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Editorial

Geo-Environmental Approaches for the Analysis and Assessment of Groundwater Resources at the Catchment Scale

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Groundwater resources constitute nearly one-third of the globe's freshwater resources. They are widely used in national economies for various key purposes, including domestic water supply, industrial uses, irrigation, medicinal uses (balneotherapy), and energy applications (low- and high-enthalpy geothermal energy). Moreover, they often form the only supply to dependent ecosystems and give rise to spectacular underground karstic formations (lagoons, river canyons, etc.). In addition, they provide the necessary mechanical strength to lose formations that host phreatic aquifers, thus preventing matrix compaction and subsidence at the ground surface that causes devastating deformations and extensive damage to infrastructures. Hence, groundwater's quantitative sufficiency and high quality are paramount to secure environmental sustainability and socio-economic prosperity. Nevertheless, groundwater systems are subject to various factors that are adverse to or deteriorate their inherent characteristics. Such factors could be geogenic or anthropogenic; geogenic factors are mainly related to natural water–rock interaction processes, whereas anthropogenic factors are primarily associated with agricultural practices, industrial activities, urbanisation, landfills, domestic effluents, and aquifer overexploitation.

Another critical aspect of groundwater management is that the proper management of groundwater is difficult after contamination. On the other hand, environmental monitoring projects that provide critical ground-truth values for groundwater quality are not always feasible due to a lack of personnel, funding, and time. In this respect, scientists and decision makers seek alternative strategic tools to spatially identify threats and subsequently design and implement groundwater protection measures towards practicing sustainable groundwater management. These tools are often diverse but interlinked methodologies, such as hydrogeological and hydrogeochemical modelling, environmental isotopes, environmental indicators, geostatistics, and artificial intelligence.

The complexity of different hydrological and hydrogeological setups, hydrodynamic patterns, site specifications, and the wide variability of internal and external factors and/or processes at the level of catchment scale necessitates combined approaches that integrate robust methods, thus leading to more accurate and reliable outcomes towards sustainable groundwater management. Sound knowledge of a studied groundwater system may reduce uncertainties in the prediction of its future evolution, thus enabling better management and protection whilst limiting the need to hypothesise. In line with the above goal, this Special Issue aims to provide successful applications or new insights on the standalone or joint considerations of groundwater resources assessment and characterisation methods and explore new state-of-the-art methodological concepts in light of a rapidly changing environment.

This Special Issue of the journal *Water* comprises 12 papers with contributions of more than 50 authors originating from 10 countries, all of which deal with various geo-environmental methods and tools. The papers include six feature papers and four editor's choice papers.

Two of these papers apply hydrogeochemical tools and methods to robustly evaluate groundwater resources quality and hydrodynamic regime. Specifically, Vrouhakis et al. [1]

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used combined hydrogeochemical and hydrodynamic characterisation to assess key aspects related to groundwater resources management in a highly productive agricultural basin of central Greece. A complementary array of tools and methods, including graphical processing, multivariate statistics, and environmental isotopes, was applied to a comprehensive dataset of physicochemical analyses and water level measurements. The outcomes proved valuable in the progression towards sustainable management of groundwater resources. The results provide spatial and temporal insights into significant parameters, sources, and processes that, as a methodological approach, could be adopted in similar cases of other catchments. Vasileiou et al. [2] investigated the hydrogeochemical processes and natural background levels (NBLs) of chromium in the ultramafic environment of Vermio Mountain, Western Macedonia, Greece. The holistic methodology proposed in this paper may be implemented in similar cases at the catchment scale to assess geogenic and anthropogenic Cr sources that degrade groundwater quality.

Falling within the broad category of groundwater quality, two papers deal with the significant problem of groundwater salinisation, which is crucial to address in arid and semi-arid coastal areas. More specifically, Bonamico et al. [3] applied an integrated hydrogeologic and geochemical methods approach to describe freshwater–saltwater interactions in a coastal aquifer in the Ostia Antica archaeological park Roma, Italy. Their assessments were based on a water monitoring program that included the installation of multiparametric probes in wells, with continuous measurement of temperature, electrical conductivity, and water table level. Field surveys, water sampling, major elements, and bromide analyses were carried out to understand the detailed stratigraphic settings of the area. The authors used oxygen and carbon isotopic signatures of calcite from well sediments and evaluated major elements and Br to determine the salinisation sources and the processes of gas–water-rock interaction. The second paper focuses on assessing the drought index as an indicator of groundwater salinisation. The research by Alfio et al. [4] was performed on the Salento aquifer (southern Italy), where in recent decades, groundwater depletion and salinisation worsened because of the increased frequency of droughts, as revealed by the documented data derived from the analysis of the Standardised Precipitation Index (SPI) calculations during 1949–2011 based on monthly precipitation levels. Groundwater level series and chloride concentrations collected over the extreme drought period 1989–1990 allowed a qualitative assessment of groundwater behaviour, highlighting the concurrent groundwater drought and salinisation.

