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Editorial

Groundwater Pollution: Sources, Mechanisms, and Prevention

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Groundwater resources are vital for ecosystems and human health and prosperity. Groundwater pollution continues to increase, further limiting the potential of groundwater resources for use. The sources of contaminants can be natural (e.g., salinity or arsenic) or anthropogenic (excess fertilizers, pesticides, industrial chemicals, sewage effluent). Groundwater pollution may emerge from point sources (which can be easily identified spatially) and nonpoint sources, which are more difficult to identify, measure, and control than the former. To deal with this phenomenon, the sources of pollution and the mechanisms of the fate and transport of pollutants in groundwater must be identified. This process is important because it forms the basis for formulating appropriate prevention and mitigation measures. The latter is preferable for any remediation effort, as adverse effects on the environment and the health of living organisms will be prevented. However, since groundwater contamination is less obvious than surface water pollution, it frequently goes unnoticed. In this case, a remediation strategy must be utilized.

For groundwater protection and restoration, scientists and engineers worldwide are continuously studying related phenomena, proposing many solutions for understanding and managing groundwater. The evolution of technology has boosted this effort in recent years with the rise of many contemporary tools such as simulation models, remote sensing, monitoring instruments, etc.

This Special Issue, entitled "Groundwater Pollution: Sources, Mechanisms, and Prevention", contains publications from around the world that present new research contributions in the area of groundwater contamination, focusing on (i) the sources, effects, and exposure of natural and artificial groundwater pollutants, hydrological processes, and the hydrochemical properties of groundwater; (ii) the intrinsic and specific vulnerability of groundwater to pollution; (iii) human health risk assessments; (iv) the recent trends in pollution management, mitigation, prevention, and remediation strategies.

The eleven manuscripts published in this Special Issue (two focusing on sites in Africa, two in America, two in Asia, four in Europe, and one theoretical) cover a variety of modern applications for different problems to be mitigated and different scales of analysis/intervention. Specifically, five papers deal with monitoring [1–5], five papers with simulation and/or optimization [6–10] and one paper [11] deals with remote sensing.

An overview of the articles in this Special Issue is presented (References).

Breall et al. [1] analyzed the quality and the potential noncarcinogenic health risks related to nitrate in groundwater in the El Milia plain, Kebir Rhumel Basin, Algeria. Moran's I and the ordinary kriging (OK) interpolation technique were used to examine the spatial distribution pattern of the hydrochemical parameters in the groundwater. The hydrochemical parameters Ca, Cl, and HCO_3 showed a strong spatial autocorrelation in the El Milia plain, indicating the spatial dependence and clustering of these parameters in the groundwater. The groundwater quality was evaluated using the entropy water quality index (EWQI). The results showed that approximately 86% of the total groundwater samples in the study area fell within the moderate groundwater quality category. The potential noncarcinogenic health risks for adults and children associated with nitrate contamination of groundwater through the drinking water pathway were assessed using the hazard

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quotient (HQ). The results revealed that approximately 5.7% of the total groundwater samples exceeded the HQ limit for adults, indicating potential health risks. Moreover, a higher percentage, 14.28%, of the total groundwater samples exceeded the HQ limit for children, highlighting their increased vulnerability to noncarcinogenic health hazards associated with nitrate contamination in the study area.

Ismail et al. [2] evaluated the groundwater potentiality and its suitability for various uses in a region of Middle Egypt using hydrochemistry and electrical resistivity studies. The groundwater potential in the study area was evaluated based on 24 VESs (vertical electrical soundings), and its quality was determined based on the analyses of 57 groundwater samples. The EC (salinity index), Na% (salt hazard), SAR (ratio of sodium adsorption), chloride risks, SSP (soluble sodium percentage), MH (magnesium hazard), and other indicators were used to determine whether the collected water samples were suitable for irrigation. Four layers in the study area were mentioned in the geoelectrical cross-sections that have been constructed. Most of the groundwater samples that were collected were safe for drinking; however, none of them were fit for home usage because of their extreme hardness. According to the SAR and US diagram, RSC, KR, and PI, most groundwater samples from the Pleistocene and Eocene aquifers were fit for irrigation.

