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Research papers

Modification to the DRASTIC framework to assess groundwater contaminant risk in rural mountainous catchments

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ABSTRACT

Mountainous headwater catchments are safeguards of quality groundwater and hence require special protection against contamination by anthropogenic sources. However, methods currently handling contamination risk fail to produce reliable results in mountainous watersheds because they overlook the influence of downhill flows and contaminant transport in the validation process. To overcome this difficulty, a new model based on so-called "concentration profiles" is presented that combines the DRASTIC framework for evaluation of intrinsic vulnerability, the categorization of land uses for evaluation of specific vulnerability to nitrate and Processing Modflow graphical user interface for simulation of nitrate transport. This model was tested in a mountainous region of Northern Portugal. The risk of groundwater contamination by nitrate was generally classified as moderate. The risky areas are regions used for agriculture and livestock production. These activities have raised nitrate concentrations of spring water (15–25 $mg \cdot L^{-1}$) downstream the risky areas. The Modflow simulations linked the risky areas (contaminant sources) to actual nitrate plumes (contaminant sinks) and modeled nitrate distributions at specific groundwater travel times. Winter plumes could be simulated for the 1-year stress period, and hence are flushable in a short time span. Spring and summer plumes could only be explained by contaminant transport during 10–20 years. In these cases, even if contaminant sources were immediately neutralized, the washout of nitrate would take decades. These results may hold back the fulfillment of sustainable development goals related to water and sanitation until 2030, and hence deserve reflection by water planners and policy makers. The modeling exercise provided extra evidence that safeguarding the catchment headwater is the keystone of groundwater quality protection in mountainous catchments. Therefore, application of this modified DRASTIC to other mountainous areas may not need to resort to Processing Modflow. The study comprises the main paper (this paper) and a MethodsX companion paper.

1. Introduction

In Europe, concerns about groundwater protection are particularly associated with the publication of a legal framework comprising the Nitrates Directive (91/676/EEC) and the Groundwater Directive (2006/118/EC). In the mean time (in 2015), the United Nations announced the Sustainable Development Goals, to achieve by 2030, attracting planetary attention to groundwater protection through Goal 6. Implementing Goal 6 on water and sanitation means achieving a number of targets related to water quality, water-use efficiency, and integrated management and protection of water resources. From the scientific standpoint, implementation of Goal 6 requires the formulation of comprehensive groundwater contamination risk models, applicable to river basins, and their integration into municipal water resources management plans.

The formulation of groundwater contamination risk models at catchment scale comprehends the assessment of aquifer intrinsic and specific vulnerability. The appraisal of intrinsic vulnerability by the DRASTIC framework, as originally developed by Aller et al. (1985, 1987), tackles the protection of groundwater resources exposed to nitrate contamination from diffuse anthropogenic sources, being applicable to the rural environment. The DRASTIC index is an aggregation of ratings attributed to seven hydrologic relevant features (e.g., D – Depth to the water table), with relevance being quantified through predefined weights. Predefinition of feature weights unlocked a worldwide discussion, because weights were claimed by many authors to be tied to local environmental settings rather than being universally applicable

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(e.g., the critical review of Merchant, 1994, and references therein, or more recently Neshat et al., 2014; Neshat and Pradhan, 2017). Numerous studies have investigated adjustments of DRASTIC feature weights to local settings, namely through map removal or single-parameter analyses, fuzzy methods, logistic regression or eigenvector techniques (e.g. correspondence analysis) (Antonakos and Lambrakis, 2007; Dixon, 2005; Lodwick et al., 1990; Napolitano and Fabbri, 1996; Pacheco and Sanches Fernandes, 2013; Pacheco et al., 2015a).

Many studies focused on the planning of groundwater quality protection have gone beyond the assessment of aquifer vulnerability and estimated contamination risk (Jafari et al., 2016; Neshat and Pradhan, 2015). Under both ISO 31000:2009 and ISO Guide 73, the definition of "risk" is no longer "chance or probability of loss", but "effect of uncertainty on objectives", thus causing the word "risk" to refer to positive consequences of uncertainty, as well as negative ones (https://en.wikipedia.org/wiki/ISO_31000). In groundwater protection studies contamination risk has been mapped using intrinsic vulnerability (DRASTIC) combined with hazard mapping (Saidi et al., 2011), or even integrating these variables with the value of groundwater resources (Wang et al., 2012). In other studies, contamination risk has been described as weighted sum of intrinsic vulnerability, deduced from the DRASTIC framework, and specific vulnerability to nitrate contamination deduced from land uses (Antonakos and Lambrakis, 2007). Specific land uses (e.g., agriculture) are likely to produce periodical (seasonal) spills of contaminants (e.g., nitrate leachates from fertilizers) and cause environmental, economic or health damage via groundwater resource degradation, in case they are distributed over highly vulnerable areas. Recently, risk assessment models and mapping have expanded towards coupling the risk of anthropogenic origin (e.g. the Antonakos and Lambrakis approach) with risks of geogenic origin (Nadiri et al., 2018).

