying and mitigating arsenic anomalies. The paper contributes towards next generation best practice through: (i) transferring and extending knowledge on the OSPRC framework; (ii) introducing 'OSPRC cells' to capture unique idiosyncrasies at each cell; and (iii) suggesting a 'soft modelling' procedure based on assembling knowledgebase of existing techniques with partially converging and partially diverging information levels, where knowledgebase invokes model equations with increasing resolutions. The data samples from the study area for the period of 2002–12 supports the study and indicates the following 'risk cells' for the study area: (i) local arsenic risk exposures at south of the reservoir, (ii) system-wide arsenic risks at its north; and (iii) system-wide arsenic risk exposures within the reservoir even after dilution.

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1. Introduction

A study is presented in this paper to the problem of identifying arsenic anomalies at a study area, where measured concentrations can exceed the WHO (2004) limit of (0.01 mg/L) > 200 times. The study area comprises the complex of the Sahand dam basin, East Azerbaijan, northwest Iran. The treatment of the problem encompasses hydrosphere, lithosphere and anthroposphere and the paper seeks risk-based approaches to the identification problem to overcome existing fragmentation on the contributing disciplines. The identification problem is akin to hazard identification, as in risk analysis, which also covers risk assessment, risk management and risk communication, see Pizzol et al. (2015) and Tiedeken et al. (2017) but the paper leans towards risk analysis more than that towards traditional identification of arsenic anomalies.

The rationale for innovations in the paper derives from integrating the following contributions: (i) a risk analysis approach is promoted towards the problem of identifying of arsenic anomalies; (ii) the problem is treated through the dimensions of Origins, Sources, Pathways, Receptors and Consequence (OSPRC) and these dimensions together form a framework, where a framework is consensual agreement on the dimensions without any empirical-theoretical basis; (ii) the system is divided into a number of OSPRC cells (risk cells) as per Khatibi (2008), each of which captures independently varying aspects of arsenic anomalies of the study area; (iii) the concept of "soft modelling" is introduced to integrate diverse range of techniques (including: statistical, graphical, multivariate analysis, geological survey and isotopic study) used both in practice and research for identifying arsenic anomalies; and (iv) the rationale in an integrated fashion forms a *conceptual model* with a full picture on arsenic anomalies and this builds on a *perceptual model* to formalise the description of the scientific understanding of the processes within physical systems largely driven by the geology of the area. The paper shows that risks in the study area were of local scope but this was transformed into a system-wide risk exposure by the provision of the impounding reservoir.

The practice of identifying arsenic anomalies is quite idiosyncratic for a range of reasons including variations in OSPRC dimensions and the diversity of techniques used to identify anomalies The authors are not aware of any critical thinking against existing methodologies. The paper seeks to formalise the methodology on the identification of arsenic anomalies through the three elements of the OSPRC framework, risk cells and soft modelling procedure, the following review is focussed on the main contributions of the paper.

Origins express a potential for the release of arsenic loads from geological formations, ores or chemical compounds but existence of arsenic at a place is not necessarily exposure to risks. Origins of arsenic anomalies are diverse and Bundschuh et al. (2011) show that arsenic anomalies are generally found in the atmosphere, water, soil, rock, and organisms in various organic or inorganic compounds. The origins of arsenic anomalies in water include: *geogenical* (Smedley and Kinniburgh, 2005; Alonso et al. 2014; Beiyuan et al., 2017), biological (Mahimairaja et al., 2005), *anthropogenic* (Smedley and Kinniburgh, 2005; Bundschuh et al., 2011; Muhammad et al., 2016; Martin et al., 2017), *geogenical* and *anthropogenic* (Johnson et al., 2014; Lapworth et al., 2017; Kazakis et al., 2017). High arsenic anomalies in groundwater are often geogenic, also called natural (Mahimairaja et al., 2005). Main natural origins of arsenic include basin-fill deposits (J. Wang et al., 2017, S. Wang et al., 2017), geothermal and volcanic activities (Nriagu and Pacyna, 1988; Bondu et al., 2017). The paper is focussed on geogenic origins, which is mostly a diffuse source and its identification from this origin is often more challenging than other origins.

