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HESS Opinions “Integration of groundwater and surface water research: an interdisciplinary problem?”

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Abstract. Today there is a great consensus that water resource research needs to become more holistic, integrating perspectives of a large variety of disciplines. Groundwater and surface water (hereafter: GW and SW) are typically identified as different compartments of the hydrological cycle and were traditionally often studied and managed separately. However, despite this separation, these respective fields of study are usually not considered to be different disciplines. They are often seen as different specializations of hydrology with a different focus yet similar theory, concepts, and methodology. The present article discusses how this notion may form a substantial obstacle in the further integration of GW and SW research and management.

The article focuses on the regional scale (areas of approximately 10^3 to 10^6 km^2), which is identified as the scale where integration is most greatly needed, but ironically where the least amount of fully integrated research seems to be undertaken. The state of research on integrating GW and SW research is briefly reviewed and the most essential differences between GW hydrology (or hydrogeology, geohydrology) and SW hydrology are presented. Groundwater recharge and baseflow are used as examples to illustrate different perspectives on similar phenomena that can cause severe misunderstandings and errors in the conceptualization of integration schemes. The fact that integration of GW and SW research on the regional scale necessarily must move beyond the hydrological aspects, by collaborating with the social sciences and increasing the interaction between science and society in general, is also discussed. The typical elements of an ideal interdisciplinary workflow are presented and their relevance with respect to the integration of GW and SW is discussed.

The overall conclusions are that GW hydrology and SW hydrogeology study rather different objects of interest, using different types of observation, working on different problem settings. They have thus developed a different theory, methodology and terminology. However, there seems to be a widespread lack of awareness of these differences, which hinders the detection of the existing interdisciplinary aspects of GW and SW integration and consequently the development of a truly unifying interdisciplinary theory and methodology. Thus, despite having the ultimate goal of creating a more holistic approach, we may have to start integration by analyzing potential disciplinary differences. Improved understanding among hydrologists of what *interdisciplinary* means and how it works is needed. Hydrologists, despite frequently being involved in multidisciplinary projects, are not sufficiently involved in *developing interdisciplinary strategies* and do usually not regard the process of integration as such as a research topic of its own. There seems to be a general reluctance to apply a (truly) interdisciplinary methodology because this is tedious and few immediate incentives are experienced.

The objective of the present opinion paper is to stimulate a discussion rather than to provide recipes on how to integrate GW and SW research or to explain how specific problems of GW–SW interaction should be solved on a technical level. For that purpose it presents complicated topics in a rather simplified, bold way, ignoring to some degree subtleties and potentially controversial issues.

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1 Introduction

1.1 The status of integration of groundwater and surface water hydrology

"Easy to say, hard to do: integrated surface water and groundwater management in the Murray–Darling Basin" is the title of a recent publication (Ross, 2012a) on the difficulties of managing integratively what should be understood as "a single resource" (Winter et al., 1998). The Murray–Darling Basin in Australia can be considered a good example of a regionally scaled catchment with a long tradition in integrated research (Blackmore, 1995), but still, as Ross (2012a) points out, there seem to be large deficits in the actual integration of groundwater and surface water management. To a lesser degree he identified the same problem setting in Colorado and Idaho (Ross, 2012b), and many other authors describe a similar separation in different parts of the world (e.g., Levy and Xu, 2011 for South Africa). Ross (2012a) studied the obstacles to integration foremost from a social science perspective with a focus on legal and economical questions. In his discussion, he mentions briefly the separation of groundwater and surface water researchers into different scientific communities as one cause of the lack of truly integrative approaches. The present article strives to look at this separation of communities as a cause of the lack of integration more closely:

- Are groundwater hydrology (or hydrogeology, or geohydrology – hereafter regarded as synonyms) and surface water hydrology just specializations of the same discipline (and thus following the same principle ideas and concepts), or is it possible that they are rather far from each other, each with their own traditions, concepts, models and objectives and thus not working together as closely as they should (or could)?
- Are these differences particularly emphasized for regional-scale research?
- Should we thus regard the *integration* of groundwater and surface water research on the regional scale as an interdisciplinary problem and try to learn and benefit from interdisciplinary research concepts applied in other sectors of science?