In Zohud et al.'s paper [3], the quality of the groundwater resources in the West Bank region in Palestine was evaluated using the water quality index (WQI) and human health risk (HHR) assessment. In the West Bank, groundwater is particularly valuable because of its scarcity and inaccessibility, and due to the nature of the area's aquifers, is currently regarded as being at a high risk of pollution. The water quality in this area is also of wide concern, with its effects being directly linked to human health. Certain parts of the West Bank groundwater suffer from high concentrations of nitrate and potassium. In total, 38.8% of the nitrate and 10% of the potassium concentrations in the well samples exceeded the permissible limit set by the WHO and PSI, and, therefore, health problems may arise as a limiting factor for life quality and welfare in this region. Moreover, 87.7% of the samples were classified as having very hard water. The WQI values showed that 78% of the well samples were of good quality. The health risk assessments were evaluated for fluoride and nitrate in drinking water for adults, children, and infants. The main values of the estimated Total Hazard Index (THI) obtained from the analyzed data on the health risk assessments revealed a diverse effect on the local population based on age. The ranges of the THI in all the sampling locations varied considerably and extended from 0.093 to 3.01 for adults, 0.29 to 3.08 for children, and 0.302 to 3.21 for infants. These results largely indicate that infants are more exposed to health risks.

Kovač et al. [4] proposed an analysis of the distance between the measured and assumed location of a point source of pollution in groundwater as a function of the variance of the estimation error. The research took place in the north of the Republic of Croatia and included the area of the Varaždin wellfield, which was closed due to an excessively high groundwater nitrate concentration. Seven different interpolation methods were used to create spatial distribution models. Each method provided a different model, a different variance of the estimation error, and estimates of the location of the pollution source. The results showed a nonlinear and monotonic relationship between the distance and the variance of the estimation error, so logarithmic and rational quadratic models were fitted to the scatter point data. The models were linearized, a t-test was performed, and the results showed that the models can be considered reliable, which was confirmed by the values of the coefficients of determination of the linearized models. The obtained results can be used in planning additional research to determine the measured location of the pollution source. The research methodology used is universal and can be applied to other locations where high concentrations of certain contaminants have been detected in groundwater in alluvial aquifers.

Correa-González et al. [5] proposed a methodology to assess nitrate in groundwater from diffuse sources considering the spatiotemporal patterns of hydrological systems using a coupled SWAT/MODFLOW/MT3DMS model. The application of the model was carried out using a simplified simulation scheme of hydrological and agricultural systems because of the limited spatial and temporal data. The study area included the Cuitzeo Lake basin in the superficial flow form and the Morelia–Querendaro aquifer in the groundwater flow form. The results within the methodology included the surface runoff, groundwater levels, and nitrate concentrations and indicated that the historical and simulated nitrate concentrations were obtained within acceptable values of the statistical parameters and, therefore, were considered adequate.

Siarkos et al. [6] presented an integrated framework to assess the environmental and economic impact of fertilizer restrictions in a nitrate-contaminated aquifer located in the southwestern part of the Chalkidiki peninsula, Northern Greece. For this task, various scenarios involving reductions (10%, 20%, 30%, 40%, and 50%) in fertilizer application were investigated, evaluated, and ranked to determine the most suitable option. The environmental assessment considered the occurrences of nitrates in the groundwater, with a specific emphasis on the nitrate concentrations in the water supply wells, as obtained by a nitrate fate and transport model, while the economic analysis focused on the losses experienced by farmers due to reduced fertilizer usage. The results showed that a 30% reduction in fertilization was the most appropriate option for the area being studied, highlighting the importance of adopting such an approach when confronted with conflicting outcomes among alternatives.

The study by Lyra et al. [7] examined the impacts of climate change and sea level rise on coastal aquifers, focusing on the influence of the components of the water cycle on seawater intrusion, and the evolution of this phenomenon in the future. The simulation of coastal water resources was performed using an integrated modeling system (IMS), designed for agricultural coastal watersheds, which consisted of inter-connected models of surface hydrology (UTHBAL), groundwater hydrology (MODFLOW), and seawater intrusion (SEAWAT). Climatic models for the adverse impact scenario (RCP8.5) and the medium impact scenario (RCP4.5) of climate change were used. The transient boundary head conditions were set to the coastal boundary to dynamically represent the rise in the sea level due to climate change. The response of the groundwater in the coastal Almyros Basin, located in central Greece, was simulated from 1991 to 2100. The findings indicated that seawater intrusion will be advanced in the future, in both climate change scenarios. The models show varying patterns of groundwater recharge, with varying uncertainty projected for the future, and sensitivity to time in the fluctuation of the components of the water cycle.

Perdikaki et al. [8] investigated the mechanism of seawater intrusion and the performance of free and open-source codes for the simulation of variable density flow problems in coastal aquifers. For this purpose, the research focused on the Marathon Watershed, located in the northeastern tip of Attica, Greece. For the simulation of the groundwater system, MODFLOW, MT3DMS, and SEAWAT codes were implemented, while sensitivity analysis and calibration processes were carried out with UCODE. Hydraulic head calibration was performed on the MODFLOW model, and the TDS concentration is validated in the SEAWAT model. The calibrated parameters of the MODFLOW model were obtained for the variable density flow simulation with SEAWAT. The MODFLOW and SEAWAT hydraulic head outputs were analyzed and compared to one another. The outcome of this analysis showed that SEAWAT produces slightly better results in terms of the hydraulic heads, and the authors concluded that parameter transferability can take place between the two models. For the seawater intrusion assessment, the use of the SEAWAT code revealed that the aquifer is subjected to passive and passive–active seawater intrusion during the wet and dry seasons, respectively. Finally, an irregularly shaped saltwater wedge was developed at a specific area, associated with the hydraulic parameters of the aquifer.

