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Editorial

Water Flow, Solute and Heat Transfer in Groundwater

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Abstract: Groundwater is an essential and vital water resource for drinking water production, agricultural irrigation, and industrial processes. The better understanding of physical and chemical processes in aquifers enables more reliable decisions and reduces the investments concerning water management. This Special Issue on "Water Flow, Solute and Heat Transfer in Groundwater" of *Water* focuses on the recent advances in groundwater dynamics. In this editorial, we introduce 12 high-quality papers that cover a wide range of issues on different aspects related to groundwater: protection from contamination, recharge, heat transfer, hydraulic parameters estimation, well hydraulics, microbial community, colloid transport, and mathematical models. By presenting this integrative volume, we aim to transfer knowledge to hydrologists, hydraulic engineers, and water resources planners who are engaged in the sustainable development of groundwater resources.

Keywords: groundwater; porous and fractured media; contaminant transport; heat transfer; parameters; colloids; microbial community; field and laboratory studies; mathematical modeling

1. Introduction

Worldwide, groundwater provides essential and valuable water resources for drinking water production, agricultural irrigation [1], and industrial processes [2]. Particularly in arid and semi-arid areas where ample surface water sources do not exist, groundwater is often the major, or even the only, drinking water resource. However, human activities, due to increasing livelihood and development demands, have contributed to the deterioration of groundwater quality. Aquifer systems are thus driven out of their natural equilibrium condition both from a quantitative and qualitative point of view. Careless operations of groundwater resources result in inadequate management and protection measures during the planning and implementation of the development projects in the recharge areas. An overexploitation of the aquifers leads to the deterioration of the groundwater quality and the almost irreversible contamination of the aquifer system. Experience in recent decades has shown that once groundwater is contaminated by chemical, biological, or radiological agents, it is always difficult to clean up these contaminants, and the remediation involves high costs [3]. Therefore, protecting groundwater from depletion and pollution is one of the major tasks for sustainable water development.

The increasing concern regarding problems related to environmental protection from pollution and the high costs of remediation policies stimulate the development and application of groundwater management models, which combine optimization procedures with groundwater flow and transport models. In decision-making that requires knowledge of the hydro-geological environment, one of the most important features is uncertainty, which mainly stems from inadequate concepts or description of the processes and inherent lack of information about the aquifer's properties. Understanding the physical and chemical processes occurring in the aquifer system enables more reliable decisions and reduces the investments concerning water management.

The papers included in this Special Issue cover a wide range of subjects that are relevant to groundwater dynamics: well hydraulics, heat transfer, protection from contamination, recharge, parameter estimation, microbial community and colloids transport, models, and numerical solution methods.

2. Special Issue Overview

This Special Issue on "Water Flow, Solute and Heat Transfer in Groundwater" contains 12 papers. In the following, we shortly describe each study.

Wang et al. (2020) [4] investigated the seepage characteristics of single ascending partially and fully penetrating relief wells using a series of laboratory sand-tank experiments and numerical simulations. They found that the seepage characteristics of ascending wells dewatering an overlying aquifer are different from those of the conventional pumping wells descending from the ground surface into the underlying aquifer because of the pronounced influence of the seepage face boundary condition along the seepage boundary of the ascending dewatering well. Modified versions of the Dupuit and Dupuit–Thiem formulae for a single ascending relief well for a degree of penetration less than the critical one for unconfined, confined, and confined-unconfined aquifers were developed.

Two papers address the topics of groundwater contamination and protection. Li et al. (2019) [5] used the numerical model of density-dependent groundwater flow and solute transport to analyze the influence of tidal fluctuation and water curtain systems on the temporal-spatial variations in seawater intrusion in an island oil storage cavern in China. The results show that the operation of an underground water-sealed oil storage cavern in an island environment has a risk of inducing seawater intrusion. The water curtain system can decrease seawater intrusion and reduce the influence of tidal fluctuation on the seepage field inside the island. Liu et al. (2019) [6] compared different wellhead protection area (WHPA) delineation methods, addressing the delineation uncertainty due to the uncertainty from the input parameters. Comparisons were performed at two pumping sites–a single well and a wellfield consisting of eight wells in an unconfined coastal aquifer in Israel. The results from single well and wellfield indicated that interferences between wells are important for WHPA delineation, and thus that only semi-analytical and numerical modelling are recommended for WHPA delineation at wellfields.

Princ et al. (2020) [7] investigated experimentally the relationship between the entrapped air content and the corresponding hydraulic conductivity for two coarse sands. The amount and distribution of air bubbles were quantified by micro-computed X-ray tomography (CT) for the selected runs. The relationship between the initial and residual gas saturation was successfully fitted with a linear model. The combination of X-ray-computed tomography and infiltration experiments has a large potential in exploring the effects of entrapped air on water flow.

