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Editorial

Groundwater Resources Management: Reconciling Demand, High Quality Resources and Sustainability

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1. Introduction

The prospect of the global population reaching 9 billion by 2050, in addition to growing urbanisation, intensive irrigated agriculture and climate change, will add extra pressures on water resources and the environment. The global demand for water has grown approximately six-fold in the last century [1]. Continued population growth and climate change in the 21st century will have a severe impact on global water resources [2]. Water scarcity occurs in many countries, particularly in Mediterranean, Middle Eastern, and African countries, and many of these countries are confronted with a crucial combination of a severe lack of and increasing demand for high-quality water. World water resources seem abundant; however, only 0.7% of this total amount is usable water. Serious water pollution problems put 20% of the world's population (approximately 1.1 billion people) at risk of water-related diseases. Competition for water that has been made scarce by intensive irrigation is already a major source of conflict in arid and semi-arid areas.

Aquifers, our planet's natural reservoirs, account for 97% of fresh liquid water. Globally, groundwater is the main source of domestic supply and irrigation; it is the most important water resource for more than half of the world's population and, consequently, it is a key resource supporting human well-being and socio-economic development [3]. Groundwater is characterized by high subtractability (one person's use subtracts from another person's use) and low excludability (it is difficult to exclude additional users) [4]. During the last few decades, there has been an enormous increase in borehole construction for the purposes of urban water supply, irrigation, and industrial processes. As a result, a widespread negative water balance has been established, which is highly problematic in the case of coastal aquifer systems which are at risk of salinification due to seawater intrusion.

Pressures on groundwater arise from pollution sources; this is a serious problem due to the use of chemicals in agriculture and due to increasing inflows of domestic and industrial wastewater into water bodies that are hydraulically connected with aquifers. Intensified fertilization has led to considerable groundwater quality deterioration, as evidenced by increased nitrate concentration.

The most over-exploited aquifers irrigate the most productive agricultural regions in the world, with additional negative effects in terms of food insecurity [5].

On the other hand, the coastal environment is now recognized as a crucial arena for future progress in terms of global sustainability. Approximately 70% of the population on Earth lives in coastal areas and many of these people depend on coastal aquifers for freshwater. Many islands face problems with water. The water demands of these islands have increased during the last few decades due to rapid urbanization, accelerated tourism-related development, agricultural activities, and a continuous increase in population since the 1970s. As a result, a negative water balance has been established in coastal aquifer systems, triggering sea water intrusion, which has negative consequences in the socioeconomic development of these areas. Many coastal aquifer systems are reported to be affected by quality deterioration due to seawater intrusion and irrational management [6].

In this framework, the challenge is reconciling demand satisfaction with quantity sustainability and durable quality of resources. The modernization of processes in order to manage the demand and distribution of groundwater resources is a specific target in this Special Issue. Action is needed to empower the local authorities, stakeholders, and institutions responsible for the sustainable management of groundwater and its protection against the most significant threats (overexploitation and quality degradation). In addition, greater effort is needed from governments, as well as hydrogeologists/ water scientists and society in general, in order to protect this crucial resource for planetary well-being and dignified human life [7].

This Special Issue includes thirteen (13) papers relevant to a variety of groundwater management issues: integrated modelling, assessment of climate change impacts on groundwater resources in terms of groundwater resource quantity and quality, artificial recharge, risk and vulnerability assessment methods, geophysical delineation of the freshwater–saline water interface, and statistical analysis of monitoring data.

The 13 papers in this Special Issue have been contributed by 69 scientists from 14 countries, located by the authors' place of work or study, across 4 continents, and hence offering a very large overview of the subject. These papers delineate four main themes concerning the groundwater management. The first theme concerns modelling efforts supporting the sustainable management of aquifer systems [8,9]. The second theme is focused on groundwater vulnerability assessments against external pollution, focusing on groundwater quality management [10–13]. The third theme explores the potentiality of geophysics tools supporting groundwater management in the case of coastal aquifers [14–16]. The fourth theme concerns problems associate with groundwater quantity [17–20]. Then, we provide a short description and discussion of this whole set of experiences from the authors' contribution to this Special Issue.

2. Integrated Modelling-Groundwater Management

Groundwater models can be classified into two main categories: (1) groundwater flow models (solve the distribution of head), and (2) solute transport models (solve the concentration of solute). A well-calibrated and verified model is a useful tool for prediction under different managerial scenarios.

