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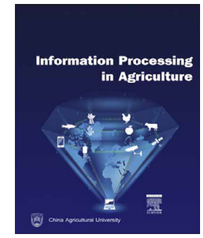

Assessment of groundwater contamination risk in an agricultural area in north Italy

Georgios Bartzas [a], *Federico Tinivella* [b], *Luca Medini* [c], *Dimitra Zaharaki* [d], *Kostas Komnitsas* [d,*]

[a] *National Technical University of Athens, School of Mining and Metallurgical Engineering, 15780 Athens, Greece*
[b] *Centro di Sperimentazione e Assistenza Agricola, Regione Rollo 98, 17031 Albenga (SV), Italy*
[c] *LABCAM s.r.l., Regione Rollo 98, 17031 Albenga (SV), Italy*
[d] *Technical University Crete, School of Mineral Resources Engineering, 73100 Chania, Greece*

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In the present study a specific approach is followed, considering the Pesticide DRASTIC and Susceptibility index (SI) methods and a GIS framework, to assess groundwater vulnerability in the agricultural area of Albenga, in north Italy. The results indicate "high" to "very high" vulnerability to groundwater contamination along the coastline and the middle part of the Albenga plain, for almost 49% and 56% of the total study area for Pesticide DRASTIC and SI methods, respectively. These sensitive regions depict characteristics such as shallow depth to groundwater, extensive deposits of alluvial silty clays, flat topography and intensive agricultural activities. The distribution of nitrates concentration in groundwater in the study area is slightly better correlated with the SI (0.728) compared to Pesticide DRASTIC (0.693), thus indicating that both methods are characterized by quite good accuracy. Sensitivity analysis was also performed to acknowledge statistical uncertainty in the estimation of each parameter used, assess its impact and thus identify the most critical parameters that require further investigation in the future. Depth to water is the parameter that exhibited the largest impact on the Pesticide DRASTIC vulnerability index followed by the impact of the vadose zone and topography. On the other hand, the SI method is more sensitive to the removal of the topography parameter followed by the aquifer media and the depth to water parameters.

1. Introduction

Contamination of groundwater in agricultural areas has become today a global concern and limits its availability as a resource for crop irrigation. The presence of several organic and inorganic contaminants in groundwater used for irrigation may cause several health problems to humans and result in loss of soil fertility and income for farmers. The impacts of groundwater contamination are more noticeable in areas suffering from desertification, salinization or when groundwater is not sufficient to support intense agricultural activities [1].

Nitrates and pesticides are the most common non-point source contaminants detected in shallow alluvial aquifers in agricultural areas. Alluvial aquifers are especially vulnerable to nitrate contamination and salinity problems due to a number of factors including shallow water table, highly permeable

* Corresponding author. Tel.: +30 28210 37686; fax: +30 28210 69554.
E-mail addresses: gbartzas@metal.ntua.gr (G. Bartzas), komni@mred.tuc.gr (K. Komnitsas).
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alluvial deposits, interconnections between surface water and agricultural related land uses usually carried out on floodplain terraces along river banks, and sea water intrusion due to over-pumping of groundwater for irrigation [2,3].

The assessment of groundwater vulnerability offers a low cost alternative to traditional groundwater quality plans and can be used to evaluate changes of risk over time, caused either from changes in land uses or because contaminants such as nitrates have migrated via preferential hydraulic flow pathways. The vulnerability of groundwater needs to be assessed as it is not only a function of the intrinsic properties of groundwater flow system (hydraulic conductivity, porosity), but also of the proximity of contaminant sources and their particular characteristics (location, chemical interaction with surface water) that could potentially increase the load of specific contaminants to aquifer systems.

However, the estimation of groundwater vulnerability is a complex procedure and depends on the temporal and spatial variability of contamination sources [4,5]. Several approaches involving the use of deterministic or stochastic methods can be used to assess soil and predict groundwater contamination in industrial and agricultural areas. Factors such as soil type, pollution load, depth of aquifer, mobility and fate of contaminants should be always taken into consideration [6–9].

