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Groundwater-surface water interactions: New methods and models to improve understanding of processes and dynamics

Jan H. Fleckenstein [a,*], Stefan Krause [b,1], David M. Hannah [c,2], Fulvio Boano [d,3]

[a] Department of Hydrogeology, Helmholtz Center for Environmental Research (UFZ), 04318 Leipzig, Germany
[b] School for Physical and Geographical Sciences, Keele University, Keele, Staffordshire, ST5 5BG, UK
[c] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston. Birmingham. B15 2TT, UK
[d] Department of Hydraulics, Transport & Civil Infrastructures, Politecnico di Torino, Corso Duca degli Abruzzi 24-10129 Torino, Italy

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ABSTRACT

Interest in groundwater (GW)-surface water (SW) interactions has grown steadily over the last two decades. New regulations such as the EU Water Framework Directive (WFD) now call for a sustainable management of coupled ground- and surface water resources and linked ecosystems. Embracing this mandate requires new interdisciplinary research on GW-SW systems that addresses the linkages between hydrology, biogeochemistry and ecology at nested scales and specifically accounts for small-scale spatial and temporal patterns of GW-SW exchange. Methods to assess these patterns such as the use of natural tracers (e.g. heat) and integrated surface-subsurface numerical models have been refined and enhanced significantly in recent years and have improved our understanding of processes and dynamics. Numerical models are increasingly used to explore hypotheses and to develop new conceptual models of GW-SW interactions. New technologies like distributed temperature sensing (DTS) allow an assessment of process dynamics at unprecedented spatial and temporal resolution. These developments are reflected in the contributions to this Special Issue on GW-SW interactions. However, challenges remain in transferring process understanding across scales.

1. Introduction

Groundwater (GW) and surface water (SW) are two interconnected components of one single resource and impacts on either of these components will inevitably affect the quantity or quality of the other (Winter et al. 1999). Although early hydrological research had already emphasized these linkages between GW and SW [43,51], GW and SW resources have long been perceived and managed as two separate entities [66]. However, with growing demands on water resources and increasing uncertainties in water supply associated with climate change the awareness for the need to manage GW and SW as a single resource has steadily grown [10,48] and also found its way into new legal frameworks to regulate the sustainable use of water resources in many countries (e.g. [62]). This new perception of GW–SW interactions and their operational importance poses new challenges to researchers and managers as it not only pertains to the management of water quantity and quality, but also increasingly to the management and preservation of groundwater dependent ecosystems and riparian habitat [34]. It is clear that an improved multidisciplinary understanding of the processes and dynamics of GW–SW interactions is an important prerequisite to tackle these new challenges.

This Special Issue (SI) addresses some of the scientific challenges in characterizing, quantifying and modeling GW–SW interactions and outlines new methods and models to improve our understanding of processes and dynamics at the GW–SW interface. Most of the papers in the SI stem from contributions to a session (HS9.5) entitled "Hydrological, biogeochemical and hydroecological processes and interactions at the groundwater-surface water interface" at the European Geosciences Union (EGU) General Assembly held in Vienna, April 19th to 24th 2009.

In the subsequent paragraphs a short historical review of hydrologic research on GW–SW interactions is provided, followed by an outline of current research areas and directions and finally an overview of the papers in this SI.

2. Background

It was not until the 1960s that researchers started to view streams, lakes and wetlands from the perspective of groundwater flow systems

* Corresponding author. Tel.: +49 0341 235 1253; fax: +49 0341 235 1837.
E-mail addresses: jan.fleckenstein@ufz.de (J.H. Fleckenstein), s.krause@esci.keele.ac.uk (S. Krause), d.m.hannah@bham.ac.uk (D.M. Hannah), fulvio.boano@polito.it (F. Boano).
[1] Tel.: +44 1782 583186; fax: +44 1782 715261.
[2] Tel.: +44 121 414 6925; fax: +44 121 414 5528.
[3] Tel.: +39 011 090 5646; fax: +39 011 090 5698.

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[55]. Early work by Toth [53,54] outlined the concepts of how topography, geology and climate control the development of nested (local, intermediate and regional) GW flow systems, which in turn drive the spatial patterns of GW–SW interactions. Theoretical studies investigated these patterns for GW-lake [37,63,64] and GW-wetland systems [38]. Rorabaugh [43] developed methods to estimate stream flow components from bank storage and aquifer outflow. Concepts to describe the GW–SW interface [45] were incorporated into the first numerical GW models in the 1980s and additional routines and modules were added to the codes to better represent GW–SW exchange processes (e.g. [42]). Early applications were concerned mainly with the management of water quantity and models were used often to assess conjunctive use scenarios [25]. Due to the relatively large scales of investigation and computational constraints the representations of the GW–SW interface in these models were typically coarse resolution in space and time. SW flow processes and dynamics were simplified and aquifers and streambeds were often described as homogeneous units. First efforts were undertaken to develop more complex integrated models of surface–subsurface components of the hydrologic cycle in the 1980s, which sought to overcome some of these deficiencies in system representation [1,2].