The discussion of how acknowledging groundwater hydrology and surface water hydrology as different disciplines may help to integrate them better is the main but not the only aspect of the present article. Recognizing a problem as interdisciplinary is a first and very important step, but developing an interdisciplinary approach from there of course requires much more. Interdisciplinarity has long become a buzzword in the scientific world. Hydrology maybe was not always at the forefront of their respective related activities, but more recently, more and more authors have argued strongly for it. Both in the groundwater community (e.g., Galloway, 2010; Langevin and Panday, 2012; Miller and Gray, 2002; Schwartz, 2013) and in the more surface water-oriented community (e.g., Montanari et al., 2013; Sivapalan et al., 2012; Wagener et al., 2010) authors argue convincingly for a more holistic perspective and more interdisciplinary approaches to hydrological research – including collaboration with social sciences and a much deeper integration of societal demands. However, all the above-mentioned authors, even if they very persuasively point out why this is necessary, do not say much about the practical ways to implement this.

It has to be pointed out that this discussion paper does not attempt to make suggestions about how integration of research in groundwater and surface water hydrology could be or should be performed in a technical (i.e., physical/chemical/mathematical) sense. It is also beyond the scope of this paper to exemplify which specific problems should be studied in an interdisciplinary way and which might not need such an approach. Many authors have discussed such aspects in excellent research and review papers (e.g., Sophocleous, 2002) or comprehensive compilations in books (e.g., Bronstert et al., 2005). The objective of this opinion paper is rather to point out that knowing what separates GW and SW research might help us to come to better mutual understanding, better communication and finally better integration. The level of this discussion is thereby rather non-technical, to avoid the key messages of the discussion getting lost in arguments about technical details.

1.2 Why the regional scale?

As pointed out before there is an overwhelming consensus among scientists and practitioners in the entire water sector that the pressing problems in water resource management can only be solved in an integrated way (Savenije and Van der Zaag, 2008). Building on this, the discussion in the present paper is foremost concerned with integration on the regional scale or catchment scale, i.e., areas between 10^3 and 10^6 km^2. This choice was made mainly because from a practical management (or societal) viewpoint, the largest need for integration and thus integrated research exists on larger scales (Bouwer, 2002; Holman et al., 2012; Refsgaard et al., 2010). The larger the area of study, the more factors and processes have to be considered (including societal aspects) – thus integrated solutions are required (Højberg et al., 2013; McGonigle et al., 2012). The smaller an area is the more likely it is that a non-integrative solution is sufficient. As with many statements in this discussion paper, the latter is one that might be discussed controversially. From a purely scientific viewpoint, it could be argued that integration can best be achieved on small scales (where it is less time-consuming) and that the found approaches could then be scaled up from there. From a more practical, management point of view, however, it may be doubted that this is feasible, in particular with respect to the integration of socio-economic aspects. At the same time it could or should be mentioned that on the other end of the spectrum of scales, more and more attempts are made to integrate an even wider range of hydrological processes on continental and global scales. These are important developments and integration on those scales may be equally important as on the regional scale.

2 Current status of integration of ground and surface water research on the regional scale

The question discussed in this article is if regarding groundwater hydrology and surface water hydrology as essentially different disciplines could help to integrate groundwater and surface water research better. This implies the assumption that the current state of integration of these two topics requires improvement. To see if this assumption is appropriate, three major domains of integrated research on groundwater and surface water are evaluated briefly:

1. Integrated regional field studies
2. Integrated regional modeling
3. Integrated regional management and assessment

Integrated regional field studies use field observations from both compartments to analyze and describe properties and processes across boundaries between groundwater and surface water. As comprehensive reviews of this subject are not available, it is difficult to provide evidence of the following statements without citing a huge number of individual references. Most readers might still agree that of the overwhelming number of scientific studies that use regional hydrological data sets (be it proprietary measurements or from public observation networks), relatively few combine groundwater and surface water observations in a truly integrated way. The majority of studies that actually do integrate observations from those different compartments are rather descriptive (e.g., in order to generate status reports, thereby often separating groundwater and surface water into different chapters) than oriented at analyzing interaction between the compartments. On the other hand, the majority of field studies that actually do look at exchange processes and feedbacks of groundwater and surface water are carried out on local scales: hillslopes, riparian systems, the hyporheic zone, flood plains, etc.