Two papers consider problems related to the technical applications of heat transfer in groundwater. Zang et al. (2019) [8] presented a new approach aiming at using geothermal water resources for residential heating. Simulations based on mathematical models of groundwater flow and heat transfer show that well spacing, reinjection temperature, and production rate are the most significant factors influencing thermal breakthrough in geothermal reservoirs. It was shown that in the case of Xinji, China, an indirect geothermal district heating system is much better than a direct geothermal district heating system, both technically and economically. The developed approach can be applied to other regions with geothermal energy utilization. Hu et al. (2018) [9] considered the effect of groundwater flow on the artificial ground freezing (AGF) projects in highly permeable formations. The numerical model to simulate groundwater flow and temperature changes was developed and used to assess the efficiency of AGF for strengthening a metro tunnel in South China. The simulation results show that the freezing wall appears in an asymmetrical shape with horizontal groundwater flow normal to the axial of the tunnel, while along the groundwater flow direction, a freezing wall forms slowly and on the upstream side the thickness of the frozen wall is thinner than that on the downstream side. The pipes' spacing influences the temperature field and closure time of the frozen wall.

Balaban et al. (2019) [10] present the results of field research related to microbial community in a fractured chalk aquitard below the industrial zone Neot Hovav in Israel, which is polluted by a wide variety of hazardous organic compounds. The spatial variations in indigenous bacterial population and their structure were assessed as a function of distance from the polluting source. The de-halogenating potential of the microbial population was tested through a series of lab microcosm experiments, thus exemplifying the potential and limitations for the bioremediation of the site. The dehalogenation of halogenated ethylene was demonstrated in contrast with the persistence of brominated alcohols. The persistence is likely due to the chemical characteristics of the brominated alcohols and not because of the absence of active de-halogenating bacteria.

Bagalkot and Kumar (2018) [11] developed a numerical model to investigate the influence of gravitational force on the transport of colloids in a single horizontal fracture–matrix system. Results suggest that the gravitational force significantly alters and controls the velocity of colloids in the fracture. The mass flux across the fracture–matrix interface is predominantly dependent on the colloidal size. An as large as 80% reduction in the penetration of colloids in the rock matrix was observed when the size of the colloid was increased from 50 to 600 nm.

Groundwater recharge (*GR*) is an important parameter affecting the use of groundwater resources. Two papers draw attention to the significance of factors influencing *GR*. Wang et al. (2019) [12] use a one-dimensional process-based vadose zone model with generated soil hydraulic parameters to simulate the soil moisture, actual evapotranspiration (Et_a), and *GR*. The simulations showed that the dependence of ET_a and *GR* on the soil hydraulic properties varied considerably with the climatic conditions and greatly weakened at the site with an arid climate. In contrast, the distribution of the mean relative difference in soil moisture was still significantly correlated with the soil hydraulic properties (most notably the residual soil moisture content) under arid climatic conditions. Adane et al. (2019) [13] studied the impact of climate forecasts on *GR* within a probabilistic framework in a site-specific study in the Nebraska Sand Hills (NSH), the largest stabilized sand dune region in the USA, containing the greatest recharge rates within the High Plains Aquifer. A total of 19 downscaled climate projections were used to evaluate the impact of precipitation and reference evapotranspiration on the *GR* rates simulated by using a HYDRUS 1-D model. To present the results at a sub-annual time resolution, three representative climate projections (dry, mean, and wet scenarios) were selected from the statistical distribution of the cumulative *GR*. In the dry scenario, the excessive evapotranspiration demand in the spring and precipitation deficit in the summer can cause plant withering due to excessive root-water stress. This may pose a significant threat to the survival of the native grassland ecology in the NSH and potentially lead to desertification processes if climate change is not properly addressed.

The simulation of two- and three-dimensional water flow in the vadose zone-groundwater system using the Richards' equation is computationally intensive and time consuming. Pinzinger and Blankenburg (2020) [14] used the free software library AMGCL (algebraic multigrid C++ library) and developed a numerical algorithm that allows a significant reduction in the computational running time without losing accuracy. This was mostly pronounced for large-scale models.

Contaminant hydrogeology models of non-aqueous phase liquid (NAPL) transport in saturated porous media account for the dissolution of residual NAPL by a Sherwood–Gilland empirical model. The standard methods of volume averaging to derive upscaled transport equations describing the same dissolution and transport phenomena typically yield forms of equations that are seemingly incompatible with Sherwood–Gilland source models. Hansen (2019) [15] developed new simplification approaches (including a physics-preserving transformation of the domain and a new geometric lemma) that allow one to avoid solving traditional closure boundary value problems and to obtain a general, volume-averaged governing equation that does not reduce to the advection-dispersion-reaction equation with a Sherwood–Gilland source.

3. Conclusions

The objective of this Special Issue was to focus on the recent advances in groundwater studies related to fundamental investigations of water flow, solute transport, and heat transfer using various experimental techniques, mathematical models of physical mechanisms, management strategies, and experience gained from case studies. Twelve high-quality papers were included in this Special Issue relating to well hydraulics, freshwater–saltwater interactions, groundwater contamination and protection, the impact of climate change on groundwater recharge, microbial community structure, hydraulic parameter estimation, colloid transport, and numerical modeling techniques.

The overview of papers published in this SI shows that fundamental research on groundwater is very important for understanding the behavior of aquifers, most of which, nowadays, are under stress conditions. The results of these studies can be directly used for developing an improved picture of groundwater dynamics and aquifer use. Future works should continue towards integrative investigations of groundwater interactions with other components of the hydro-geochemical cycle, such as atmosphere, surface waters, soils, and lithosphere.

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