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Research papers

Your work is my boundary condition! Challenges and approaches for a closer collaboration between hydrologists and hydrogeologists

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ABSTRACT

Hydrologists and hydrogeologists both study the flux and storage of water with the numerous interactions and feedback mechanisms of surface water and groundwater. Traditionally however, focus, models and scales of the studies differ. In this commentary, situations are illustrated where boundary conditions that each discipline assumes, preserves and actively uses, can and have to be overcome. These situations occur when the domain of one discipline cannot be separated from the other one because of existing interaction and feedback mechanisms at the boundaries. Highlighted are especially these boundary conditions, where closer collaboration between catchment hydrologists and hydrogeologists would be most useful. Often such collaborations would be relatively straight-forward and rather requiring an increased awareness than novel methods.

1. Introduction

While hydrologists and hydrogeologists both study the flux and storage of water including the numerous interactions and feedback mechanisms between surface water and groundwater, they do this traditionally with a different focus and different models and often at different scales. Hydrology was originally more an engineering discipline and its initial focus was to estimate design values for floods or droughts or to assess water balances for catchments. Later, hydrology developed also into a scientific discipline with strong links to geoscience, ecology and environmental science. Hydrogeology was developed as a sub-discipline of geology, and many hydrogeologists have a background in geology rather than engineering. Traditionally, hydrogeology focuses on questions related to the quantities of water stored in the subsurface and the abstraction of groundwater for water supply as well as groundwater flow. More recently, the fate of contaminants and strategies for groundwater remediation have become an important topic in hydrogeology (Miller and Gray, 2008; Stephens, 2008).

The separate development of the two disciplines comes along with confusion and misunderstandings regarding the terminology, with different emphasis in field campaigns, different educational approaches, and different conceptual models. Several of these aspects have been recently discussed by Barthel (2014). Simplified assumptions about surface and subsurface fluxes at the boundary of the modelled domain, so-called boundary conditions, are an important part of the different model concepts in the two disciplines. Often the boundary conditions of the system, which is investigated or simulated, are in the focus of the respective other discipline. This implies that the two disciplines can provide each other with boundary conditions such as recharge or groundwater heads. In the USGS publication "Surface Water and Groundwater - One Resource" Winter et al. (1998) discuss the numerous interactions and feedback mechanisms between surface and groundwater across different spatial and temporal scales, different landscapes and the hydrologic cycle in general. Despite this compilation of themes, and problems to be treated jointly by hydrogeologists and hydrologists, only marginal progress has been made in tackling these problems in a joint effort in the last two decades.

We wrote this paper as a joint effort between catchment hydrologists and hydrogeologists to show the large potential of collaboration that comes with more detailed information about a boundary condition from the other discipline. The term "boundary" is used as the physical boundary of the system and "boundary conditions" refer to the fluxes, or pressure states, that are assumed to occur at the boundary of the simulated system and are used in any hydrological or hydrogeological model. An example for a boundary condition in classical

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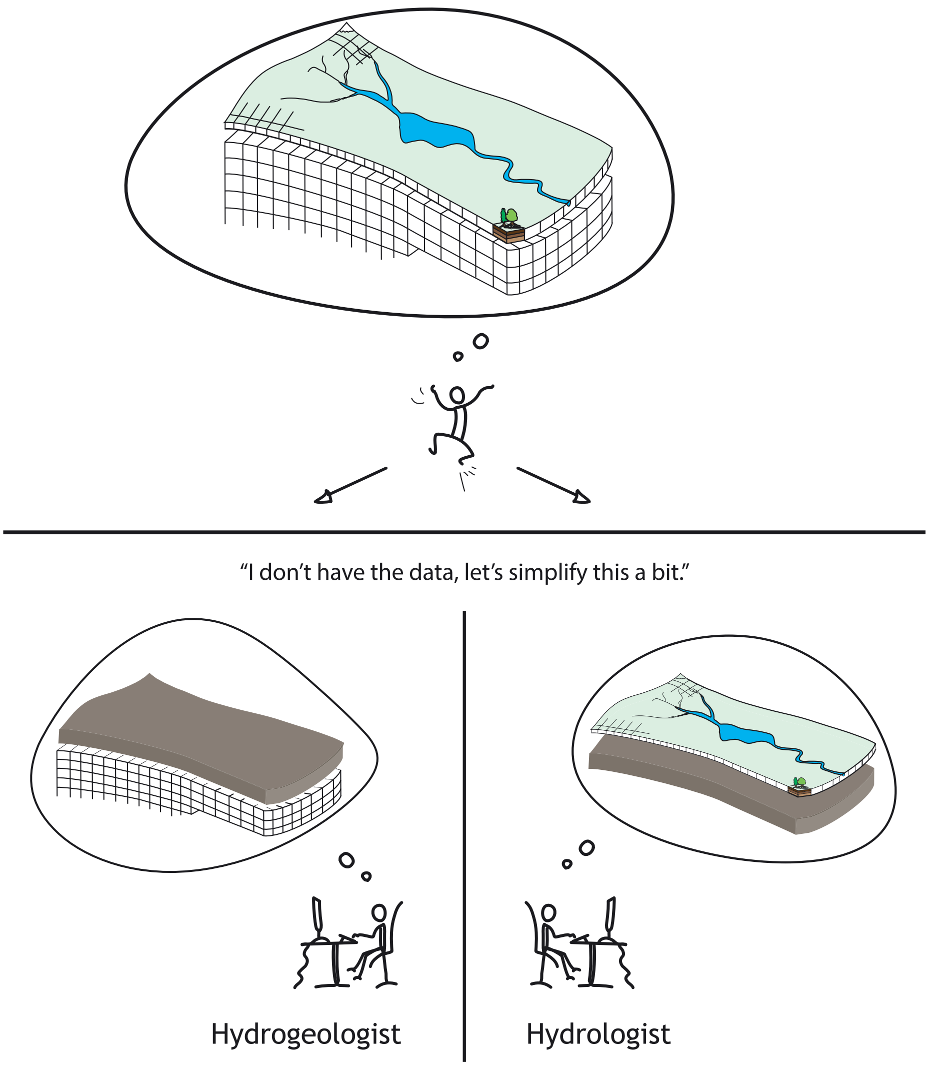

