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Editorial

Groundwater–Surface Water Interactions: Recent Advances and Interdisciplinary Challenges

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Abstract: The interactions of groundwater with surface waters such as streams, lakes, wetlands, or oceans are relevant for a wide range of reasons—for example, drinking water resources may rely on hydrologic fluxes between groundwater and surface water. However, nutrients and pollutants can also be transported across the interface and experience transformation, enrichment, or retention along the flow paths and cause impacts on the interconnected receptor systems. To maintain drinking water resources and ecosystem health, a mechanistic understanding of the underlying processes controlling the spatial patterns and temporal dynamics of groundwater–surface water interactions is crucial. This Special Issue provides an overview of current research advances and innovative approaches in the broad field of groundwater–surface water interactions. The 20 research articles and 1 communication of this Special Issue cover a wide range of thematic scopes, scales, and experimental and modelling methods across different disciplines (hydrology, aquatic ecology, biogeochemistry, environmental pollution) collaborating in research on groundwater–surface water interactions. The collection of research papers in this Special Issue also allows the identification of current knowledge gaps and reveals the challenges in establishing standardized measurement, observation, and assessment approaches. With regards to its relevance for environmental and water management and protection, the impact of groundwater–surface water interactions is still not fully understood and is often underestimated, which is not only due to a lack of awareness but also a lack of knowledge and experience regarding appropriate measurement and analysis approaches. This lack of knowledge exchange from research into management practice suggests that more efforts are needed to disseminate scientific results and methods to practitioners and policy makers.

Keywords: aquifer–stream interface; hyporheic zone; benthic zone; lacustrine groundwater discharge; submarine groundwater discharge; riparian corridors

1. Introduction

Recent years have seen a paradigm shift in understanding the importance of interactions between groundwater and surface water bodies. While for a long time surface waters and aquifers had been defined as discrete, separate entities, it is now understood that they are integral components of a surface–subsurface continuum [1]. This has fostered more holistic perspectives on a variety of ecosystem services at risk, such as the consideration of groundwater as a source of surface water pollution and ecosystem degradation (eutrophication, organic micropollutants, etc.) and vice versa (i.e., surface water as groundwater pollutant). The protection of potable water resources requires clean and safe water quality of both surface and subsurface waters.

This paradigm shift has triggered intense investigations of the water and mass transport processes across aquatic–terrestrial interfaces. Nevertheless, there is still a lack of mechanistic understanding and standardized methods to measure the processes involved. For example, it is well accepted that the reactive interface between surface water and the subsurface is of great importance for the quality and the quantity of exchange fluxes [2]. However, experimental and validated model-based evidence of the magnitude of the involved processes as well as of the underlying controls are scarce. One of the many reasons for this is that groundwater–surface water interactions integrate a large variety of scientific disciplines. Researchers from hydrology, biogeochemistry, microbiology, biology, physics, and chemistry work on the complex process interactions that require them to consider relevant aspects from other scientific fields. Additionally, interactions between surface and subsurface water take place in a range of different marine and freshwater systems, but the potential to transfer technologies and approaches as well as resulting knowledge and process understanding to other fields is not adequately exploited.

The aim of this Special Issue is to collectively present and integrate novel outcomes from interdisciplinary research on groundwater–surface water interactions. The presented studies cover a large variety of thematic areas, scales, and experimental and modelling-based methodologies and approaches, and thus promote interdisciplinary discussion and reveal knowledge gaps and future research needs.

2. Overview of the Special Issue Contributions

This Special Issue consists of 20 original research papers [3–23]. The majority of the contributions [3,5,8–11,15–17,19–23] focus on the interactions between rivers or streams and groundwater. Three studies [6,13,14] investigate the interactions between lakes and groundwater, while two studies [4,18] deal with the exchange between groundwater and oceanic water. Two additional contributions [7,12] show the relevance of groundwater exchange processes in wetlands. In the following we provide an overview that integrates the knowledge gains and innovations of the aforementioned studies and outlines the potential for knowledge and method exchange across study system boundaries.

