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Research article

Introducing the risk aggregation problem to aquifers exposed to impacts of anthropogenic and geogenic origins on a modular basis using 'risk cells'

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ABSTRACT

Proof-of-concept is presented in this paper to a methodology formulated for indexing risks to groundwater aquifers exposed to impacts of diffuse contaminations from anthropogenic and geogenic origins. The methodology is for mapping/indexing, which refers to relative values but not their absolute values. The innovations include: (i) making use of the Origins-Source-Pathways-Receptors-Consequences (OSPRC) framework; and (ii) dividing a study area into modular Risk (OSPRC) Cells to capture their idiosyncrasies with different origins. Field measurements are often sparse and comprise pollutants and water table, which are often costly; whereas supplementary data are general-purpose data, which are widely available. Risk mapping for each OSPRC cell is processed by dividing a study area into pixels and for each pixel, the risk from both anthropogenic and geogenic origins are indexed by using algorithms related to: (i) Vulnerability Indices (VI), which identify the potential for risk exposures at each pixel; and (ii) velocity gradient, which expresses the potency to risk exposures across the risk cell. The paper uses DRASTIC for anthropogenic VI but introduces a new framework for geogenic VI. The methodology has a generic architecture and is flexible to modularise risks involving any idiosyncrasies in a generic way in any site exposed to environmental pollution risks. Its application to a real study area provides evidence for the proof-of-concept for the methodology by a set of results that are fit-for-purpose and provides an insight into the study area together with the identification of its hotspots.

1. Introduction

The formulation of a methodology to aggregate aquifer risk indices related to impacts of anthropogenic and geogenic origins is the primary goal of this paper. The major problem to be solved is: (i) to devise a framework to calculate risks from both anthropogenic pollutions and geogenic contaminants using sparse site-specific data supplemented by general-purpose data from hydrosphere, lithosphere and anthroposphere related to aquifers under study; and (ii) to use the same framework on a modular basis to aggregate risks from more than one origin. The capability for aquifer risk mapping exposed to anthropogenic pollutions pools together a set of existing algorithms; whereas that exposed to geogenic origins requires a new algorithm on top of existing one, as to be detailed in due course. Notably, mapping or indexing refers to relative risk values. To the best knowledge of the authors, modular risk aggregation is not quite topical in the current state-of-the-art in risk analysis and inevitably the developments by the paper is in a background where even benchmarking is not quite feasible.

The rationale for the aquifer risk aggregation problem is innovative, which pools together knowledge transfer as follows: (i) it uses the Origins-Source-Pathways-Receptors-Consequence (OSPRC) framework, see Khatibi (2008), Khatibi (2011), Nadiri et al. (2018a); (ii) it breaks down a study area into mutually exclusive and modular OSPRC (risk) cells, where each captures an

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idiosyncrasy, see Khatibi (2008) and Nadiri et al. (2018a); and (iii) the study area is also broken down into grid cells or pixels. The paper forms two risk cells: (i) Risk Cell 1 to account for anthropogenic pollutions; and (ii) Risk Cell 2 to account for geogenic contamination. The above is sufficient to lay down a modular architecture to index risk for all idiosyncrasies, where there is no restriction for: (i) the choice of algorithms at each module; and (ii) the number of risk cells. The combined effect is the emergence of a new modular capability for aggregating risk indices with different idiosyncrasies and the paper is focussed on proof-of-concept for the development.

Risk analysis (risk assessment, risk management, risk communication) practices are diverse and ongoing published works on risk to aquifers may be categorised as follows. (i) Risk assessment practices are often procedures to manage: *developmental pressures* e.g. DPSIR (GWRA, 2004); *risk to health*, e.g. USEPA (2001); *cancer risks*, e.g. USEPA (2001), Jang et al. (2009); or *prioritisation* of risk-based decision to maintain the good quality status of groundwater, e.g. Pizzol et al. (2015). (ii) Groundwater remediation schedules are developed through pump-treat-inject technologies (USEPA, 2001), to optimise the schedule, e.g. Li et al. (2015) and Li et al. (2016a, b). (iii) Groundwater contamination risk is mapped in terms of hazard and vulnerability by GIS overlay analysis, e.g. Chen et al. (2006); Wang et al. (2012); Zhang et al. (2012); Li et al. (2012); Li et al. (2016a, b) and Matzeu et al. (2017).