Fig. 1. Contrasting modelling approaches. Hydrologists and hydrogeologist treat opposite ends of the hydrological cycle in more detail and more spatially resolved. The main processes considered in the hydrogeological models are groundwater fluxes and storage as well as movements of contaminants. The main processes considered in the hydrological models are interception, evapotranspiration, infiltration, runoff generation processes and percolation. Despite the idea of fully-integrated models, the "fully integrated models" that are applied by hydrologists/hydrogeologists are simplified due to available data, relevance given to a process, etc.

hydrogeological models is the recharge flux (surface and lateral); important boundary conditions for hydrological models are the meteorological conditions above the vegetation and the zero flux at the bottom of the system, assuming negligible deep drainage. This paper also aims at identifying the requirements to make such a collaboration happen. Complementary to Barthel (2014), who puts emphasis on the differences between the two disciplines on a regional scale and discusses the possibility of using interdisciplinary strategies to work together, we highlight specific fields where and conditions under which collaboration is inevitable for studying water resources at the catchment scale and we suggest when approaches from the two disciplines can be integrated.

In the first part of this paper (Section 2), we briefly describe some differences between the two disciplines including differences in education, data collection and usage, as well as common modelling approaches. In the second part (Section 3), we focus on discipline-specific assumptions on boundary conditions by hydrologists and hydrogeologist, respectively. By presenting discipline-specific assumptions in different research contexts, we want to show that hydrologists and hydrogeologists have to take a step toward an integrated view to benefit from each other, instead of conceptualizing an important part of the hydrological cycle by a simple boundary condition. In this way, both disciplines together could make process on important current challenges for society.

2. Boundaries between hydrologists and hydrogeologists

2.1. *Object of interest and terminology*

Catchment hydrologists and hydrogeologists have in common that they are interested in hydrological processes and often adopt a system perspective. However, the object of investigation and the perspective of the disciplines are often different. Accordingly, also the concept and level of detail with which various parts of the water cycle are studied are different. This is reflected in textbooks and terminology. There is no textbook available that covers both hydrology and hydrogeology in a balanced way (Barthel, 2014). During lectures and in textbooks some processes are only mentioned, some introduced, and some are explained in detail, and the weight that is given to the explanation of a process originates from the "classical" problems of the respective discipline.

The boundaries of aquifers, which are the focus of hydrogeologists, align to varying degree with catchment boundaries. In the case of alluvial aquifers systems, there is usually a direct relationship between the aquifer geometry and the current catchment organization. Geological and hydrological processes that have led to the formation of the aquifers might still be active. In such cases, it is relatively easy to find common ground among hydrologists and hydrogeologists because their objects of interest are similar and aligned. Deeper aquifers have often formed under geological and hydrological conditions that were distinctly different from today, and the pattern of groundwater flow can defy current catchment logics. Groundwater might flow across catchment boundaries or in opposite direction of flow paths at the surface, aquifers might stretch across numerous catchments (e.g., large aquifer systems such as Guarani aquifer in South America, Great Artesian Basin in Australia or Milk River Aquifer in North America), and rivers that are at the core of a catchment can be the boundary of a groundwater flow system (e.g., the Geneovese aquifer that stretches between the Arve and Rhône river, Geneva, Switzerland).

This misalignment of catchment boundaries that are only defined by surface topography and aquifers is one of the reasons for discrepancies in the concepts and terminology among the two fields (Fig. 2c). Furthermore, there are tendencies to resolve processes in different parts of the hydrological cycle in more detail, meaning both disciplines focus on different processes. It is instructive to analyze the conceptualization and terminology of processes that transfer water between the domains of main interest of catchment hydrologists and hydrogeologists, i.e., water leaving the surficial zone, which is usually treated in greater detail in catchment hydrology, to become groundwater, and water leaving the subsurface to become streamflow.

For water leaving the surficial zone, researchers from both disciplines use the term *groundwater recharge,* but the conceptualization and considered boundary differ. Catchment hydrologists put a stronger emphasis on surface processes that influence streamflow while groundwater recharge to deeper zones in many hydrological models receives little attention and groundwater processes are lumped into one or a few simple reservoirs (Fig. 1). The boundary across which recharge occurs tends to correspond to the depth at which water only percolates downward, starting somewhere below the root zone, and recharge rates are often quantified with soil water balance approaches. In contrast, hydrogeologists consider the water from any direction that enters the saturated zone with the consequence that the unsaturated zone (i.e., depending on the thickness of this zone, the top 1–100 m) is often not explicitly considered. Groundwater recharge includes for hydrogeologists also delayed lateral inflow such as mountain block recharge (Ajami et al., 2011; Gilbert and Maxwell, 2017; Wilson and Guan, 2004), which is often not considered by hydrologists but can be hydrologically relevant (Welch et al., 2012). Processes upstream of the boundary, across which recharge occurs, receive little attention. Between recharge boundaries in catchment hydrology and hydrogeology often lies the vadose zone as a 'no man's land' that is treated in neither domain with much detail. Most studies focus on the upper part of the vadose zone typically close to the topsoil. Regarding field studies, there are rather few that investigate more extensive vadose zones (e.g., larger than 5 m) between top soil and water table (Dahan et al., 2009; Rimon et al., 2007; Turkeltaub et al., 2015). The flow dynamics and transport/reactive processes in more extensive vadose zones are not well understood yet. A major reason is that this zone is very difficult to instrument.