2.1. Groundwater–River Interactions

2.1.1. Catchment-scale Hydrological Studies

The increasing awareness of the relevance of groundwater–surface water interactions leads to increased research into the quantification of water balances in systems with interacting river flow and aquifer dynamics. In this Special Issue, several studies aim at investigating the hydrological interactions between rivers and aquifers at a regional catchment scale. For example, Kelly et al. [8] used river gauges to quantify the baseflow indicator (BFI) in order to evaluate the relevance of groundwater dynamics and trends for an African river system. Vrzel et al. [19] applied different modelling approaches to groundwater and stream gauge data to disentangle and quantify the influence of precipitation and river water on an important aquifer system in Slovenia. Similarly, Parlov et al. [15] applied two- and three-component mixing models on stable isotope data to quantify the contributions of precipitation and surface water to aquifer recharge. Focusing on water fluxes crossing the interface in the other direction, Steiness et al. [16] aimed at localizing and quantifying the contributions of groundwater to stream flow. They therefore integrated a wide range of analysis methods (inter alia electrical resistivity tomography, ground penetrating radar, slug tests and hydraulic head measurements in catchment and riverbed, temperature measurements in the hyporheic zone, stable isotope measurements) in order to derive a spatially highly resolved picture of flow paths (a) from the catchment to the river and (b) in the hyporheic zone. Tang et al. [17] looked at the influence of groundwater as a significant proportion of stream discharge on temperature and chlorophyll-a dynamics. This study represents the only one in this Special Issue conducted in a karstic environment.

2.1.2. Hyporheic Zone Studies

Exchange fluxes across sediment–water interfaces are frequently studied in detail with a specific focus on the hyporheic zone (i.e., the zone of the stream–groundwater interface where groundwater and stream water mix). Lewandowski et al. [22] discuss the valuable ecosystem services provided by the hyporheic zone. Several studies focus on fluxes across the hyporheic zone by using temperature as a tracer. For example, Mojarrad et al. [11] used the temperature difference between groundwater and surface water to numerically model up- and downwelling areas in the hyporheic zone. Le Lay et al. [9] and Gilmore et al. [5] applied fiber-optic distributed temperature sensing (fo-DTS) for pattern identification as a prerequisite for optimized point measurements of groundwater exfiltration into a river. Le Lay et al. [10] used the diurnal atmospheric temperature signal propagating vertically through the hyporheic zone with a characteristic attenuation and phase shift to calculate vertical flow velocities. Yao et al. [23] used this approach to analyze the effects of a low-permeability sediment lens and surface discharge velocity on hyporheic flow. For this, they applied an innovative artificial rectangular sediment cuboid of a known heterogeneous sediment composition and placed it in a real streambed environment. Gilmore et al. [5] combined their fo-DTS measurements with traditional methods to calculate Darcy fluxes in order to minimize measurement efforts. Some of the research presented here used modelling tools to derive and improve the understanding of hyporheic flow mechanisms. For example, Broecker et al. [3] developed an innovative integral formulation for the sediment–water interface as an alternative to coupled modeling approaches that are frequently applied in groundwater–surface water modelling studies. Mojarrad et al. [11] used the empirical data from their study site to model the effects of sediment permeability and river discharge dynamics on hyporheic flow.

While most studies presented in this Special Issue focus on the investigation of exchange fluxes across groundwater–surface water interfaces, there are a few that focus additionally on biogeochemical processes at the interface. Ward et al. [20] used the resazurin–resorufin reactive tracer system to study aerobic microbial transformation at sediment–water interfaces and found that the resazurin-to-resorufin transformation rate was highest in youngest storage locations (i.e., that increasing residence times do not necessarily increase the reaction potential of solutes). Wolke et al. [21] systematically studied the impact of bed form movements on oxygen dynamics in the hyporheic zone. The advantage of such flume studies is the ability to conduct analyses under well-controlled environmental parameters. However, Wolke et al. [21] is the only study in this Special Issue using a lab flume for hyporheic research.

2.2. Groundwater–Lake Interactions

The discharge of groundwater to lakes is called lacustrine groundwater discharge (LGD) [24]. The opposite flow direction (i.e., the recharge of the aquifer) has often been studied in the context of bank filtration as a method of drinking water production [25–27]. However, there are no studies on this topic within the Special Issue. Han et al. [6] show that the direction of interactions between aquifer and lake can change seasonally. They sampled precipitation, lake water, river water, and groundwater for chloride concentrations and water-stable isotopes to delineate discharge and recharge areas for the dry (cold) and the wet season in the complex hydrogeological environment of Lake Hulun. Nisbeth et al. [13,14] found that geogenic P might be a much more important P source in some instances than is generally assumed. Their study contributes to the still-overlooked problem of LGD-induced lake eutrophication [24,28–30].