Kontos [9] investigated the optimal remediation process in an aquifer using Modflow 6 software and genetic algorithms. A theoretical confined aquifer was polluted over a long period of time by unnoticed leakage from a pipeline conveying leachate from an adjacent landfill to a wastewater treatment plant. When the extended leakage and groundwater pollution were discovered, the optimal planning of the remediation strategy was investigated using the pump-and-treat method and/or hydrodynamic control of the pollution. The practical goal was to find the optimal locations and flow rates of two additional pumping wells, which would pump the polluted water and/or control pollution, protecting an existing drinking water pumping well, securing its full operation even during the remediation process with the minimum possible cost, simply represented by the pumped water volume of the additional wells. The remediation process was considered complete when the maximum concentration in the aquifer dropped below a certain limit. The Modflow software (handled by the Flopy Python package: Version 4) simulated the flow field and advective–dispersive mass transport, and a genetic algorithm was used as the optimization tool. The coupled simulation–optimization model, Modflow-GA, complemented by a sophisticated post-processing results analysis, provided optimal and alternate sub-optimal remediation strategies for the decision-makers to select from.

The study by Ibn Salam et al. [10] aimed to elucidate an aquifer's contaminant transport mechanisms by determining longitudinal and transverse dispersivities through inverse modeling. The aquifer being studies was in the municipal wellfield in Collierville, Tennessee, and it was contaminated with trichloroethylene (TCE) and hexavalent chromium (Cr (VI)) due to industrial operations dating back to the 1970s and 1980s. Utilizing MT3DMS for contaminant transport simulation, based on a well-calibrated groundwater flow model, and leveraging Python's multiprocessing library for efficiency, the study employed a trial-and-error methodology. The key findings revealed that the longitudinal dispersivity values ranged from 5.5 m near the source to 20.5 m further away, with horizontal and vertical transverse dispersivities between 0.28 m and 3.88 m and 0.03 m and 0.08 m, respectively. These insights into the aquifer's dispersivity coefficients, which reflect the scale-dependent nature of the longitudinal dispersivity, will be crucial for optimizing remediation strategies and achieving cleanup goals. This study underscored the importance of accurate parameter estimation in contaminant transport modeling and contributed to a better understanding of contaminant dynamics in the Collierville wellfield.

EL-Bana et al. [11] proposed an integrated remote sensing and GIS-based technique for mapping groundwater recharge zones. To identify groundwater potential zones, the study was conducted in Central Saudi Arabia, southwest of Riyadh. The analysis employed a multi-criteria approach that relied on remote sensing and geographic information systems. The variables employed in this technique included geology, rainfall, elevation, slope, aspect, hillshade, drainage density, lineaments density, and land use/land cover (LULC). The Analytical Hierarchical Process (AHP) was used for assigning weights to the parameters, and the corresponding significance of each parameter's several classes for groundwater potentiality. Different groundwater potential zones were identified by the study: very high (16.8%), high (30%), medium (26.7%), low (18.6%), and very low (7.9%). Only two of the observation wells were located in the "medium" potential zone, but the other ten wells were observed in the "very high" and "high" potential zones, according to the validation survey. Consequently, the results may demonstrate that the approach used, which combined improved conceptualization with AHP to define and map groundwater potential zones, has a greater chance of producing accurate results and can be used to reduce the threat of drought in broader arid regions.A plethora of focused and contemporary knowledge on groundwater pollution is presented in this Special Issue. The papers published herein contribute significantly to the advancement of groundwater pollution research at three levels: sources, mechanisms, and prevention. They promote the combination of widely used methodologies, such as remote sensing, and the use of indicators to optimally assess the status of an aquifer and find the sources of pollution. The creation of groundwater simulations with appropriate software and new methodologies in the context of integrated management will help scientists better understand the mechanisms of groundwater pollution. Finally, through the proposal of innovative strategies and contemporary practices such as genetic algorithms, not only is optimal prevention aimed for but also the remediation of groundwater pollution. One of the most important reasons why this Special Issue was created was so that the research within it gained as much visibility as possible. We hope that all the proposed methodologies and research on groundwater pollution presented in this Special Issue will be reflected in operational strategies and projects by decision-makers and stakeholders, ensuring groundwater protection and restoration.

Conflicts of Interest: The author declare no conflict of interest.

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