For water leaving the subsurface, catchment hydrologist and hydrogeologists also use the same term, *baseflow*, but mean different things. What matters most for catchment hydrologists is the effect on streamflow, i.e., baseflow is the contribution from delayed sources to streamflow. Baseflow is characterized operationally as the slow flow component, irrespectively of its origin (Hall, 1968). In contrast, for hydrogeologists baseflow corresponds to streamflow component that originates from aquifers only. Since a substantial proportion of the rapid flow component can originate from aquifers, the quantity of water considered as baseflow can vary considerably for the two disciplines (Barthel, 2014).

2.2. Data collection and usage

Which observations are made and how they are used differs strongly between hydrology and hydrogeology. In hydrogeology, the studied systems are storage dominated, i.e., storages are large compared to fluxes. There are relatively long residence times, which sometimes are decoupled from seasonal variations. Compared to this, hydrologists focus generally more on surface water and storage at or close to the surface with relatively short residence times. Therefore, in hydrological studies it can often be assumed that it is possible to close the water balance within a year and fluxes (e.g. annual precipitation or annual discharge) are larger than the dynamic storage (Barthel, 2014; Staudinger et al., 2017). It should be mentioned however, that recent studies have started exploring the influence of deep groundwater storages on flow dynamics and residence times next to storage close to and at the surface (e.g., Benettin et al., 2015; Danesh-Yazdi et al., 2018).

While streamflow can be relatively easily and accurately measured, the direct measurement of groundwater fluxes is only possible in exceptional situations (e.g., spring discharge). In hydrology, the main type of observations are streamflow time series derived from stream gauges, point measurements of precipitation and soil moisture, but also more detailed surface mappings including remote sensing data. Hydrologists frequently measure also groundwater levels although the focus is rather on shallow groundwater at the hillslope.

Groundwater heads measured in piezometers are the main type of observation in hydrogeological applications. The interpretation of these observations can be challenging, especially in areas with large subsurface heterogeneities. In most cases, it must be inferred indirectly using Darcy's law, whose key parameter, the hydraulic conductivity can vary over orders magnitude. Geophysical data (Kirsch, 2009) is used to get an idea about subsurface heterogeneities. Groundwater dating methods, for instance from stable isotopes and noble gases, can provide an indirect means to constrain groundwater flux simulations.

2.3. Modelling approaches

The emphasis on different parts of the hydrological cycle in the two disciplines led to contrasting modelling approaches. While neither discipline can ignore the continuity of the hydrological cycle, often complementary parts are simulated in detail versus being treated in a lumped manner (Fig. 1). Especially earlier on, when computational resources were more limited and data scarcer, the spatial scale of the studies object and the temporal dynamics of considered processes influenced the model structure as well. Finally, the objective of models play an important role, i.e., whether the model is used in a scientific context to improve process understanding or in an operational mode for water resources management or prediction.

In hydrogeology, flow processes were simulated already in early studies in a physically-based and spatially resolved way. This was aided by the simplicity of the underlying flow equation, which is a simple linear equation, and the often-low temporal dynamics, allowing for a coarse time-stepping. However, the influx across the boundaries that drives groundwater flow systems is often represented in a simplistic and coarse way, and processes are lumped together into simple boundary conditions. Despite many other methods to estimate recharge using tracers (Moeck et al., 2017), isotopes or water (Joshi et al., 2018) table fluctuation (Fan et al., 2014), traditionally, groundwater recharge is derived by some simple equation based on precipitation input without considering how detailed surface properties or vegetation influence the recharge component. In the model building process of hydrogeological models, surface properties like topography and vegetation as well as snow dynamics and rainfall dynamics are typically not included, as a lot of effort has been devoted to the improvement of the representation of subsurface heterogeneity.

In many cases, these complex surface properties are lumped into one boundary condition, e.g., recharge or hydraulic head in the river or lake and rainfall dynamics. The temporal resolution of hydrogeological models is often also relatively coarse. For short and intense precipitation events, this is not always adequate, especially for models where surface-runoff and infiltration processes are simulated explicitly. For example, a given amount of precipitation will in many cases result in more or less groundwater recharge if it distributed over a day, as compared to the same amount of precipitation distributed over shorter periods, where overland flow process will become more important. Streams are often conceptualized using fixed head boundary condition (first type, Dirichlet) or using a fixed head and a flux (third type, Cauchy). Although a spatially-resolved simulation of groundwater flow is in principle straightforward, also in hydrogeology lumped-parameter models are sometimes employed because subsurface data to parameterize and to calibrate models are rather scarce. Such lumped parameter models in hydrogeology are generally based on analytical solutions for highly simplified aquifer geometries and are most commonly used for the interpretation of environmental tracer data. Here, the choice of the model is often justified based on the aquifer type, e.g., an exponential model represents the travel time distribution in an unconfined aquifer (exponent depends on recharge rate versus aquifer thickness), a piston model corresponds to a confined aquifer, etc.