Integrated regional modeling. In comparison to integrated field studies, models are not immediately constrained by the size of the study area and the costs of observations. On the contrary, one essential purpose of models is to describe indirectly and evaluate processes and properties in between or in the absence of direct observations. This is why regionally integrated models that provide coupled descriptions of groundwater and surface water processes are quite abundant. Generally, two main types of integrated groundwater–surface water models can be distinguished: (i) fully coupled models, where equations governing surface and subsurface flows are solved simultaneously, and (ii) loosely coupled models – iterative solution methods, where models are linked by using the results of one model as an input to another. The full capacity of fully coupled codes like ParFlow (Kollet and Maxwell, 2006) and HydroGeoSphere (Brunner and Simmons, 2012) has so far foremost been demonstrated in study areas smaller than what was defined as *regional* in the present paper. The more common approach on the regional scale is loose coupling, with typically a focus on either groundwater or surface water, where the respective “less important” side is represented by rather simplified equations and geometry (Furman, 2008; Markstrom et al., 2008). In general, the vast majority of regional models cannot be called integrated in a process-based sense. Rossman and Zlotnik (2013), who reviewed 88 regional groundwater-flow modeling applications from the US, found that only 7 % of those made an attempt to couple groundwater and surface water. An interesting observation regarding integrated groundwater–surface water models on the regional scale is that calibration (validation, verification) is often done using *only* surface water observations (Hattermann et al., 2004; Sebben et al., 2013).

The objective of *integrated regional management and assessment* is to manage the technical, environmental, social and economic aspects of groundwater and surface water resources and their interaction. While field studies and modeling can be carried out on any scale, the regional scale is the typical scale for integrated water resource management and assessment. The lack of integration of groundwater and surface water in water resource management was already pointed out at the very beginning of the article. While integrated water resources management (IWRM) is by now a well-known and accepted concept (Savenije and Van der Zaag, 2008), the success of integrated management and assessment is different and greatly dependent upon traditions, water law, and hydrological/hydrogeological conditions in different countries and regions (Ross, 2012b). Various deficits and challenges encountered in the integrative management of groundwater and surface water are addressed by several authors (Brugnach et al., 2007; Croke et al., 2007; Foster and Ait-Kadi, 2012; Jakeman and Letcher, 2003; Junier and Mostert, 2012; Ross, 2012a). The integrated management of groundwater and surface water inherits the foremost technical problems for integrated field studies and integrated modeling described above as it is necessarily based on these. Additionally, it faces institutional problems and social conflicts that even add another dimension – showing a need for a much wider scope of integrated groundwater–surface water research on the regional scale (see Sect. 5.2).

3 Differences between groundwater and surface water hydrology

The previous section indicated that integration of groundwater and surface water on the regional scale, be it in research or practical management, is not as advanced as it should be and could be. The following section will look at manifestations of differences between groundwater and surface water hydrology to be able to evaluate whether or not these differences are responsible for the deficiencies in integration. The discussion of the differences is mainly done based on a comparison of terminology and concepts used in both fields. As terminology and concepts are usually understood and applied differently depending on individual perspectives and context, it is foreseeable that readers may agree or disagree to different extents. However, it should be acknowledged that the purpose of this discussion is not to draw clear lines and to arrive at unique definitions, but to raise awareness of obstacles that might not be immediately obvious.

3.1 Definitions of hydrology and hydrological research areas

"Hydrology" according to many general dictionaries, including for example Merriam-Webster[1], is seen as the science of the properties, distribution, movement, use and management of water in the earth system. Brutsaert (2005) presents a short overview of definitions of the term "hydrology". He draws the conclusion that the most widely agreed on definition of hydrology limits its scope to continental (terrestrial) water processes. In fact, there seems to be strong consensus that water in the oceans (oceanography), the atmosphere (meteorology, climatology), but to some degree also lakes (limnology) and glaciers (glaciology) are not the central focus of what most hydrologists mean when talking about their profession. Groundwater (groundwater hydrology, hydrogeology), on the contrary, is never explicitly excluded from "hydrology", yet there seems to be a relatively large group of scientists within the hydrological sciences that think of "hydrology" more or less exclusively as the science of terrestrial, (flowing) *surface* waters, that is rivers and their catchments.

Groundwater hydrology is often seen as the specialization of hydrology, which focuses on subsurface considerations. At the same time, a large number of people see *hydrogeology* as a sub-discipline of geology (note that this is the only occasion where this paper makes a distinction between groundwater hydrology and hydrogeology). The rationale behind this is that properties and processes in the subsurface are the domain of the discipline of geology, and understanding stratigraphy, structural geology, mineralogy and geochemistry are essential to understanding groundwater systems.