Two other papers deal with the conceptualisation and application of index and overlay methods to assess groundwater vulnerability, considered a significant, proactive measure towards successful decision making and rationale management. Kim et al. [5] evaluated the vulnerability to seawater intrusion by classifying the existing GALDIT method into static parameters (groundwater occurrence (G), aquifer hydraulic conductivity (A), and distance from shore (D)) and dynamic parameters (height-to-groundwater level above sea level (L), impact of existing status of seawater intrusion (I), and aquifer thickness (T)). Data indicating averages of measurements over a 10-year period for each month were used, representing the seasonal characteristics of local water cycles. To reflect subtle monthly variations, the range of scores was divided into deciles to capture the temporal dynamics of seawater intrusion. The proposed modified method can determine where to apply countermeasures to vulnerable coastal areas and develop water resources management plans considering vulnerable seasons. Vrouhakis et al. [6] assessed the intrinsic perspective of groundwater vulnerability in central Greece's highly productive agricultural area. A novel index-based method (RIVA) was applied to the Tirnavos basin to assess susceptibility to surface-released contamination. Data from field surveys, previous studies, and the relevant literature were used to calculate factors constituting the RIVA method, which was demonstrated to be a data-intensive and efficient method, thus a sound investment to reach highly accurate results. Overall, RIVA proved to be a robust tool for reliable groundwater vulnerability assessments and could be further exploited for risk assessment and decision-making processes in the context of groundwater resource management.

Fuentes-Arreazola et al. [7] estimated aquifer parameters in the Mexican wine-producing region Guadelupe Valley from fluctuations in levels of groundwater. They proposed an alternative tool with significant advantages in studying the groundwater-level response due to variations in pore pressure caused by internal deformation of the aquifer structure induced by barometric pressure and solid Earth tide. This analysis reveals helpful insights that can help to establish a framework to design and assess management strategies for groundwater resources in similar cases.

Two other papers provided insights into the application of modelling in groundwater resources. Lyra et al. [8] presented an integrated modelling system to evaluate the availability of water resources in coastal agricultural watersheds. Their modelling system was made from an ensemble of surface and groundwater hydrology models, crop growth/nitrate leaching, contaminant transport, and seawater models. Its efficacy to simulate the quantity and quality of water resources was tested at the Almyros basin in Thessaly, Greece. The proposed modelling system could be used as a tool for the simulation of water resources management and climate change scenarios. Further research on the plausibility of modelled nitrate concentrations in the leachate on the scale of federal states in Germany was performed by Wolters et al. [9]. This research aimed to model nitrate concentrations in leachates as a robust tool for water resources management, in line with the requirements enforced by the EU Water Framework Directive. The validity of simulations was checked against values from 1119 preselected monitoring stations from shallow springs and aquifers filtered near the surface with oxidising properties. The case study revealed that the applied model system (RAUMIS–mGROWA–DENUZ) can reliably represent interrelationships and influencing factors that determine simulated nitrate concentrations in the leachate. Moreover, it was demonstrated that observed nitrate concentrations in groundwater may provide a solid source of data for checking the plausibility of modelled nitrate concentrations in leachate in cases in which certain preselection criteria are applied.

Pisinaras et al. [10] studied the effects of agricultural water management in a Mediterranean coastal aquifer under current and projected climate change conditions. Their research focused on the coastal delta plain of River Pinios, central Greece. Such areas are significant for the Mediterranean region because of their high soil fertility and agricultural productivity. Nevertheless, they also constitute fragile systems in terms of water resource management due to the interaction of underlying aquifers with the sea. Soil and Water Assessment Tool (SWAT) and SEAWAT models were combined to simulate the impact of current practices in water resource management on the main groundwater budget components and groundwater salinisation of the shallow aquifer developed in the area. Moreover, the potential impact of climate change was investigated using projected data gathered from the Regional Climate Model for two periods (2021–2050 and 2071–2100) and two sea-level rise scenarios (increasing by 0.5 and 1 m).

The combined impact of the hydrological and socio-economic perspectives on the sustainability of groundwater resources was examined by Oke and Alowo [11]. Their research presented a spatial interpolation of the anticipated impact of the above factors on groundwater systems and predicted the sustainability of the Modder River catchment in South Africa. The results were presented with sustainability maps indicating areas with differing groundwater dynamics in the catchment. The key finding in this paper may assist groundwater managers and regulators to effectively plan groundwater resources utilisation, especially with regard to the prevention of licencing and overpumping practices.

Finally, a relatively new and challenging field of joint tools for hydrological sciences was addressed by Namous et al. [12]. Their research focused on the spatial prediction of groundwater potentiality in a large semi-arid karstic mountainous region by using a combination of machine learning models, such as random forest (RF), logistic regression (LR), decision tree (DT), and artificial neural networks (ANNs). A total of 24 groundwater influencing factors (GIFs) were selected based on a multicollinearity test and the information gain calculation. The results of the groundwater potentiality mapping were validated using statistical measures and the receiver operating characteristic curve (ROC) method.

Compared with individual models, the combined models proved the most stable and suitable tools to map groundwater potentiality in mountainous aquifers, based on success and prediction rate.

The sustainability and environmental welfare of human civilization are based on utilising sufficient volumes of water with acceptable quality. As the impacts of climate change intensify, water resources safety becomes of primary concern. Groundwater resources impose extra challenges regarding their management, as these sources are invisible, thus needing proactive and carefully designed measures. World Water Day for the year 2022 is devoted to making the invisible, visible. This Special Issue provides a series of papers that propose state-of-the-art methodologies, technologies, and approaches that exactly contribute to this goal.

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