Complex, fully-distributed catchment models, such as the SHE model, simulate groundwater flow in a detailed way. However, simpler bucket-type hydrological runoff models conceptualize groundwater flow by using linear reservoirs in different arrangements. Despite such simplistic approaches for the subsurface processes, streamflow dynamics can often be simulated ‘acceptably’ well. A crucial issue in hydrological catchment modelling is the appropriate representation of the functioning of the soil storage as a control of the distinction between water becoming groundwater recharge and eventually streamflow, interflow that is reaching the stream and the evaporative fluxes. Given the lumped nature of many hydrological models, it is hardly possible to include detailed information on subsurface geology. The hydrological model building process does often not include geological information on the catchments boundaries (Sivakumar et al., 2015). Frisbee et al. (2011) found a scaling mismatch between hydrological catchment boundaries and larger scale aquifer-flow-systems, which are not represented by the gauging station (Käser and Hunkeler, 2016). While hydrologists are fully aware that subsurface geological structures might influence the real catchment boundaries, they usually ignore this possibility or are constrained by the limited representation of geological settings in their models. Thus, often only surface topography is used to obtain catchment boundaries.

The main variable(s) and the associated calibration parameters lead to different calibration strategies for hydrogeological models versus hydrological models. Hydrologists typically calibrate their models based on simulations of streamflow data at the catchment outlet. This ignores that also calibration as well as validation with baseflow (e.g., Hailegeorgis and Alfredsen, 2015) or water solutes as well as many other variables might be possible. This is partly owing to the challenge that most times the use of additional variables used for testing implies the need for additional model parameters (Seibert et al., 2019). The main variables in hydrogeological modelling include typically hydraulic heads at various locations, and sometimes groundwater fluxes and streamflow. However, most models are calibrated using hydraulic heads only (Simmons et al., 2012). If the purpose of the model is to predict heads, this type of observation data can be sufficient. However, large uncertainties are expected for the simulated fluxes resulting from a model that was only calibrated using hydraulic heads. Regardless of the type of model, there is the risk that a model provides good fits in terms of process variable it was calibrated to e.g. streamflow in hydrology, but does so with a poor representation of internal processes (Kirchner, 2006; Klemeš, 1986).

3. Overcoming boundaries between catchment hydrologists and hydrogeologists

The separate development of the two disciplines, the different modelling approaches and the different types of field data limit a holistic understanding of the hydrological cycle and water resources in general. A classic example is the interactions between surface water and groundwater, where many authors have pointed out that only a joint consideration of surface water and groundwater will allow advancing our understanding of fluvial systems (Alley et al., 2002; Fleckenstein et al., 2010; Sophocleous, 2002; Winter et al., 1998). Groundwater-surface water interactions are especially important during low flows. However, on a conceptual basis, recent advances in modelling approaches from both the hydrological and hydrogeological community have taken the initiative to overcome the previous limitations. Numerical models based on the original blueprint for a physically based model (Freeze and Harlan, 1969), e.g., MikeSHE, HydroGeoSphere or ParFlow-CLM, are conceptually capable of jointly simulating surface and subsurface processes, and, thus, could constitute a useful tool for a more integrative and holistic consideration of surface water groundwater interactions (Fig. 1). Such models can conceptually integrate the observations and expert knowledge from both hydrologists and hydrogeologists. In fact, there are many other examples where a closer collaboration between hydrologists and hydrogeologists and the application of such integrative models is required to go beyond the marginal advances of recent years (Barthel, 2014; Barthel and Banzhaf, 2016).

For some classical problems, the fastest, most pragmatic modelling approach is to conceptualize either the surface or the subsurface as a simple boundary condition. However, for all situations where feedback mechanisms between the two domains surface and subsurface exist, the implementation of a simple boundary condition can cause problems. A collaboration between the disciplines can then help avoid these problems. Below we provide a brief and not comprehensive overview of situations where neither the subsurface nor the surface should be simplified too much, and the integration of data covering both surface and subsurface is highly recommended.

3.1. Fluxes between surface waterbodies and groundwater

Surface-water groundwater interactions involve both surface water flow processes, as well as groundwater flow processes. This has been recognized and widely discussed in the current literature (e.g., Boano et al., 2014; Partington et al., 2017; Winter et al., 1998). Interactions between surface flow and subsurface flow occur at a wide range of different temporal and spatial scales and affect ecological (Woessner, 2017) and sedimentological processes (Partington et al., 2017), temperature, water quality as well as the exchange fluxes. These processes largely occur in the hyporheic zone. Modelling approaches of the hyporheic zone require the consideration of flow processes in the river, as well as flow processes in the streambed. These processes themselves are governed by larger-scale boundary conditions in the aquifer and the stream and lead to complex feedback mechanisms between the surface and the subsurface (Trauth et al., 2014).

Streambeds constitute an interface between surface water and groundwater. Erosion and sedimentary processes in the streambed are continuously shaping the streambed topography as well as the streambed sedimentary composition (Boano et al., 2014). Velocities of surface water flow are crucial for erosion and deposition processes. More recently, the importance of upwelling groundwater and hyporheic exchange fluxes on the deposition and erosion processes has been observed in both field and laboratory settings (Partington et al., 2017).

The hydraulic properties of the streambed, as well as its topography, control the exchange fluxes between surface water and groundwater. Recent studies (e.g., Gianni et al., 2016) have shown that the hydraulic conductivity of the streambed can change by several orders of magnitude after flood events, therefore undermining the commonly made modelling assumption in both the hydrological and hydrogeological modelling community of constant hydraulic properties of the streambed. This leads to a bias in predictions of groundwater surface water exchange fluxes.