One gap in above practices is that they are often framed for risks from a single origin as there are outstanding problems to aggregate/compare risks from different origins/sources, Khatibi (2011) discusses in some detail, problems in comparing risks from different origins/sources, as risk techniques do not often reflect local idiosyncrasies at the same platform. One framework for aggregation may be built on the Dempster-Shafer theory of evidence (Shafer, 1976; Dempster, 1967). Another framework is suggested by Khatibi (2008) to pool together risks with different idiosyncrasies using the OSPRC framework, as detailed in due course.

Khatibi (2011) reviews the emergence of the concept of risk and its evolution and diversification. The basic definition of risk is that it is a mathematical product of consequences of a hazard (with adverse effects) and its likelihood. This concept of risk provides the tools to quantify risk in absolute terms through the dimensions of: (i) consequences of hazards; and (ii) likelihood of consequences. For insufficient data, it is not feasible to quantify each dimension. The paper replaces the consequences of a hazard with aquifer vulnerability in response to contaminants, as it is widely known that higher vulnerabilities encourage higher risks. Also, likelihood is replaced with aquifer flow velocity as a measure of spontaneity.

OSPRC is pivotal to modularise risks from different origins, where it is an extension of the widely-known SPRC framework, i.e. the OSPRC framework without the origin dimension. Khatibi (2008) traces the emergence of the SPRC framework to 2000. He suggests its possible uses for integrating risks with different idiosyncrasies and Nadiri et al. (2018a) make a successful use of the OSPRC. The paper differentiates the term origin from source, in which the term *origin* refers to the potential to risk without any spontaneous mechanisms to actuate risk processes; whereas the term *source* indicates its actuation. Arsenic anomalies are used to illustrate the distinction between origin and source (Nadiri et al., 2018a). Sorbed arsenic loads are often interspersed into members of igneous formations and can be present due to various sources, e.g. biological, anthropogenic and geothermal activities. Source refers to the actuation of the potential for arsenic anomalies at the presence of water, through ion exchange processes.

The methodology is applied to the aquifer in Khoy plain, West Azerbaijan, northwest Iran to seek a proof-of-concept for the methodology, in which Risk Cell 1 accounts for contaminations from anthropogenic origins using the DRASTIC framework; and Risk Cell 2 accounts for contaminations from geogenic origins. However, there is no framework for geogenic vulnerabilities and therefore the paper introduces a new framework (SPECTR), which is the acronym of 6 data layers to be detailed in due course). Notably, the paper does not use intrinsic vulnerability indices and when modelled vulnerability is referenced to proxy measurements. The paper refers to the model outputs as specific vulnerability when they are trained using measured values of pollution/contamination concentrations as proxy VI values.

2. Study area and triggering event

2.1. Background

Khoy plain, shown in Fig. 1, is located to the north of the West Azerbaijan province, where the plain is approx. 3370 km^2 and the aquifer forming the study area is approx. 670 km^2. The historic cultural city of Khoy is at the centre of the study area and the population of the city alone is just below 200,000.

Based on Emberger (1930), the prevailing climate in the study area is sub-humid within a cold climatic zone. The average annual precipitation is 344 mm and mean annual temperature is 12.2 °C (Khoy synoptic station 2005–2015).

Agriculture is the main economical preoccupation in the study area. Khoy plain is highly active in agriculture, livestock and industry with some mining industry and is therefore exposed to unregulated use of water, their impacts and to subsequent untreated wastewater. Water supply was traditionally based on the qanat system in the region, which was interwoven into the fabric of the past way of life. However, in recent years pumped abstraction wells have changed this supply pattern.

2.2. Geological context

The study area is an alluvial plain (see Fig. 1), which aggregates past magmatic and metamorphic activities. The facies of the rocks in the region are therefore complex and include sedimentary, igneous and metamorphic features (Nabavi, 1976; Mahab Ghodss, 1986) and these affect the quality of surface and underground waters in the area. In general, the activity at Aland, Qotur and Qazan Rivers have led to alluvial deposits over Khoy plain. The hydrogeology of the plain is directly affected by sediments of this area due to their grain size and their high expansion properties. These sediments mostly consist of sand and clay but some of the terraces are old and the particles are bonded with clay loams and this reduces their permeability. New terraces consist of sandy grains and located along the river that have very high permeability.

Past geophysical studies have produced exploratory logs and geological information at the study area shows that the main aquifer in the study area comprises alluvial deposits of the quaternary period. These studies have also shown that the quality of water resources is impacted by the dissolution of some carbonaceous and similar rocks and by evaporation and this gives rise to increasing the concentration of some ions in their composition. The authors are progressing in other research work to carry out a detailed analysis of the ions in the region.

There are several faults in the Khoy basin. The most important fault extends from northwest to southeast that is caused by tensile and pressure phases. The tensile phase is responsible to a greater number of springs in this study area.