As mentioned above, a feature of many countries is that their agricultural economy relies heavily on groundwater (agricultural groundwater economies), exploited through numerous private boreholes and wells. Many researchers warn of the possible collapse of such economies [21].

Lyra et al. [8] highlight the effects of agronomic and water resources management scenarios on groundwater balance, seawater intrusion, and nitrate pollution and the comparison of the developed scenarios relative to the current crop production and water management regime in the coastal agricultural Almyros basin in the Thessaly region, central Greece. This area is characterized by intensive agricultural activities and increased water needs for irrigation purposes. The analysis was conducted with the use of an Integrated Modelling System for agricultural coastal watersheds, which consists of coupled and interlinked simulation models of surface water hydrology (UTHBAL), reservoir operation (UTHRL), agronomic/nitrate leaching model (REPIC), and groundwater models for the simulation of groundwater flow (MODFLOW) and contaminant transport of nitrates (MT3DMS) and chlorides (SEAWAT). The pressure on water resources has been estimated with the Water Exploitation Index and the reservoirs' operation with the Reliability index to cover the water demands. Agronomic and water resource scenarios were simulated and analysed for a period of 28 years, from 1991 to 2018. This very complex and multi-methodological approach allows the authors to achieve useful results. It is verified that the best results for the sustainability of water resources are achieved under the deficit irrigation and rain-fed scenario, while the best results for water resources and the local economy are achieved under deficit irrigation and reduced fertilization scenario.

Lo et al. [9] discuss a relevant management experience dealing with the temporal and spatial evolution of groundwater levels under excess abstraction. They use a numerical model to draw up a groundwater management strategy for ensuring the sustainability of groundwater resources in the future. In addition, a series of numerical simulations were carried out to consider detailed hydrogeological data, artificial and natural discharges of deep wells, and boundary effects in Semarang City, Indonesia. It is pointed out that, since 1900, Semarang City has met its industrial water needs by pumping groundwater through urban aquifers. The trend toward exploiting groundwater resources has driven the number of deep wells and their production capacity to increase and, therefore, has led to the water table dropping from time to time, which has been marked as one of the primary causes of land subsidence. The groundwater modelling was calibrated under two flow conditions of the steady state from 1970 to 1990 and the transient state from 1990 to 2005 for six observation wells distributed in Semarang City. Four scenarios that reflect potential management strategies were developed, and then their effectiveness was systematically investigated. Based on the results of the simulation, the authors suggest that the implementation of proper groundwater control management and measures can restore the groundwater level in Semarang City which, in turn, will help to achieve better sustainability of groundwater resources and the mitigation of the land subsidence phenomena.

3. Vulnerability Assessment and Groundwater Quality

Groundwater is under pressure from many different human activities that affect its quality. The protection of groundwater resources is necessary for protecting human health, maintaining food supplies, and conserving ecosystems. The concept of vulnerability assumes that the environment can provide a protection degree of groundwater quality. Assessment of groundwater vulnerability to pollution is essential for adequate groundwater protection and management.

Lwimbo et al.'s [10] case study emphasizes the impacts of farmers' intensive use of agrochemicals (fertilizers and pesticides) on groundwater quality in the Kahe catchment, Tanzania. For this study, water samples were collected during the wet and dry seasons and analysed for the presence of agrochemicals in the water. Groundwater chemistry was dominated by magnesium-sodium-bicarbonate (Mg-Na-HCO_3). The cations levels were in the trend of $Mg^{2+} > Na^+ > Ca^{2+} > K^+$, whereas anions were $HCO_3^- > Cl^- > SO_4^{2-}$ for both seasons. The NO_3^- had an average value of about 18.40 ± 4.04 and 7.6 ± 1.7 mg/L in the wet and dry season, respectively. Elevated levels of nitrate, sulphate, phosphate, and ammonium were found in water samples collected near the large-scale sugarcane plantation which covers a relevant aquifer portion. For both seasons, Pb, Cd, Fe, Mn, Zn and Cu concentrations averaged approximately 0.08 ± 0.03, 0.11 ± 0.03, 0.16 ± 0.02, 0.11 ± 0.01, 0.46 ± 0.05, and 0.55 ± 0.02 mg/L, respectively. On the other hand, the concentrations were higher in shallow wells than in the deep boreholes. The pesticides' residues were negligeable in all sampled groundwater. The findings from this study provide important information for groundwater quality management in Kahe catchment, as a water management action plan and a set of measures, including monitoring (water quality, groundwater level, water abstractions, etc.) and an aquifer vulnerability assessment, were suggested for application in the protection of the groundwater quality.