3.2 Manifestations of differences between groundwater and surface water hydrology

Different definitions are biased by the educational background and perspective of the respective discipline, but also by national scientific traditions and the historical development of educational programs, and in some cases by regional geological/hydrological conditions. Much more interesting than making semantic considerations is to analyze the practical manifestations of the differences between groundwater hydrology and surface water hydrology. The following paragraphs address some of the differences observed by the author. To keep this short, some rather complicated topics are presented in a rather simplified, bold way, to some degree ignoring controversial aspects and dissenting perspectives. As always, things are simply not just pure black or pure white. The differences between GW and SW hydrology presented here are thus not defined by clear separating boundaries; it is often rather tendencies in one or the other direction.

Different objects of interest. Most researchers in groundwater hydrology are foremost concerned with processes in the saturated domains of the subsurface. Thus, their central focus of interest is *aquifers or aquifer systems*. Also by necessity, groundwater hydrologists must be interested in water movement into and out of the saturated zone. Therefore, the unsaturated zone ("groundwater recharge from precipitation") and to a lesser degree surface waters ("infiltration of surface water through the river bed") play a certain role. They form important "boundary conditions" to groundwater systems, and it is of interest how these boundary conditions influence the groundwater system as such and not so much what outside processes create the conditions at the boundaries. Surface water hydrology has a focus on terrestrial, flowing surface waters; the main targets of surface water hydrology are thus rivers and the near-surface parts of their *catchments*. Groundwater is often seen as an essential part of a catchment's characteristics. However, the focus is much less on processes within the groundwater system than on how groundwater contributes to the runoff network at the land's surface (as a source term or boundary condition).

Aquifers (groundwater systems) and *river catchments* are rather different spatial objects with respect to a large number of properties and processes (the term "groundwater catchment" that is eventually used is excluded from this discussion because of its ambiguity):

- Catchments can easily and almost unambiguously be delineated, based on relief, while groundwater systems in most cases have no clear limits in any direction. Their boundaries are often highly dynamic as a result of natural and anthropogenic influences and often remain unknown due to limited accessibility.

- In- and out-flows of catchments can be clearly defined and measured (with some practical limitations), while the in-flows and out-flows of groundwater systems can hardly ever be measured and even a conceptual description can be difficult or impossible even if the location of boundaries is known (see previous item).

[1]http://www.merriam-webster.com/dictionary/hydrology, visited 10/01/2014.

– Aquifers or groundwater systems are strictly three-dimensional objects, often with a vertical differentiation into independent sub-systems. On the contrary, much of the spatial variability of a surface water catchment can be explained by the variability of near-surface properties within the two horizontal dimensions.

– Data on groundwater systems are often only accessible by drilling or indirect observations, while very important characteristics of catchments can be retrieved by mapping the surface and remote-sensing data.

– Groundwater systems are dominated by saturated flow, while flow in surface catchments is separated into surface runoff, open channel flow and unsaturated flow. Although governed by the same principle laws of fluid mechanics, the dominant processes are essentially different on the scale of process description and have thus led to entirely different sets of mathematical formulations. In groundwater systems, the main direction of flow is often horizontal, but strong and deep-reaching vertical flow components with strong spatially varying magnitude may occur. On the contrary, the typical flow components studied in detail in surface hydrology are concentrated at or near the surface following topographical gradients rather than pressure gradients.

– Catchments and aquifers have different dynamics. Catchments are flow dominated, with typically relatively short residence times in the domains that are most interesting to surface water hydrology. It is often possible to close the water balance within one year, and in-flow and out-flow are much larger than storage. Aquifers are often storage dominated, i.e., they can have very long residence and response times and can even be almost fully decoupled from seasonal variations. Storage can be huge in comparison to in- and out-flows. This difference, however, is an apparent one created by different perceptions.

Different types of observations. In both surface water and groundwater hydrology there is a large and growing number of observational methods that can be used to characterize river catchments and groundwater systems and a wide variety of properties and processes therein. To simplify matters, this discussion disregards the fact that many of the observations are related to water quality/chemistry. The focus of this discussion is on water quantity, i.e., discharge measured at gauging stations, and groundwater head or water table elevation in observation wells (piezometers). Both types of observations can be used to measure hydrographs, i.e., time series of water levels or discharge. However, even if hydrographs of piezometric head and discharge often look quite similar, they have essentially different characteristics:

– A discharge hydrograph is, with some limitations, an integral measurement summarizing the processes that occur within the catchment. On the contrary, groundwater level observations are representative of a certain location and a certain depth only. This is a consequence of subsurface heterogeneity and hydraulic barriers or connections in both the horizontal and vertical directions paired with the fact that those structures are often hidden in the inaccessible subsurface.