The 1980s also saw the first studies to link hydrologic dynamics at the GW–SW interface with ecological functions [26,49] and with biogeochemical processes [3,27]. Bencala and Walters [5] formulated their transient storage model, which marked the starting point of intensive research on the effects of hyporheic exchange and temporary storage of solutes in dead zones on solute transport and biogeochemical processes in riparian systems [4,28,56]. These activities lead subsequently to a Special Issue *in Advances in Water Resources* on modeling hyporheic zone processes [44].

Since the 1990s research activities on GW–SW interactions have increased steadily in disciplines ranging from hydrology and hydrogeology to ecology, biogeochemistry and environmental management and law [33]. More complex models of SW flows have been linked to existing groundwater models [30,50] and an entirely new class of fully integrated models have been developed that can simulate coupled GW–SW system as a continuum [31,32,41,57]. The 1990s also marked an increasing interest in smaller scale GW–SW exchange processes [20,40] and associated biogeochemical processes and ecological functions [9,18,68]. For example Brunke and Gonser [11] emphasized the ecological importance of the hyporheic zone and outlined the intricate linkages between hydrology and ecology.

Around the turn of the century three review papers addressed this new multidisciplinary interest in GW–SW interactions and outlined the state of the science [48,65,67]. Since then scientific interest in the topic has mushroomed as reflected in the number of citations of the aforementioned review papers since 2000 (Fig. 1). This growing awareness of the importance of GW–SW interactions for ecological functions in riparian zones and other groundwater dependent ecosystems as well as its manifestations in new legal regulations such as the EU Water Framework Directive have lead to significant research activity on topics associated with the GW–SW interface [33] with a truly multidisciplinary perspective [34]. These developments were the motivation for this SI. The following section briefly outlines some current areas and future directions in research on GW–SW interactions with a focus on hydrologic processes and dynamics.

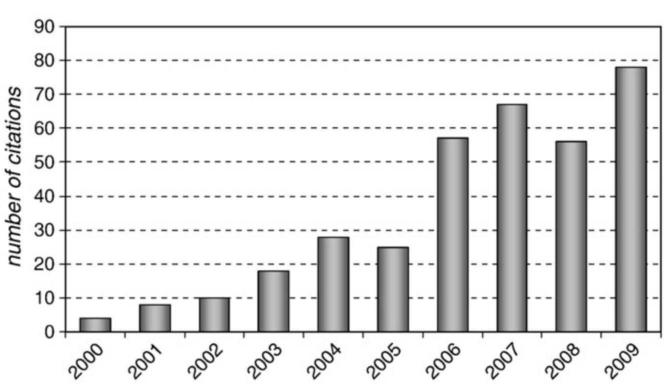

Fig. 1. Number of citations of three influential review papers on GW–SW interactions (Winter 1999, Woessner 2000, Sophocleous, 2002) since 2000, based on a search in the ISI Web of Science (http://apps.isiknowledge.com).

3. Research areas and directions

The described shift in orientation from larger-scale questions of GW–SW interactions with a focus on water quantity management to smaller scale, process-oriented questions of exchange dynamics and the associated biogeochemical processes and ecological functions defines current activities and trends in research on GW–SW interactions [33,48]. The new multidisciplinary questions that need to be addressed, such as the potential of the GW–SW interface to attenuate pollutants, the management of GW-dependent ecosystems or the impact of climate change on riparian systems, to name a few, require the characterization and quantification of GW–SW exchange fluxes at increased spatial and temporal resolution. Consequently significant effort has been devoted to the development of new and improved methods to assess GW–SW interactions such as the use of natural tracers [16,35,47,58,59,61], geophysical and statistical technique to describe and quantify process dynamics [15,36,39,60] or improved transient storage models [46].

Our understanding of the dynamic processes at the GW–SW interface (e.g. the interplay between hydrologic dynamics and biogeochemical processes) is still weak. Combining spatially and temporally resolved field or laboratory data with physically based numerical models to identify key dynamics and to improve process understanding is an area of active research [13,17,19,52,61].

On a more conceptual, theoretical level, numerical models are increasingly used for explorative modeling of GW–SW systems at different spatial scales to elucidate process dynamics in controlled scenario simulations [6,8,12,23,24,29]. Using the insights gained from explorative modeling studies to develop new conceptual models of GW–SW interactions and strategies to upscale processes from the reach to the river and basin scales poses an important future research challenge. Linking the river channel to the extended alluvial aquifer and incorporating geologic heterogeneities at different scales into models of GW–SW interactions [21,22] remains another challenge. Process based models that link hydrologic dynamics and biogeochemical processes are still in their infancy [7,14] and are not yet fully applicable to complex field situations.