The potentiality of quality analysis to support groundwater management was highlighted by Benett et al. [11]. They collect hydrochemical and hydrogeological data to study the high fluorite (F^-) groundwater concentration in an active volcano area of Tanzania. In addition, the authors analysed the impact of rainwater recharge on groundwater chemistry by monitoring spring discharges during water sampling. The results show that the main groundwater type in the study area is $NaHCO_3$ alkaline groundwater (average value of pH = 7.8). High F^- values were recorded in 175 groundwater samples; the concentrations ranged from 0.15 to 301 mg/L (21.89 mg/L as mean and 9.67 mg/L as median), with 91% of the samples containing F^- values above the WHO health-based guideline for drinking water (1.5 mg/L), whereas 39% of the samples have Na^+ concentrations above the WHO taste-based guideline of 200 mg/L. The temporal variability in F^- concentrations between different seasons is due to the impact of the local groundwater recharge. The authors recommend a detailed eco-hydrological study of the low-fluoride springs from the high-altitude recharge areas (on Mount Meru, inside the Arusha National Park). These springs are tapped for drinking purposes. An ecohydrological study is required for the management of these springs and their potential enhanced exploitation to ensure the sustainability of this water extraction practice. Another of the authors' suggestions for obtaining safe drinking water was to use a large-scale filtering system to remove F^- from the groundwater.

The complexity of the hydrostratigraphic framework could be a key feature to be clarified for groundwater management purposes, especially in the case of a coastal plane, as shown by Cianflone et al. [12]. They define the hydrostratigraphic framework and physicochemical status of the Gioia Tauro Plain, Tyrrhenian coast, southern Italy. The authors investigated the hydrostratigraphic framework of the area, identifying a deep aquifer (made by late Miocene succession), an aquitard (consisting of Pliocene clayey and silty deposits), and a shallow aquifer (including Late Pleistocene and Holocene marine and alluvial sediments) using subsoil data (boreholes and geophysics). The reconstruction showed that the structural geology controls the spatial pattern of the aquitard top and the shallow aquifer thickness. Furthermore, they have evaluated the hydraulic conductivity for the shallow aquifer modifying an empirical method, calibrated by slug tests, obtaining values ranging from 10^{-4} to 10^{-5} m/s with a maximum of 10^{-3} m/s located close to inland dune fields. The piezometric level of the shallow aquifer recorded a significant drop between the 1970s and 2021 (-35 m as the worst value). This is due to the effect of climate and soil use changes, the latter being the increased water demand for kiwi cultivation. Despite the overexploitation of the shallow aquifer, shallow groundwater is fresh (736 µS/cm as mean electrical conductivity) except for a narrow coastal area where the electrical conductivity is more than 1500 µS/cm, which can be due to seawater intrusion. What was more complex was the physicochemical status of the deep aquifer, characterized by groundwater high temperature (up to 25.8 °C) and electrical conductivity up to 10,520 µS/cm along the northern and southern plain boundaries, marked by tectonic structures. This issue suggested a dominant role of the local fault system that is likely affecting the deep groundwater flow and its chemical evolution. Finally, Cianflone et al.'s analysis shows the important relationship between the tectonic structure and the hydrogeological regime of the area.