For essentially all the processes mentioned above, it is important to consider the feedback mechanisms between the surface and the subsurface. The conceptualization of one compartment through a simple

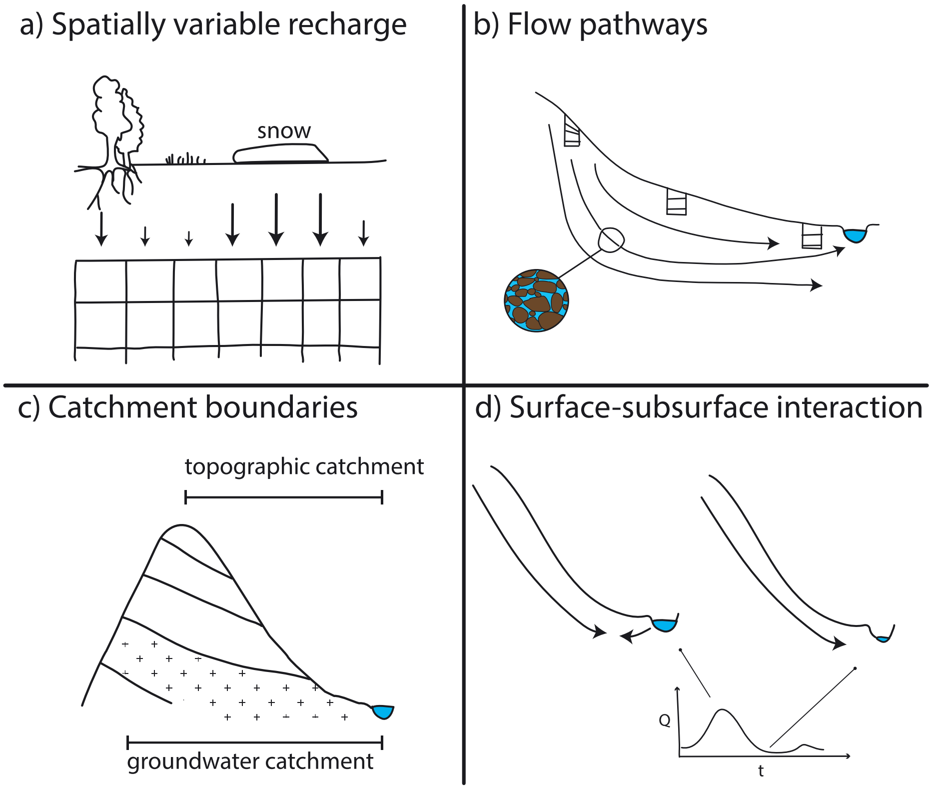

Fig. 2. Examples of how to overcome boundaries between hydrologists (H) and hydrogeologists (HG): (a) Information on lateral redistribution of water (H) → groundwater recharge estimates (HG), benefit: more realistic groundwater recharge pattern; (b) (1) explicit modelling of solute input from soils (H) → estimate of biogeochemical input (HG), (2) explicit modelling of groundwater flow paths (HG) → groundwater transport processes (H), benefit: complementary approaches guided by the nature of the problem; (c) estimated/measured subsurface outflow and nested catchment approaches (HG) → definition of catchment boundaries (H), benefit: closed water balance; (d) streamflow dynamics (H) → incorporation in hydrogeological models (HG), benefit: improved modelling of fluxes/ more robust prediction; lower right: explicit modelling of exchange fluxes (HG) → more realistic surface water groundwater exchange (H), benefit: more robust prediction of high and low flows.

boundary condition prevents a coupled and thus holistic understanding of these processes.

3.2. Soil hydrology and runoff generation processes

The interface between soil and bedrock or soil and unconsolidated material like moraines is an important boundary between hydrology and hydrogeology. For soil hydrology, the soil-vegetation-atmosphere boundary is the key location for partitioning precipitation into runoff, evapotranspiration, and recharge. Since soil and vegetation properties are highly heterogeneous in space, this boundary strongly determines how much water leaves the soil and hence how much water enters the groundwater from above (Fig. 2a).

During more intense or longer rainfall events, or during snowmelt conditions, the infiltrating water is not only increasing the soil moisture storage, but runoff generation can trigger overland flow and subsurface stormflow (or interflow), resulting in lateral redistribution of water and solutes on the surface and within the soil (Bachmair and Weiler, 2011; Weiler et al., 2005). In particular, subsurface stormflow is a key element for soil development within a hillslope, for slope stability processes due to high pore water pressure at the soil-bedrock interface, and for delivering substantial runoff amounts via subsurface flow to the streamflow (Bachmair and Weiler, 2011). For rainfall events, these processes and flow pathways are highly dynamic, and the water commonly follows shallow lateral flow pathways within the upper meter(s) of the soil, where the event water may also mobilize old water, which then is frequently seen in the streamflow response (Bachmair and Weiler, 2014). The slower, but more continuous snowmelt events can trigger subsurface runoff, even in hillslopes without a distinct soil-bedrock boundary, but also in slopes with continuously decreasing hydraulic conductivity resulting in subsurface stormflow and in percolation-excess subsurface flow (Smith et al., 2014).

Runoff generation processes typically happen at a time scale of minutes and hours, and surface and subsurface runoff is a loss term for groundwater recharge as well as for soil water storage in the areas of runoff production. The lateral redistribution of water can, however, also produce more infiltration, percolation and recharge in areas where water from upslope enters the soil and increases both soil moisture storage and recharge. This effect can be quite extreme in urban areas, especially with low-impact storm water management structures. In a case study in Freiburg, Germany, groundwater recharge was simulated in such an urban area and resulted in recharge of over 38,000 mm in two 500 m long swales (Steinbrich et al., 2018; Leistert et al., 2018). Also, in natural catchments, where subsurface or surface runoff are important runoff generation mechanisms, recharge can increase by several factors to even orders of magnitude when laterally redistributed water enters permeable areas in hollows, sinks, dolines or the interface between hillslope and flat valley bottoms (Fig. 2a).