In risk assessment studies related to aquifer exposure to nitrate, validation of risk scores is frequently addressed. Authors generally agree on the approach to adopt, which is based on a direct comparison of risk and nitrate concentration in shallow groundwater. The comparison is made through establishment of a linear correlation between these variables, while robust fits were accomplished by Panagopoulos et al. (2006) in a flat area. Following this initial study, several authors used the nitrate concentration method to validate risk estimates in different topographic contexts. In mountainous catchments where this method was applied (e.g., Arauzo, 2017; Kazakis and Voudouris, 2015; Pisciotta et al., 2015; Shrestha et al., 2017) model fits of risk to nitrate were, however, much less robust than the fit of Panagopoulos et al. (2006). To overcome this disparity, Fijani et al. (2013) developed the SCMAI model based on artificial intelligence that ensures high-nitrate levels in the highest vulnerability areas, through non-linear fits between the two variables. Similar approaches were used by Nadiri et al. (2017a,b,c) in various regions of Iran. However, these studies lack hydrologic justification for the need to replace linear by non-linear fits in the validation process. The limited linear correlation between risk and nitrate scores was explained by Pisciotta et al. (2015) or Secunda et al. (1998), who related the poor fits to lateral groundwater flows across the shallow aquifers. The need to consider horizontal pathways in assessments of groundwater contamination risk using nitrate concentrations was recently emphasized by Nadiri et al. (2018). Although recognizing the possible cause, these authors have not yet attempted to confirm the lateral flow hypothesis through contaminant transport modeling.

Understanding the relationship between groundwater contamination risk and downhill flows in mountainous areas is therefore crucial for the correct planning of groundwater quality protection. Otherwise, planners may end up restrict land uses where nitrate concentrations are high, paying less attention to the areas where the sources of nitrate are located. The main purpose of this study is to present a validation approach based on the relationship between groundwater contamination risk and nitrate concentration in shallow groundwater, adjusted to mountainous areas where lateral groundwater flows prevail imposed by the craggy topography.

In brief, this new approach combines a risk assessment based on intrinsic (DRASTIC) vulnerability and specific (land use) vulnerability to nitrate contamination, with contaminant transport modeling (USGS Processing Modflow graphics user interface, https://www.simcore.com, with MT3D to model transport) to explain non-linear relationships between risk and nitrate concentration. In a first stage, a conceptual framework model is presented whereby theoretical non-linear relationships are anticipated for specific spatial distributions of recharge areas (catchment headwaters), discharge areas and risky areas. These theoretical relationships are termed "concentration profiles" because the aforementioned spatial distributions are evaluated along the catchment's longest flow path. Subsequently, Processing Modflow is run to verify which theoretical relationships are valid for the studied watershed. The pilot study was conducted in three sub-basins of Azibo River, which are tributaries of the Sabor River watershed located in a mountainous region of Northern Portugal.

Besides the validation of risk, this study aimed to estimate the time required by contaminant plumes to move from contamination sources to emergency areas. This research topic is relevant for the planning of groundwater quality protection, especially where the aforementioned time is long, hampering the cleansing of polluted shallow aquifers in reasonable time. Overall, the study is valuable for water planners and policy decision makers because the modeling exercise sheds light over the areas of a mountainous catchment that require special attention for an effective protection of groundwater quality.

2. Materials and methods

2.1. Study area

The territory of continental Portugal is encompassed by four hydrogeologic domains (Fig. 1a), namely the ancient crystalline massif, the West and South sedimentary borders and the alluvial plains of Tejo and Sado river basins. The study area comprises the Sabor River basin that was totally shaped on the ancient crystalline massif fundamentally characterized by fissured aquifers of reduced hydraulic conductivity and yield (Almeida et al., 2000). The river's spring blooms out in the province of Zamora (Spain) while the main water course flows through the Sierra of Montesinho located in the northeast of Portugal, before debouching into the Douro River.

The Portuguese sector of Sabor River basin drains an area of approximately 2742 km^2 (Gaspar et al., 2016). Topography is contrasting among lowland valley plains of dendritic arrangement and craggy reliefs from the watershed boundary and neighboring hillsides. Altitudes in the basin vary between 110 and 1465 m.a.s.l., while the average hillside slope is 14.1% (Fig. 1b). Geology is characterized by Paleozoic metassediments (e.g. phyllites, quartzites, greywackes) that enclose the so-called Morais massif mostly composed of ophiolitic rocks such as amphibolites, serpentinites and flaser-gabbros (Quesada, 1992; Ribeiro et al., 1990). The area was tectonically active during the Alpine Orogeny, when important fragile large-scale tectonic structures were defined with NNE-SSW orientation. These and other ductile WNW-ESE structures control morphology and landscape in the region, besides contributing to secondary permeability of the rocks where the fissured aquifers developed controlling regional groundwater flow (Pacheco, 2015). Climate is characterized by alternating wet (October-May) and dry (May-September) periods, with a maximum water surplus in February and deficit in August (Pacheco and Van der Weijden, 2002). On average, annual precipitation and temperature are $P \approx 720$ mm and $T \approx 12\,^{\circ}C$, whereas evapotranspiration is $ET \approx 420\ mm \cdot yr^{-1}$ (58% of P). The differences in elevation help explain the rainfall range of 480 $mm \cdot yr^{-1}$ in the lowlands and 1360 $mm \cdot yr^{-1}$ in the highlands (http://snirh.apambiente.pt/). Natural recharge of aquifer systems occurs through rainfall or lake water infiltration across the saprolite layer of local leptosols and the underlying fracture network. Groundwater accumulates in the saprolite and the fissured aquifer and flows through