Mustafa El Badba et al. [13] present the results of groundwater vulnerability and nitrate contamination assessment using DRASTIC and geostatistical analysis in the Gaza Strip. This area is characterized by a diachronic water shortage; the local coastal aquifer is the only freshwater source but is increasingly depleted and polluted, especially by nitrate. The assessment of the aquifer vulnerability to contamination is derived by applying the DRASTIC procedure, firstly with original default weights and ratings and, secondly, improved by estimating rating values by multiple linear regression of observed log-transformed nitrate concentration in groundwater, with DRASTIC factors extended to land-use. The results are very different because high- and low-vulnerability areas shift considerably. Subsequently, a geostatistical analysis of the spatial distribution of the nitrate concentration is performed, firstly by ordinary kriging interpolation of the observed nitrate concentration and secondly by regression kriging using DRASTIC factors and land use as indicators of the spatial variation in nitrate occurrence. These maps differ because the map obtained by regression kriging interpolation shows much more detail in terms of environmental factors such as dunes, ridges, soil types, and built-up areas that affect the presence of nitrate in groundwater. The authors suggest that the results of this study can be used by the Palestinian authorities concerned with sustainable groundwater management in the Gaza Strip. Finally, the paper shows that the availability of valid and high-quality data is necessary for groundwater quality management purposes, in addition to highlighting the need to find the optimal solutions from the application of vulnerability assessment methods.

4. Geophysical Support to the Management of Coastal Aquifers

The practice of monitoring groundwater quality is a key issue for optimal groundwater management. In the case of coastal aquifers, if necessary, periodic target checks and modifications of management criteria and rules should be realized, focusing on groundwater salinity spatial and temporal variations. Indirect survey methods are primarily based on geophysical techniques. These techniques permit surveys of wide surfaces with a high density of measurements reason for which the scientific research on these methods and applications has been ongoing for decades [6].

The use in coastal aquifers of geophysical resistivity methods, i.e., electrical resistivity tomography and continuous resistivity profiling, is often very effective to investigate the salt–freshwater distribution, but it can be difficult to interpret quantitatively [14]. This is the case for coastal plains where the high spatial variability of grain size ranges from clay to sand, as is common worldwide. This situation creates relevant difficulties for the accurate geophysical interpretation needed to assess the variation of fresh submarine groundwater discharge, as experienced on Belgium's west coast [14]. Paepen et al. investigated Belgium's west coast with resistivity methods and image appraisal tools to quantitatively interpret inversion models. Synthetic resistivity models, which reflect the existing situation on Belgium's west coast, are first created and assessed quantitatively by means of the model resolution matrix, cumulative sensitivity matrix, and depth of investigation index. The field data show freshwater outflow from the lower beach to below the low water line, and they indicate that managed aquifer recharge has a positive impact on fresh submarine groundwater discharge, while groundwater extraction reduces the outflow of freshwater to the North Sea.

The integrated use of more geophysical tools offers new potentialities and more accurate results, as shown by Sarker et al. [15]. The integration of vertical geophysical well logs of different types, vertical electrical soundings, electrical resistivity tomography and direct measurements of groundwater electrical conductivity permit the accurate assessment of the saltwater/freshwater interface depth in southwest coastal areas of Bangladesh. In these areas, the population suffers low availability of potable water and ignores the interface depth interface, causing many unsuccessful waters wells drilling. The interface depth is assessed between 190 and 285 m (locally, as shallow as 146 m) and is worsened by upconing of fresh water from the deep aquifer [15]. Moving from the site-specific results to a global view, this research shows that the integration of geophysical tools can support the optimal management of coastal groundwater, highlighting the main sources of vulnerability to salinization.

If the coastal aquifer bottom is not generally much lower than the sea level, detailed knowledge of the bottom surface can efficiently guide sustainable aquifer utilisation, which in turn prevents or reduces seawater intrusion. This is the case for many coastal plains, in which merging geophysical and geochemical surveys can be a basic approach to management. Muzzillo et al. [16] assess the proneness to seawater intrusion, testing a multidisciplinary approach based on hydrochemical and geophysical investigations of a coastal plain located along the Ionian coast of southern Italy. This coastal plain, as is observed to be widespread at a global scale, has suffered relevant anthropogenic modifications during the 20th century, with the effects of groundwater availability and quality degradation. The geoelectrical surveys showed the aquifer bottom pattern in detail, where it is deeply incised by paleovalleys, defining the main hydrostratigraphic features, as it is necessary to prevent seawater intrusion worsening. Tens of groundwater samples were analysed to define the groundwater chemical characteristics, highlighting patterns with higher seawater intrusion proneness. The acquired measurements show the high proneness to seawater intrusion, especially where the aquifer bottom is very deep below the sea level and far from the coast, and detailed knowledge of the aquifer bottom is relevant in supporting the management of seawater intrusion.

