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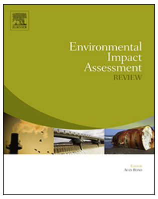

Introducing a risk aggregation rationale for mapping risks to aquifers from point- and diffuse-sources–proof-of-concept using contamination data from industrial lagoons

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ABSTRACT

Proof-of-concept for a methodology is presented on mapping risks to aquifers impacted from point- and diffuse-sources, where mapping or indexing refers to relative but not absolute values. The methodology is generic but tested by investigating impacts of a risk exposure from industrial wastewater lagoons. The methodology is innovative for using the qualitative Source-Pathways-Receptors-Consequences (SPRC) framework to aggregate risks from both point-sources and diffuse-sources through breaking down a study area into SPRC risk cells. In this paper, two risk cells are required as: (i) Cell 1 is directly impacted from a point-source; and (ii) Cell 2 is impacted by diffuse-sources to slowly contaminate the aquifer by infiltration over a large area. Indexing both types of risk cells generically comprise three tiered processes: (i) *binary indexing* establishes if a grid cell is at a potential risk or not; (ii) *graded indexing* measures the strength of the risk pathways from source to receptors; and (iii) *local indexing* measures intrinsic potentials at the grid cell to propagate the risk. These three processes apply to both point- and diffuse-sources but with different mathematical formulations. The proof-of-concept for the methodology of risk aggregation using the SPRC framework is supported by results of a study area, in which a set of performance metrics are used by comparing with the measurements. The results are found to be fit-for-purpose for serving as proactive management tools and to provide a deeper insight into potential impacts of adverse effects.

1. Introduction

A methodology is formulated in this paper to use the concept of risk with a primary innovation on aggregating risks from different sources and idiosyncrasies. It is applied to aquifers with sparse data availability, in which the risks to aquifers may be point-sources and/or diffuse-sources. The paper is focussed on risks to aquifers but studies on flood risks are more topical, where the thinking is reflected by Penning-Roswell and Peerbolte (1994), Todini et al. (2005), Khatibi (2011) and Alfieri et al. (2018). Analytical capabilities in current practices on flood risk are often based on frequency analysis if possible but it is argued that there is no theoretical platform yet available for practicing engineers to aggregate risks from all sources. Although the flood directive (FD2302, 2003) requires a consideration of flood risks from all sources, the available techniques are ad hoc. A review of current practices on risk analysis of floods and contaminated aquifers shows that risk aggregation is a challenge yet to become topical and the paper takes up the challenge through an innovative approach at its stage of proof-of-concept and applies it to aquifers.

The paper does not aim to be exhaustive in the review of the literature on groundwater risk assessment, but they may be categorised as follows. (i) The DPSIR (Drivers, Pressures, State, Impacts and Response) framework is a popular approach, (see GWRA, 2004; US EPA, 2001), which uses the best available information to serve as proactive aquifer risk management tools. (ii) Groundwater contamination risk is mapped in terms of vulnerability and hazard using the reliability analysis by GIS overlay analyses, e.g. Shrestha et al. (2017), in which risk indexes on aquifer contamination can be compared from different regions. (iii)

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Risk-based groundwater management strategies are developed by considering the potential for cancer risks via US EPA (2001) procedure, e.g. Li et al. (2016). (iv) Groundwater remediation schedules are developed through pump-treat-inject technologies (US EPA, 2001), in which optimised schedules are constrained by risk to health, e.g. Li et al. (2016). (v) Groundwater management strategies are prioritised by improving the quality status of groundwater, e.g. Pizzol et al. (2015).

The above techniques are not capable of quantitative aggregation of risks from all sources. Arguably, risk aggregation practices from all sources are ad hoc and modular approaches are yet to emerge. Khatibi (2011) discusses in some detail that there are problems with comparing risks from different sources. This is because quantitative techniques do not often treat local idiosyncrasies at the same platform. One framework for aggregation may be built on the Dempster-Shafer theory of evidence (Dempster, 1967; Shafer, 1976) but this has not been applied to groundwater problems. Another framework is possible, which is presented in this paper by the authors, as to be outlined below.

The paper introduces a rationale to aggregate risks from any sources but it is applied to aquifers through pooling together innovations and knowledge transfer including: (i) the use of the Source-Pathways-Receptors-Consequence (SPRC) framework, where Khatibi (2008), traces its emergence to 2000; (ii) the breakdown of a study area into mutually exclusive and modular SPRC (risk) cells as suggested by Khatibi (2008), where each captures an idiosyncrasy; and (iii) a study area is also broken down into grid cells or pixels, within each of which there is a generic common architecture to index risk for all idiosyncrasies; notably various learning techniques or different sets of algorithms can be employed without constraints to account for anthropogenic and geogenic origins, such as uncertainty analysis associated with hydraulic conductivity and groundwater potential mapping. The authors are intensively engaged with the uptake of risk cells and one of its implementations is presented by Nadiri et al. (2018) for the aggregation of arsenic anomalies from different sources. The paper later shows that the risk aggregation rationale introduced here integrates a number of concepts including SPRC framework, reliability analysis and tiered risk and discusses similarities of these frameworks in a case study.