4. Papers in this special issue

The papers assembled in this SI focus on some of the research areas and directions listed above and seek to advance methods and/or understanding of the processes and dynamics of GW–SW interactions. A short description of each article is given below, with summaries arranged in the running order of this SI volume.

In the paper by Vogt et al. [58] the utility to use variations in river water electrical conductivity (EC) to trace bank filtration water is investigated. Cross-correlation analysis and non-parametric deconvolution are applied to time series of EC measurements from the River Thur in Switzerland. Estimated travel times of infiltrating water to several riparian GW wells correlate well with residence time calculations based on radon-222 measurements from GW samples. Differences in travel times obtained from the diurnal EC signal, which could best be traced during periods of low river flow, and from the general EC variations, which were dominated be individual high flow events, are attributed to different infiltration regimes during low and high flows. These dynamic patterns and the lack of a clear relationship between residence time and distance from the river channel suggest complex exchange pathways between the river and its adjoining alluvial aquifer, which are controlled by the hydrologic dynamics in the river and structural characteristics of the river channel and its immediate interface with the alluvial aquifer. As EC signals, in contrast to e.g. temperature signals, propagate up to several meters into the aquifer, the authors conclude that EC can be a viable alternative to other natural tracers.

Schornberg et al. [47] investigate the range of applicability and limitations of methods to calculate exchange fluxes between GW and SW from an inversion of measured vertical temperature profiles with analytical solutions to the 1D heat transport equation. Exchange fluxes between a virtual alluvial aquifer and an overlying river channel are systematically investigated for different scenarios of aquifer heterogeneity and non-ideal boundary conditions using a numerical flow and heat transport model. Geologic heterogeneity in the aquifer is represented by a geostatistically generated binary medium with variations in K-contrast and structure and global proportions of the materials. Comparisons between the simulated exchange fluxes and flux estimates obtained from fitting the analytical solution to vertical temperature profiles sampled from the numerical model reveal that K-contrasts between the geologic materials can be a significant source of error in flux estimates, especially under low flux conditions. Errors introduced by deviations from ideal quasi steady state thermal boundary conditions (caused by diurnal and seasonal temperature fluctuations in the SW) are evaluated for different flux rates over the course of a typical year.

Ward et al. [60] couple simulations of near-surface electrical resistivity (ER) with conservative solute tracer transport to determine the utility of ER to predict space and time dynamics in solute exchange between the river channel and hyporheic zone. This novel research is a first attempt to interpret ER data during a solute tracer study. Their results show temporal moments (notably mean arrival time and variance) of ER to be well correlated with solute transport data for locations where advective transport is not the dominant process. This work reveals potential to estimate diffusive mass transport from such datasets and in the use of ER to improve process understanding and modeling of the fate and transport of solutes at the GW–SW interface.

In their investigation of hydraulic coupling between lakes and a complex sequence of quaternary aquifers in the Schorfheide-Chorin biosphere reserve (Germany), Lischeid et al. [36] apply a principal component analysis to identify GW–SW interactions from time series of GW and lake water levels. Damping of the input signal (GW recharge) is assessed by analyzing the extent to which fluctuations in the time series of GW heads or lake water levels are smoothed and delayed with respect to the input signal. Their results indicate substantial variability in the damping behavior of lake water levels, suggesting variable impacts of deep GW contributions. While the majority of groundwater wells exhibited a linear increase of signal damping with depth to the water table, at some wells the damping behavior appeared to be independent from depth. Confined aquifers without connection to adjacent lakes were identified by high-pass filtering of water table data when these were inversely correlated with barometric pressure fluctuations. This study demonstrates the utility of statistical tools applied to time-series data to assess GW–SW interactions.

Cuthbert et al. [17] investigate the impact of gas accumulation in the streambed of the river Tame, UK on hydraulic and thermal riverbed properties such as specific storage, hydraulic conductivity, effective porosity and thermal diffusivity. Gas concentrations of up to 14% by volume, attributed to microbial denitrification, were observed. Using a variably saturated numerical flow and transport model the authors show that the observed riverbed gas concentrations can cause a significant alteration of the proportions of groundwater discharge from the river banks in comparison to the river bed during low flow conditions. During storm events the increased compressible storage of the riverbed gas phase and the reduction of effective porosity due to the gas lead to an increase in simulated surface water infiltration into the streambed and greater penetration depths of the infiltrating water. Furthermore accumulated gas in the streambed affects hyporheic heat transport. Based on heat transport simulations with a 1D analytical equation fitted to observed temperature time series it is shown that diurnal temperature variations within the gaseous riverbed are between 1.5 and 6 times larger at depth between 0.1 and 0.5 m than for fully water saturated sediments due to the alteration of bulk thermal properties.