5. Quantity Management Issues, Indicators, and Social-Ecological Effects

The most over-exploited aquifers irrigate the world's most productive agricultural regions or feed mega-cities, with negative effects observed such as aquifer depletion, food insecurity subsidence, and, in the case of coastal areas, seawater intrusion [5,6].

Dhaka city could be considered the fastest-growing megacity due to its more than 20 million inhabitants and a growth rate of 3.62% [17]. Unplanned and rapid urbanization, coupled with exponential population growth, has significantly increased groundwater withdrawal. Islam et al. [17] study the evolution of long-term piezometric heads of two main local aquifers, the upper and the middle aquifers (UDA and MDA, respectively) operating on long-term hydrographs, piezometric maps and synthetic graphical overviews of piezometric trends. The piezometric level has declined deeper than −65 m in both aquifers. The highest rate of decline was observed below a large city portion, ranging from 4.0 to 5.7 m/year in both aquifers. The deep depression cones in both aquifers highlight a considerable threat to groundwater resources, indicating that the current exploitation is unsustainable.

Garamhegyi et al. [18] provide an in-depth study of the long-term changes in shallow groundwater and its drivers in one of the most important agricultural areas in Hungary, the Danube–Tisza Interfluve (8000 km^2). They use a combination of multivariate time series and geomathematical methods to explore the subregions most sensitive to dewatering. The dataset includes 190 piezometric time series, covering a semicentennial period (1961 to 2010). Three validated clusters correspond to different subregions. The piezometric time series were investigated for long-term trends and compared with local climate time series (precipitation, evapotranspiration, etc.). As a result, shallow recharge and discharge zones, a gravity-driven flow system, and the discharge zone of a deeper, over-pressured flow system could be discerned with distinctive long-term changes in water levels. Different climatic processes driving the semicentennial trends prevail in the shallow groundwater, showing the high vulnerability of the recharge zone, while the outlined over-pressured flow system seems to act independently from semicentennial precipitation trends. These results show groundwater managers where the most vulnerable subareas for irrigation are located, using mainly shallow groundwater. The results also call adaptation-strategy decision-makers to initiate a more effective and area-focused intervention.

Groundwater has been globally threatened by various pressures with different types of negative effects, especially in coastal areas. A novel framework for identifying critical factors to coastal groundwater could be extremely useful for a wide range of practical management objectives. Lee et al. [19] consider 5856 indicator results of the City Blueprint Approach (CBA) from 122 cities. The correlation between these indicators led to the city blueprint networks using a complex network modelling approach for three groups of cities: all 122 cities, 40 coastal, and 82 non-coastal cities. Focusing on a subset of Korean cities, the authors identify the indicators that indicate potential risks regarding coastal groundwater; the novel approach unveils underestimated or hidden groundwater factors, which allows extensive options for sustainable groundwater management.

The diagnostic approach of social-ecological systems (SES) to analyse the institutionalised governance process of groundwater is a way to characterised undirect effect of groundwater depletion risks. Yan Zhang [20] applied this approach to Lijiang (Yunnan, China), renowned for its natural beauty and exotic cultures and as a UNESCO World Heritage site, defining two significant findings. Institutional arrangements may play an essential role in resource management, but their analysis is lacking between macro modelling and micro surveys of individual and community behaviour. The SES approach offers a tool to fill this gap. Finally, the designation of Lijiang's outstanding universal values as a world heritage site seems damaging to its local cultural intimacy, which nurtured generations of collective action for the local traditional people, escalating the tragedy of its groundwater commons.

6. Conclusions

The articles of this Special Issue deal with topics related to: (1) modelling efforts supporting the sustainable management of aquifers, (2) groundwater vulnerability assessment against external pollution, focusing on groundwater quality management, (3) the potentiality of geophysics tools to support groundwater management, and (4) groundwater quantity management issues, indicators, and social–ecological effects.

The increasing demand for groundwater is forcing water scientists to improve and develop new methods and approaches for integrating groundwater management and protection. The results of the studies presented in this Special Issue offer insights for further multi-methodological and multi-purpose research on the topic of groundwater management. There are still challenges to be accepted and overcome in order to ensure a sustained and sufficient supply of good quality groundwater for future generations.

The authors of this article and the 69 scientists who contributed to this Special Issue are certainly already at work to pursue these goals. The presentation of their results here is a starting point for future research.

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