Despite the temporal scale of runoff processes, most groundwater recharge models run on daily or longer time scales. Hence, infiltration and percolation excess are rarely simulated since daily average rainfall intensities of sub-daily rainfall events are too small to generate overland or sub-surface flow. In addition, recharge models are typically one-dimensional models that do not allow for lateral redistribution of water, which results in significant over- or underestimation of recharge in both time and space. Instead, most groundwater recharge models use correction terms (Armbruster, 2002; Armbruster and Leibundgut, 2001) to account for the ‘loss’ of recharge by surface and subsurface flow. Information on runoff generation processes from hydrologists could help increase the realism of spatial and temporal recharge patterns in hydrogeological models. This effect may also be very relevant under climate change, as runoff generation processes are highly non-linear or even threshold-like processes (Meerveld and Weiler, 2008; Tromp-van Meerveld and McDonnell, 2006). For instance, if recharge is generated mainly during snowmelt conditions under current climate conditions, a shift to more mid-winter snowmelt events or to rainfall events could dramatically change the runoff generation resulting in disproportionally more or less recharge.

3.3. Water quality aspects

Water quality is another important field where collaboration between hydrologists and hydrogeologists is indispensable and should be intensified. Numerous catchments scale water quality studies have been published (Wellen et al., 2015). Although many studies use the broad term 'water quality' in their title, most of them deal with diffuse contaminant sources mostly from agriculture, which will also be the focus of this discussion. The objective of water quality models is to predict solute concentration trends at a given location in the stream, and sometimes in groundwater. For robust predictions, such models need to take the temporal and spatial pattern of the solute input into account (e.g., Schuetz et al., 2016). Transport dynamics along multiple pathways cause a time lag between input and output, there are sorption and reactive processes along these pathways, and mixing of waters of different origin and with different chemistries in the stream. Among these models, we focus here on the most commonly used ones as identified in Wellen et al. (2015), namely SWAT, INCA, AGNPS/AnnAGNPS, HSPF and HBV. With the term hydrogeological model, we refer to the classical groundwater models such as Feflow or Modflow with related transport codes. These two model types differ in their spatial resolution, with hydrological models usually discretizing catchments into sub-catchments, while hydrogeological models describe flow and transport in a spatially distributed manner.

Hydrological models generally emphasize the effect of surface features (e.g., topography, soil properties) on the partitioning of water among slow and rapid flow paths and on the solute fate. Biogeochemical processes that govern the solute input from the soil zone (Fig. 2b) are explicitly simulated. In contrast, in hydrogeological models, only the fraction of water that infiltrates is considered further, while 'excess' water is not considered in the model. Solute input from soils is usually not simulated but specified as a boundary condition. Approaches of varying complexities are used from tabulated solute loads as a function of land use irrespectively of site-specific conditions to the simulation of the solute input dynamics with a separate model.

For transport through the shallow and deep subsurface, the situation is reversed. Hydrological models strongly simplify subsurface processes by representing aquifers as single reservoirs. While for hydrogeological models, water moving along rapid flow paths is not considered, in some hydrological model, water reaching a deep groundwater reservoir is no longer considered. For streamflow, a simplified representation of groundwater can be adequate, whereas for water quality a more detailed representation of flow pathways and transit times becomes necessary. Some of the hydrological models (e.g., INCA) represent the delay between solute input and its appearance in the stream by defining a fixed time constant for the groundwater reservoir. However, solute breakthrough in streams or wells is usually governed by a broad transit time distribution due to variations in flow path lengths and velocities among them (Fig. 2b).

Furthermore, solute breakthrough patterns also depend on where solutes enter the subsurface relative to the receptor, which is disregarded in the case of single groundwater reservoirs. In hydrogeological models, subsurface flow paths are resolved spatially, hence reproducing both the effect of spatial variations of solute sources and differences in solute flow paths. Due to their higher data requirement and calculation times, they are usually only implemented for subsections of catchments often focusing on productive aquifers used for water supply. Furthermore, especially in the context of applied modelling for water resources management, also in hydrogeology, simplified lumped approaches are used that resemble those in hydrology. Often solute transport is approximated with a transfer function approach whereby the transit time distribution is characterized by a simple lumped parameter analytical model. Such an approach can reproduce water quality trends in groundwater with sufficient precision, especially if constrained with environmental tracer methods. Refined versions have also been proposed that take the spatial variability of solute input into account.

Many models include separate soil and groundwater zones, but usually simplistic formulations are used to describe how the two domains are connected. Often the output of the soil zone directly enters groundwater. However, a large mass of solutes is often stored in the vadose zone, in case of nitrogen sometimes referred to as the nitrate time bomb. In some hydrological models (e.g., SWAT), the vadose zone reservoir is coarsely represented by a fixed time delay between water leaving the soil and entering the aquifer. Common hydrogeological models can simulate flow and transport under variably saturated conditions, and thus vadose zone processes can be included in a physically-based way. However, as the governing equation for flow is strongly nonlinear and vadose zone processes are more dynamic than processes in groundwater, calculation times strongly increase making it challenging to couple vadose zone and groundwater processes for large catchments (Barthel, 2006).

Solute breakthrough in a stream or well is often strongly influenced by sorption and reactive processes (Fig. 2b). Hydrological models tend to assume that solutes remain stable once they have reached the groundwater box (e.g., INCA) or, given that only discrete reservoirs are considered, a spatially homogenous reaction rate is specified (e.g., SWAT). However, reactive processes often vary spatially with hot spots of enhanced reactivity. For example, reactivity often shows a depth dependence due to more strongly reducing conditions at depth. Or enhanced reactivity occurs in riparian zones, modifying the groundwater composition shortly before it exfiltrates. The effects of such zones crucially depend on how much flow occurs through such zones (i.e., the turnover is transport controlled) and thus an explicit simulation of subsurface flow paths is required.

Finally, another difference among hydrological and hydrogeological models are the receptors that are considered. While hydrological models provide groundwater concentrations, they cannot directly be associated with concentrations measured at a specific location such as a pumping well. In reverse, classical hydrogeological models can provide solute fluxes to streams, which act as boundary conditions, but cannot predict stream water concentrations.