– While discharge hydrographs typically often show cyclic behavior with recurring features (wet and dry seasons occurring every year with only moderate long-term fluctuations – exceptions such as hydrographs in tidally influenced regions are of course possible), a groundwater hydrograph can be completely dominated by low frequencies without any significant seasonal behavior as a result of the long residence and response times of groundwater systems.

– Measurements of river discharge and river levels at a gauge can be much more directly interpreted with respect to consequences (flooded areas, general water availability). On the contrary, a piezometric head or water table elevation has no immediate clear and simple relation to water availability. To interpret a groundwater level, local knowledge and/or other, often difficult to obtain information are required and conceptually difficult transformations need to be carried out. The meaning of a hydraulic head is always specific to the individual location and the geological/hydrogeological conditions there.

Different timescales. Quite often, when differences between GW and SW hydrology are discussed, different timescales are mentioned as a separating feature. Processes in SW hydrology are considered to be faster, and thus shorter periods are studied, while processes in GW hydrology are considered to be less dynamic. These differences are technically very relevant, in particular for the coupling of GW and SW models. They might, however, play a minor role as a reason for the separation of GW and SW hydrology, and the author refrains from discussing this further here. It is, however, important to acknowledge that integration on a regional scale has to look on longer timescales on either side.

Differences in practical problems and applications. Leaving water quality/chemistry aspects aside again, much research in groundwater hydrology is centred on the question of what the influence of pumping/infiltration on groundwater systems is, both locally (“aquifer testing”) and regionally (“water resource management”). The underlying questions are often related to how much is stored in a groundwater system and how much/how fast one can withdraw from storage – usually over long periods of time. In surface hydrology there is a lot of emphasis on the prediction of discharge, often in relation to floods. The temporal dynamics are quite often more interesting than the average conditions. Differences in problem context and application are difficult to frame in a few sentences, in particular because it is well known that in the long run groundwater and surface water problems cannot be decoupled. However, it is still important to keep in mind that groundwater and surface water research historically started from different types of questions and that this had and still has a large impact on the development of the respective scientific studies.

Different methodology. Even if the basic physical (and chemical) laws are the same for surface and subsurface hydrological processes, the different objects of interest, different types of observations and different sets of problems lead to the development of different methodologies. Many approaches to predicting the behavior of groundwater systems follow mechanistic continuum approaches, with the aim of describing flow and transport pathways explicitly in space and time. In contrast, the characteristics of surface water hydrographs and the integral character of catchments (see above) have opened ways for more conceptual empirically based and statistical approaches. Concepts such as the unit hydrograph or the concept of linear storage cascades are only feasible because of the assumption that all water going into a catchment (minus evapotranspiration losses) ends up at the gauge at the outlet of the catchment. Making a prediction of what might happen in the future based on a statistical analysis of the past behavior of a catchment, as is done for example by deriving flood return periods from past data, is a concept hardly known in groundwater hydrology. This is probably not so much because of methodological constraints, but because such an approach usually does not yield any answers to typical groundwater problems. On the other hand, all the methods used in groundwater hydrology to derive groundwater flow direction, velocity and origin are not necessarily applicable and/or meaningful in surface hydrology.

Different models. A discussion of all the different modeling approaches and strategies in surface and groundwater hydrology is clearly beyond the scope of this paper. The huge number of modeling concepts and codes in both the groundwater and the surface water fields makes even a brief description of this subject difficult. What adds to the problem is the different use of modeling terminology – even within groundwater or surface water hydrology, respectively (see next paragraph). Even if this might be debateable in many cases, one could say that in general in subsurface hydrology on the regional scale, the majority of models used are distributed numerical models based on a continuum approach, i.e., the governing differential equations describing flow and transport are solved numerically for a given domain that is accordingly discretized into elements. These models can be called mechanistic, i.e., based on physical and chemical laws and the use of parameters that are assumed to represent measurable properties. In surface hydrology, as a tendency, many more models are "conceptual", ranging from black box models to more physically based distributed process models, but in general, surface hydrological models often involve "parameters" that have no direct relation to measurable physical or chemical properties. Such parameters are often determined by calibration. It may very well be argued that there is "not much physics" in hydraulic conductivity calibrated for a 100×100 m model cell in a groundwater flow model, but probably still more than in a purely empirically determined recession coefficient of an SW hydrological model. There is a very strong tendency for SW water models to be more conceptual and for GW models to be more physics based, but there is no clear separation and many exceptions exist on either side. In summary it can be said that models in surface and subsurface hydrology necessarily *have to be different*, because they are used to describe different objects, attempt to match different types of observations, and answer quite different questions.