A series of tracer tests has been performed by Schmid et al. [46] in two Austrian and Italian streams in order to explore the influence of different hydrological conditions on stream-aquifer exchange. The field observations are in agreement with previously reported relationships between stream discharge and subsurface exchange rates and residence times, and provide a confirmation of the existing correlations between stream hydrodynamic properties and storage parameters. Considerations about prediction errors caused by extrapolations of model parameters to different discharge conditions are also included.

The study by Cardenas [13] employs a Boussinesq aquifer model to analyze the response of the water table in a fluvial island to dam-induced river stage fluctuations. The comparison between model predictions and observed levels of water table demonstrates the potential, as well as some limitations, of Boussinesq models in reproducing field observations. The numerical simulations point out how the dynamical behavior of the island water table exhibits peculiar spatial patterns of hydraulic head that greatly enhance surface–subsurface exchange fluxes. The study also discusses how the interplay between the fluctuation period of river stage and the response timescale of the aquifer can dramatically increase the exchange flux.

The temporal dynamics of the interactions between stream and aquifer are also investigated by Boano et al. [8]. They present a numerical analysis of bedform-driven exchange for unsteady conditions. Using long time series of simulated daily streamflows, this research shows that modeled exchange fluxes and residence time distributions exhibit significant temporal variations in presence of unsteady stream discharge. The analysis of the statistical properties of exchange fluxes reveals that the average properties of exchange can be estimated using the mean value of discharge despite the nonlinearities of the system. The temporal variations of exchange flux and residence times are damped compared to those of stream discharge, and the degree of variability is found to be strongly correlated to the coefficient of variation of the streamflow time series.

The complex three-dimensional (3D) flow patterns between an alluvial gravel-bar aquifer and a large river (the Danube in Austria) are subject of the paper by Derx et al. [19]. Observed gradients in GW heads, which respond very dynamically to changes in river stage, are simulated with a 3D variably saturated groundwater flow model. Transport simulations for a conservative tracer are conducted to assess the exchange processes between the river and aquifer. Simulation results show dynamic flow reversals, circular flow patterns and increased advective and dispersive mixing caused by short-term fluctuations in river stage. Their study clearly demonstrates the 3D, highly dynamic nature of river-aquifer exchange processes and the importance of accounting for short-term river stage variations in assessing mixing processes between rivers and aquifers.

Frei et al. [23] present a study of the hydrologic dynamics and runoff-generation processes in a riparian wetland. In numerical experiments the effects of surface micro-topography (hollows and hummocks) on runoff generation and the relationship between streamflow and riparian groundwater levels in a virtual peat-forming wetland are investigated. The virtual wetland resembles the physical characteristics of a wetland in an experimental watershed in Germany. Simulation results show threshold controlled dynamics of runoff generation with frequent shifts between surface and subsurface flow dominance that replicate observed non-linear, hysteretic relationships between GW levels in the peat and generated streamflow volumes. Impacts of individual storm events on streamflows are buffered by the riparian micro-topography. This study suggest that in humid headwater catchments small-scale variations in topography may be responsible for streamflow moderation and typically observed non-linear relationships between riparian groundwater levels and streamflow.

The processes that govern solute exchange between a stream and its bedform-covered streambed are the subject of a study by Jin et al. [29]. Laboratory experiments of NaCl exchange are used together with numerical simulations in order to identify the different contributions of advective and dispersive processes to solute exchange with the sediments. The results of this research show clearly that solute transport in a shallow sediment bed is dominated by advection, while dispersion must be considered to correctly reproduce accurately exchange with the deeper sediments.

Westhoff et al. [61] combine a salt and heat tracer experiment in a small stream in Luxembourg with a hydraulic channel flow model and a 1D advection–dispersion transport model to evaluate tracer transport and transient storage along the stream. Temperatures in the stream are measured with a distributed temperature sensing (DTS) system. Retardation of heat along the channel could not be fully accounted for by heat exchange with the stream bed alone. A term that describes the fraction of the stream cross-section occupied by rock clasts is added to the storage term in the transport equation to account for transient storage of heat in the rocks and to better match the observed break through curves. The study demonstrates that caution is needed in the interpretation of temperature data, which is provided at increasingly better spatial and temporal resolution by technologies like DTS, due to the non-conservative behavior of heat as a tracer.

The breadth of contributions and findings presented in this SI reflects the vibrancy of current research on GW–SW interactions. Challenges remain in fully utilizing the new methods and models to develop new concepts and theories of GW–SW interactions that will reach across disciplines and scales and will enable us to answer some of the pressing questions that are posed. The research papers presented here may serve as a starting point in this process and we hope that this SI will foster further scientific discussion and exchange to advance our understanding of GW–SW interactions at multiple scales.

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