The methodology developed in the paper is applied to the aquifer in Maragheh-Bonab plain, East Azerbaijan, Iran. The aquifer is known for being a rich groundwater resource but suffers extensive contamination from the breach of industrial wastewater lagoons in April 2010. Data availability is poor and hence risk indexing is particularly appropriate to the study area.

2. Study area and triggering event

The aquifer at Maragheh-Bonab plain, southwest of the East Azerbaijan province, northwest Iran (see Fig. 1a) forms the study area, which covers Sufichay floodplains. Sufichay (the River Sufi) rises at one of the Sahand peaks and flows towards the historic city of Maragheh (Maragha). The Sufichay basin covers an area of approximately 330 km^2 formed by alluvial deposits (see Fig. 1a) and flows to Lake Urmia. Aquifer recharge in this unconfined aquifer is continuous with high groundwater yields at its north, lower yields at its northwest and moderate yield at the rest of the basin. The quality of groundwater of the aquifer is considered to be high.

Maragheh is traditionally renowned for a diverse range of agricultural products, particularly different sorts of grape. Traditional industries of the city are yet to enjoy an appropriate level of support and modernisation but modern food processing industries have developed in the region, as well as some industrial complexes around the city. One of these industrial complexes produce wastewaters but these are supposedly mitigated through evaporation and sedimentation by lagoons with a total area of approximately 110 ha, see Fig. 1(a). These lagoons are located nearby a watercourse (known locally as Varjovichay) which flows to Sufichay. The breach due to a flooding incident on 25 April 2010 released an uncontrolled amount of pollution through a considerable amount of stored wastewater (possibly one million m^3). The impacts of this incidence are only considered by the paper with respect to the contamination of the aquifer.

The Maragheh-Bonab aquifer is known to have 65 deep and 6852 semi-deep abstraction water wells, 51 springs and 48 qanats (EA, 2010). Estimates indicate that approximately 39 MCM (Million Cubic Metre) of groundwater was withdrawn (EA, 2010) from the wells during the year 2010 but a more systematic study is needed to understand the nature of the problem.

The study area may be categorised in terms of hydraulic conductivity as follows: (i) low hydraulic conductivity–often composed of old and fine granular sedimentary; (ii) intermediate hydraulic conductivity–often composed of carboniferous sedimentary and old alluvial terraces; and (iii) high hydraulic conductivity–largely young terraces playing a key role in the formation of aquifers and this group draws from the erosion of old formations.

The spatially distributed Groundwater Elevation (GWE) is depicted in Fig. 1(b), as prepared by the data from 33 observation wells in 2014 based on interpolation using the Ordinary Kriging technique. The geoelectrical survey for the plain is the basis to delineate the thickness of the Maragheh-Bonab aquifer (conducted by General Consulting Engineering Co., 1964). The bedrock of the plain is of the Miocene formations and generally dips towards Lake Urmia, see Fig. 1(c).

Electric conductivity (EC) of the aquifer ranges from 500 μs/cm in the west to 4000 μs/cm in the east towards Lake Urmia. This trend coincides to Chebotarev trend (Nadiri et al., 2013a, 2013b) which indicates that the EC values increase from the upper basin to the lower basin of the aquifer. There are two anomalies: in the middle of the plain with 4000 μs/cm and at the southeast near the lagoons with 6000 μs/cm, where the EC of the lagoons storing wastewater has a value of 140000 μs/cm (Fijani et al., 2013). Notably, there are also studies in the literature, which investigate the integrated electrical conductivity (IEC) as a tool for aquifer vulnerability analysis (e.g., see Gemail, 2012 and Gemail et al., 2017).

3. Methodology

The concept of risk is defined as the mathematical product of the consequence of a hazard (or an adverse effect/incident or losses) and its likelihood, see the review by Khatibi (2011). Risk quantification techniques depend on data availability for the two main dimensions of risk (probability of adverse incidents and their magnitude) and frequency analysis is used if adequate data are available; whereas risk indexing is used when the data are sparse. In documents related to the Water Framework Directive (see GWRA, 2004), discussion on two possible approaches: (i) direct methods involve groundwater quality monitoring to indicate water quality degradation, where the available data make it possible to apply frequency analysis approaches; and (ii) indirect methods involves surveys of subsurface contaminant loads and the vulnerability of underlying aquifers to pollution. Risk indexing or mapping may be contrasted with risk quantification, in which risk values in the former approach are relative and expressed in terms of index values between 0 and 1 but the latter in often monetary terms. The paper explores indirect methods and uses appropriate mathematical approaches to contextualise the problem and map risks to aquifer contaminations.

The problem of aquifer risk indexing is processed for each grid cell of a study area and the methodology developed by the paper embeds the following concepts together: (i) types of sources (ii) the SPRC framework; (iii) risk cell or SPRC cell; (iv) the concept of tiered risks; and (v) the reliability analysis. These are presented in this section and captured in Table 1 and illustrated in Fig. 2.