In summary, hydrologist and hydrogeologists simplify the complex problem of water quality modelling in different and complementary ways building on concepts and tools that have evolved within their respective discipline. This also leads to inconsistency in terminology. Interestingly, in the hydrological literature models like SWAT or INCA are often judged as process-orientated (Bouraoui and Grizzetti, 2014) although these models represent groundwater in a very simplistic way. How a water quality problem is simplified should be driven by the nature of the problem (e.g., the type of solute considered) and not by traditions within a discipline. For example, for strongly sorbing contaminants, it can be sufficient to grossly simplify subsurface processes, as transport mainly occurs along surficial flow paths, while for well-soluble compounds such as nitrate, long-term concentrations trends will not be captured if deeper groundwater reservoirs are ignored or merely act as a sink. Or for a problem where a biogeochemical time lag dominates over the hydrological time lag, it is particularly important to explicitly simulate biogeochemical processes.

In some cases, researchers already leverage on the complementary of the approaches by using one type of model to simulate one part of the system, for instance, soil, and specifying the model output as boundary conditions for the second. However, there is much scope for collaboration towards a joint framework on how to best conceptualize and model solutes with different properties at the catchment scale. The effect of the different flow pathways and transit times relates mainly to water quality aspects. From the hydrological (quantitative) perspective, the focus is often on faster flow pathways, while deeper, and longer flow pathways are ignored. The hydrogeological perspective has the opposite bias. Short, surface flow pathways might be ignored, although they can be highly important for streamflow water quality. One way to overcome the difference here could be to include tritium-based transit times (Stewart and Morgenstern, 2016) that could bridge the perspectives of hydrologists and hydrogeologists, i.e., hydrological models could be structured with the help of tritium and stable isotopes derived transit times.

3.4. Low flow periods

Special situations in which groundwater surface water interaction gains importance are low flow periods (Smakhtin, 2001) that occur after prolonged dry weather or when water is stored in the snowpack. During low flow, only contributions from delayed sources sustain streamflow (Hall, 1968). One of the major delayed contributions to streamflow is groundwater discharge from aquifers, which are often assumed to dominate catchment storage even though there are other delayed sources such as snow or glacier melt.

When these delayed sources contribute to the stream, low flow variability is driven by climate variability and geological catchment properties, which shape storage functioning in catchments (Van Lanen et al., 2013; Schneider, 1957; Stoelzle et al., 2014). Catchment storage properties (Staudinger et al., 2017) at the surface (snow, vegetation, soils) have an effect on recharge to aquifers and storage properties in the subsurface have an effect on discharge from aquifers and hence ultimately on the streamflow during low flow periods (Garner et al., 2015; Kirchner, 2009; Lauber et al., 2014). This is why catchment storage properties are important when studying low flows.

There are many hydrogeological studies that focus on the low flows of springs, for instance, large karst springs (e.g., Fiorillo, 2009; Kovács et al., 2005) but few studies explicitly relate the dynamics of aquifers to streamflow under low flow conditions at the catchment scale (e.g., Käser and Hunkeler, 2016). While there are many hydrological studies that focus on low streamflow, the attribution of the governing mechanisms, climate variability, and geological catchment properties, is still not fully understood. To better understand these mechanisms, we must think about our simplified boundary conditions that separate hydrology from hydrogeology again:

Catchment hydrologists analyze low flows often from a water balance perspective (e.g., Garner et al., 2015), i.e., streamflow during low flow periods in the absence of precipitation is seen as a function of catchment storage (Kirchner, 2009) low flows are quantifiable, the water stored in the catchment is not. Groundwater contribution and its characterization are based on two assumptions: (1) streamflow integrates all water releasing processes in the catchment (e.g., snowmelt increases the flux, evapotranspiration decreases the flux) and more importantly, (2) streamflow represents the depletion of catchment storage during prolonged dry weather. Under these assumptions, streamflow is a function of storage and metrics like streamflow recession coefficients, or baseflow indices can be used to characterize or even to estimate catchment storage from streamflow variability. In hydrological practice, the groundwater contribution to streamflow is often estimated with recession analysis methods, which recently have been improved (Roques et al., 2017; Stewart, 2015; Stoelzle et al., 2013; Thomas et al., 2015). Nevertheless, recession segments are only representations of a part of the storage depletion process and often superimposed by streamflow contributions of other delayed sources next to groundwater such as snowmelt in alpine catchments. It would be beneficial, for instance for low flow regionalization, to distinguish between groundwater storage estimate and other delayed sources. It is still an open question on which geological information that should be based on, but such a storage characterization is crucial for more comprehensive low flow studies and regionalization approaches (Bloomfield et al., 2015; Stoelzle et al., 2015). In traditional hydrogeology, aquifer characterization often prioritizes high permeability zones suitable for groundwater extraction, which often have a limited spatial extent relative to the size of catchments. For low flow, bedrock aquifers can become more important as they can release water over an extended period, but much less is known about their characteristics. Development of new geophysical methods to gain better information on the geometry and properties of these bedrock aquifers might help receive important information for storage characterization.

Since storage is important to understand low flow variability, satellite-based approaches to estimate terrestrial water storage on large spatial scales (e.g., GRACE) have been recently linked to periods with less water availability (Houborg et al., 2012). Small-scale gravimeters can help estimate total storage in catchments (Creutzfeldt et al., 2012, 2014; Hasan et al., 2008). However, a reliable estimation of catchment storage for mesoscale catchments remains challenging (Creutzfeldt et al., 2014; Van Loon et al., 2017), especially in mountainous regions due to the uncertainty of remote sensing data and a lack of groundwater level information in those regions. Cosmic ray soil moisture devices (e.g., Heidbüchel et al., 2016) can continuously measure soil water storage over larger areas and depths, which is a promising approach for an improved understanding of catchment storage and to identify the relative importance of soil water storage. Different types of catchment storages (e.g., dynamic, total, immobile storage) have been discussed in the hydrological community (Staudinger et al., 2017) highlighting that different methods assess different types of storage.