2.3. Groundwater–Ocean Interactions

Submarine groundwater discharge (SGD) is the discharge of groundwater to oceans and their coastal areas [24]. Despite SGD having been studied much more intensively than LGD, there are still many knowledge gaps that need to be addressed, and there is still a need to develop appropriate measurement methods for SGD. Tirado-Conde et al. [18] compare the results of traditional seepage meter measurements with several analytical approaches of vertical sediment temperature profiles in a lagoon in Denmark. Duque et al. [4] applied stable isotopes of water to delineate flow paths and the origin of water in a coastal aquifer. This enabled them to draw valuable conclusions on nutrient transport and their fate along the vector from freshwater to saline environments.

2.4. Interactions of Groundwater with Wetlands

Wetlands often rely on intense interactions with groundwater [31], highlighting that in order to be successful and efficient, restoration efforts in groundwater-dependent terrestrial ecosystems need to consider these interactions. Two studies in this Special Issue provide valuable support for decision making in wetland management. Neff et al. [12] conceptually modelled the influence of depressional wetlands on groundwater flow at the landscape scale and found strong effects such as increased groundwater discharge and the generation of flow divides. From their results they developed an extensive guide for practitioners on how to determine the groundwater connectivity of wetlands. Harvey et al. [7] present an approach based on thermal infrared (TIR) to map groundwater influence in a wetland before and after restoration. They could show that TIR is a very promising tool for the establishment and monitoring of wetland restoration measures aiming at reestablishing groundwater connectivity.

3. Conclusions

The contributions to this Special Issue represent the immense variety of scopes and scientific disciplines that come together in researching the interactions between groundwater and surface water. The research questions addressed in this Special Issue cover, inter alia, the extensive spectrum of mechanistic process understanding of hydrological and biogeochemical interactions including the identification of drivers and controls as well as testing and improving methods and approaches for pattern identification and flux quantification. This Special Issue demonstrates how active and diverse the research community currently is, and proves the high relevance of groundwater–surface water interactions.

The research in this Special Issue covers a wide range of spatial scales, from point measurements to catchment approaches. While a large number of the contributions focused on the local-to-reach scale, the regional and catchment scales have also been studied. Several studies are dedicated to identifying the contribution of groundwater to the water balance of lakes, rivers, or watersheds. Two articles focus on recharge sources of aquifers in the Sava river catchment (Balkans). This indicates an increased awareness of the need to protect drinking water resources in the light of potential alterations of regional water balances in the future. However, there is still the need to improve the mechanistic understanding of processes at smaller scales, as indicated by the large proportion of contributions focusing on hyporheic zones.

Moreover, 15 out of 20 research papers in this Special Issue have a purely hydrological focus, while only five consider hydrological and biogeochemical interactions. In fact, only two contributions (both by Nisbeth et al. [13,14]) focus on mass transport between groundwater and surface water by determining groundwater-borne phosphorus loads to a lake. This could be due to the challenging complexity of groundwater–surface water exchange processes alone, because the investigation of related mass fluxes adds to further complexity. Given that exchange processes between groundwater and surface waters can facilitate the transport but also retention of nutrients and pollutants, the low number of studies here suggests that the scientific investigation of such cases is still difficult.

Furthermore, the large variety of methods and modelling approaches and their different applications might indicate the need for standardized approaches to specific recurring questions, especially at the applied level. Groundwater–surface water interactions will only be regularly considered in management and protection when simple and robust methods and analysis procedures are readily available. Therefore, we would like to call upon all scientists working in this field to reach out and actively share their experiences with practitioners and policy makers to foster the urgently needed attention for groundwater–surface water interaction in freshwater management and protection. In this context, Harvey et al. [7] provide an excellent example of how the application of thermal infrared (TIR) can effectively support wetland restoration planning and success monitoring. Additionally, Neff et al. [12] give well-developed hands-on advice on how to assess the groundwater connectivity of wetlands.

This Special Issue is another step forward in our understanding of surface water–groundwater interactions. The articles reveal not only the environmental and societal relevance of this interface but also identify many open questions and tasks that need to be addressed in future. Especially in the light of future challenges such as climate change, water scarcity, eutrophication, and the retention of pollutants such as pharmaceuticals and microplastics, there is an urgent need to continue our efforts to better understand the processes involved in groundwater–surface water exchange in order to be able to restore and sustain the ecosystem services provided by the groundwater–surface water interface.

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