During the past decades, several methods for assessing groundwater vulnerability using different evaluation factors and approaches have been developed, including GOD [10], SINTACS [11], AVI [12] and the PI method [13]. Apart from all these methods, the DRASTIC method, developed by the US Environmental Protection Agency (US EPA), remains one of the most frequently used approaches to assess vulnerability to groundwater contamination in porous aquifers [14,15]. DRASTIC uses seven parameters, namely Depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity as weighted layers to enable a reliable assessment of vulnerability [16–18].

Recent studies have revealed that land use is also a key issue that has to be taken into account when predicting potential future hydrological responses and the effect of anthropogenic activities on groundwater quality [19,20]. Within this context, the Susceptibility index (SI), developed by Ribeiro [21], is a contemporary adaptation of the Drastic method and has also been applied in this study to assess the effect of the land use on groundwater vulnerability in an agricultural coastal plain where adverse land use changes are common [22]. The Sustainability index enables an in-depth and comprehensive analysis pertinent to the impacts of continuous urban development against the shortage of land resources for agricultural purposes.

Pesticide DRASTIC and SI methods may be combined with GIS technology and remote sensing to develop an integrated approach, especially for heterogeneous media, that considers geological, hydrological and geochemical data to improve the reliability of risk estimation [23–25]. The major advantage of GIS-based groundwater vulnerability mapping is the use of data layers and the consideration of spatial variability of the parameters used for risk estimation [26,27]. The resulting vulnerability maps can be easily used by local authorities, decision- and policy makers for designing groundwater protection and remediation strategies [28].

The objective of this paper is to estimate groundwater vulnerability to contamination in the agricultural area of Albenga, in north Italy, using two appropriate methods (Pesticide DRASTIC and SI) suitable for shallow alluvial aquifer systems and determine risk levels based on calculated GIS-based vulnerability indices. Special emphasis is given on testing the reliability of the approach followed, in order to delineate the most vulnerable areas in the proximity of the defined Vulnerable Zone in terms of nitrate contamination. Furthermore, sensitivity and statistical analyses were conducted to evaluate, compare and validate the obtained results in terms of subjectivity, degree of parameter independence and variation effect.

2. Study area description

2.1. Location and climate

The study site is an experimental farm with coordinates 44°04′05.54″N and 8°12′45.51″E that belongs to the Centre for Agricultural Experimentation and Assistance (CERSAA), in Italy (Fig. 1). It is located about 1.5 km north from Albenga, a town at the Ligurian coastal region in the province of Savona, belonging to the geographical zone of Ligurian Alps in the north Italy. The municipality of Albenga has a territory of 36.50 km^2, 24,200 inhabitants (in 2013) and a high density of population (663 inh/km^2). The size of the area selected for risk analysis is 59 km^2, extends from Albenga to Ceriale and is characterized by a steep sandy coastal zone with numerous human settlements, intensive agricultural activities and low forest cover.

The climate of the study area is typical Mediterranean, with mean summer temperature ranging between 16.9 and 21.2 °C, and mean winter temperature between 8.8 and 9.9 °C [29]. The mean annual temperature over a 20 year period (1991–2010) is 15.4 °C. The annual precipitation for the same period ranges from 280 to 1150 mm with its mean value being 664 mm/year. Three quarters of the precipitation falls between May and October. The mean precipitation for summer is less than 28.4 mm (June–August), and increases to 85.8 mm during winter. Sudden showers occur very often in autumn causing flood events. The most recent floods (November 1994 and October/November 2000) have caused great damages to settlements, particularly in the town centre of Albenga.

The Albenga coastal plain is a characteristic example of shallow alluvial aquifer chronically affected by nitrate pollution from agricultural activities. In the last decades, the general trend towards more intensive and industrialized agriculture has led to the exploitation of almost the entire Albenga plain and the subsequent abandonment of traditional agricultural management practices. In addition, land-use changes due to the growing demand for urbanization and the pressure for touristic development, together with regional policies such as inadequate groundwater monitoring planning and inaccurate spatial establishment of the boundaries of nitrate vulnerable zones without a full and continuously updated evaluation of the related impacts, have resulted in gradual environmental degradation of this important natural ecosystem. Today, the Albenga coastal plain lacks a