There are two reasons for additional data in the context of low flow that could lead to more integrated approaches. First, data is needed to better understand how much water leaves catchments during low-flow periods by including subsurface outflow. This can be achieved by paired groundwater-surface water gauging stations. Many gauging stations do not measure all water flowing out of the catchment, but there is often a substantial flow below the gauge. This subsurface outflow might contribute a significant part of the total outflow from the basin particularly during low flow periods. Käser and Hunkeler (2016) showed that groundwater discharge below the gauging station can be substantial and is not negligible.

Second, additional data is needed to better understand and estimate groundwater storage and release and its effect during low flow in different aquifer units within a catchment, which is more challenging. For low flow dynamics, water storage in the bedrock can play a critical role, but often in these formations, there are no observation wells. A starting point to better understand the groundwater storage changes is thus to gain more data for bedrock aquifers. The issue of missing data is also present at the surface. Missing measurements and measurement quality of streamflow data are an issue in low flow studies when streamflow measurements are often not precise enough.

During periods of zero flow, there can be still groundwater flow out of the catchment (below the streamflow gauging station) indicating a lost connection between surface water and groundwater (Käser and Hunkeler, 2016) and a fully depleted dynamic catchment storage, i.e., the storage that controls streamflow (Staudinger et al., 2017). As further downstream by-passed groundwater can be discharged to the river again, hydrological models should consider subsurface flow as a part of total streamflow. This becomes especially important during prolonged low flow periods.

When modelling these low flow periods, it is hence important to include subsurface flow as part of total streamflow. If subsurface flow is not considered in the water balance calculation, simulated evapotranspiration might be erroneously increased to compensate this. Although a model that is calibrated with parameters that overestimate evapotranspiration may provide good results in term of performance criteria (i.e., differences between simulated and observed streamflow), internal model variables might be wrong and may induce biases in low-flow processes which should be avoided when the model purpose are predictions.

Hydrological models that use a bucket-type representation of the dynamic storage have to be applied carefully for low flow simulations and can benefit from hydrogeological information. Payn et al. (2012) found that topographic controls decreased with progressing streamflow recession, while the influence of multiple aspects of the subsurface structure of the catchment increased with longer recessions. Staudinger et al. (2011) found poor low flow performances of bucket type models related to the model structures representing the subsurface. These findings suggest that in hydrological models a bucket-type representation of the dynamic storage might be only adequate as long as a uniquely defined streamflow-aquifer system controls regional low flows. Hence, we have to analyze when and where the assumption of a uniquely defined streamflow-aquifer system holds, and find better ways to represent aquifer depletion (e.g., Le Moine et al., 2007) as well surface water-groundwater exchange (Fig. 2c)) in bucket-type hydrological models (Staudinger et al., in preparation). Stoelzle et al. (2015) suggest that relatively simple changes of groundwater storages boxes in hydrological models can improve baseflow simulation for different geological settings. This indicates that information on hydrogeology can directly improve low flow modelling in hydrology.

Many hydrogeological models are calibrated with heads only, but are used to predict, e.g., fluxes or residence times. It is challenging to calibrate a hydrogeological model based on heads only. As follows directly from Darcy's law, the same head configuration can result in many different fluxes depending on the hydraulic conductivity. Thus, it is important to constrain a model with some measured fluxes. Particularly under low flow conditions, when most water in the river should originate from groundwater, incorporating stream flow provides such an opportunity to consider fluxes in hydrogeological modelling, as is possible in coupled (Furman, 2008) or integrated models (Barthel and Banzhaf, 2016).

4. Concluding remarks

This paper was written jointly by catchment hydrologists and hydrogeologists to discuss the large potential of collaboration for utilizing more detailed information about a boundary condition from the respectively other discipline. We discussed general differences between the two disciplines hydrogeology and hydrology, how these disciplines evolved separately and which consequences this implies for study foci, data collection, modelling approaches and education. One important issue is that the two disciplines, despite all differences, often use a similar terminology. However, sometimes terms have different meanings, and we must be careful when communicating and working together to avoid serious misunderstandings.

We further discussed the respective boundary conditions, i.e., assumptions at the boundaries of the investigated system when we apply hydrological and hydrogeological models, such as recharge rate (hydrogeology) or zero flux at the bottom of the system (hydrology). We described situations, where the work of hydrologists and hydrogeologists should be brought together and where groundwater surface water interactions urge for a more integrated and joint approach. Often in these situations, the boundary conditions that each discipline defines can be refined with information from the other discipline that studies these boundary conditions as being the focus of their investigations (Fig. 2). The discussion included direct groundwater-surface water interactions, soil hydrology, runoff generation, water quality aspects, and low flow periods. Within these issues, we highlighted especially boundary conditions, where closer collaboration between catchment hydrologists and hydrogeologists would be most useful. Often such collaborations would be relatively straight-forward, and require an increased awareness rather than fancy methods. For instance, simply accounting for ungauged subsurface flow out of a catchment can greatly increase the reliability of predictions as the water balance becomes more realistic and model calibration does not artificially increase evaporation to compensate for the subsurface outflow. We hope that this paper contributes to an increased awareness of the need for collaboration between hydrologists and hydrogeologists, because your work might be my boundary condition.

Conflict of interest

The authors declared that there is no conflict of interest.

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