Source: This refers to the processes of arsenic ions leaching out of geological formations through hydrogeochemical processes. Leaching out sorbed arsenic ions at sources are associated with triggering risks, which expresses the likelihood of adverse effects. If the loads remain local at the source, the risk is likely to remain local and even may not trigger risk exposures. Notably, the interchangeable use of the terms origin and source in some of the published works is not uncommon. The literature on identifying arsenic anomalies at source is vast (Chuah et al., 2016; Bondu et al., 2017) and the various techniques are outlined in Section 3, which include: wide applications of statistical method e.g. Nadiri et al. (2013), Graphical method e.g. the Piper diagram (Piper, 1944), Durov diagram (Durov, 1948; Lloyd and Heathcote, 1985); and Stiff diagram (Stiff, 1951; Hem, 1989), multivariate analysis (J. Wang et al., 2017, S. Wang et al., 2017; Uher et al., 2017), geological and hydrogeological studies (Hounslow, 1995), isotopic studies (Clark and Fritz, 1997). These techniques serve as tools for both practice and research to investigate hydrochemical and hydrogeochemical processes. It is not common practice to compare these techniques but published works seems uncritical on the absence of their inter-comparisons.

Pathways and **Receptors**: The focus of the paper is on either leached out arsenic ions triggering local risk exposures at the source or system-wide risk exposures propagating through **pathways** to each remote **receptors**. The authors are not aware of systematic research works on pathways whereas research on receptors includes studies on the social dimension in terms of vulnerability and resilience but the authors are not aware of studies in risk exposure related to arsenic anomalies.

Consequence: Arsenic is carcinogenic (Pershagen, 1981) and the consequences of exposures to arsenic in water have recently been evaluated (Kapaj et al., 2006) including cancers, several dermatologic and vascular diseases, cerebrovascular disease, infant mortality, and reduction in birth weight (Tseng, 1977; Bhattacharya et al., 2007). Exposures of this nature occur in many parts of the world with each occurrence often seems quite idiosyncratic and recent studies have focused on arsenic anomalies in various parts of the world, e.g. Bangladesh (Anawar et al. 2011), China (Ning et al. 2007), Northern Greece (Kouras et al. 2007), Pakistan (Nickson et al. 2005), India (Rahman et al. 2005), Latin America (Bundschuh et al. 2011), Costa Rica (Hammarlund and Pinones 2009), Guatemala (Cardoso et al. 2010), Colombia (Tassinari et al., 2008), west Africa (Bretzler et al., 2017). There is no published work related to the study area on any specific consequences of arsenic anomalies other than stating here that approx. the 60,000 population of Hashtrud is likely to be exposed to the risks; as well as an unknown number of people downstream of the dam. Already some of at-risk villages are abandoned by migrating from the area to avoid health impacts but these have not been documented yet.

Soft Modelling: A set of overlapping techniques, referred to above and to be detailed in due course, have been developed over the years since the 1940s and applied to diverse sites. Whilst the authors promote the techniques listed above, to their knowledge, a critical view on these techniques remains outstanding and therefore both research and practice is based on selecting a number of them for analysis. Arguably, these techniques overlap and their solutions display both convergent and divergent features and this is similar to soft systems, in which the term 'soft' underpin convergent and divergent human behaviours, for more information see (Checkland and Scholes, 1990; French et al., 2005; Nidumolu et al., 2006). Thus, the paper formulates a 'soft modelling' procedure to exploit convergence/divergence behaviours among different techniques.

Shortfalls in existing techniques include: (i) absence of any concept on convergence/divergence of these techniques; (ii) serious problems in knowledge integration among different techniques; and (iii) absence of modelling procedure similar to those in in physical sciences. Arguably, shortfalls retard the practice of identifying arsenic anomalies but soft modelling procedures would fill these gaps.

2. Specification of basic information on the study area

2.1. Geographical location

The study area covers approximately 384 km^2 of land, in the East Azerbaijan province, Iran, and located between cities of Maragha and