Different terminology. Groundwater and surface water hydrologists often use the same terms, yet with a slightly, sometimes even a completely different meaning. For example, the term "conceptual model" has a completely different meaning in groundwater hydrology than it has in surface hydrology. The author wants to avoid a lengthy (and hopeless) discussion of such terms and trusts that most readers recognize such terminology issues. It should be mentioned that the ambiguous use of model-related terminology is discussed within the respective fields, but such discussions of model terminology hardly span both groundwater and surface water models (see, e.g., Beven and Young, 2013).

The problem of different use of terminology goes beyond modeling. A specific example of this ("groundwater recharge") will be given in Sect. 4. The problem is that because the same terms are used in a similar context, it is often assumed that they have the same meaning – with the consequence that the differences are not detected at all or only after these misunderstandings have led to problematic situations.

Differences in administration, management and legislation. In many countries, groundwater and surface water were traditionally managed by different agencies (surveys) and under different legislation. The consequences of this for research might not be immediately obvious:

- Administration and policy makers have always sought advice from research. Questions coming from different agencies have thus led to the development of different problem settings (see above) and different solutions.

- Monitoring networks for groundwater and surface water developed largely independently and were not designed to monitor interactions between the systems. Their implementation followed the sectorial problem settings and has thus created data sets that can foremost be used only in a specified context.

Different education. In Sect. 3.1, different ways to place groundwater and surface water hydrology in different disciplinary contexts were presented. These differences are reflected by different disciplinary educational programs. Different national and regional traditions and the increasing number of programs and specializations again make it difficult to cover this field in a few sentences. A good proxy to indicate the difference and separation of education might be the relatively clear distinction between textbooks on groundwater hydrology (here usually "hydrogeology") and surface water hydrology. Typically, a groundwater- or a surface water-oriented textbook will contain a shorter sub-section of the respective other subject, but books with a balanced coverage of both subjects do not exist to the knowledge of the author.

3.3 Different scientific communities

Without being able to prove this with quantitative data, the author observes that groundwater hydrogeologists and surface water hydrologists tend to separate into different scientific communities who have their own conferences, organizations and networks. This might differ from country to country as a result of different scientific traditions, but even if the existence of different communities might not be considered to be a hard fact, there are some indications that this separation exists and has consequences everywhere. For example, it might be the reason why the convincing concepts of PUB (Predictions in Ungauged Basins) (Sivapalan et al., 2003) that were discussed intensively for more than a decade in (surface water) hydrology have not found much recognition in groundwater hydrology.

4 Different perspectives and misunderstandings: examples

The discussion presented in the previous sections indicates first a lack of integration and second quite large differences between research in surface water hydrology and groundwater hydrology on the regional scale. The following section will illustrate the practical implications of these using two examples. The description of these examples is rather brief. Interested readers are referred to Barthel (2006) and Götzinger et al. (2008), where those examples were presented in more detail. It is important to acknowledge that example 1 is mainly, if not exclusively, relevant on the regional scale, where processes in the entire catchment (and not just in a river reach or an aquifer) are integrated. This means, e.g., that from an SW hydrology point of view, percolation of water through the unsaturated zone must be regarded as a main process in generating baseflow. This again opens a new discussion on whether or not infiltration or percolation through the vadose zone is a hydrological or rather a soil science topic. Again, the presentation here is rather bold, ignoring the subtleties.

4.1 Example 1: different perspectives on groundwater recharge and baseflow

Within the hydrological cycle, groundwater, surface water and the unsaturated zone form a continuum without clear boundaries in a strict mechanical sense. However, from a practical point of view, one can observe quite essential changes in properties and processes at relatively distinct locations, forming conceptual boundaries in a less strict sense. Fully coupled approaches to describing groundwater-unsaturated zone surface water systems as a continuum are feasible, but difficult to implement on the regional scale. Therefore, integration across conceptual system boundaries is quite often done by looking at each of the systems separately and coupling them through the processes that occur at the boundaries. In the following, two major connections between the compartments will be discussed:

1. Fluxes across the bottom of a river. Depending on climate, relief and geology this flux can occur in different directions and under different saturation conditions (see, e.g., Sophocleous, 2002), but the example will only look at the contact of a river with a saturated aquifer and discuss the flux directed to the river exclusively. This flux is often referred to as "baseflow".

2. Fluxes across the transition between saturated and unsaturated zones. Here, the example looks only at the vertically downward directed flux from the unsaturated into the saturated zone, which is commonly called "groundwater recharge".

Baseflow and groundwater recharge play an essential role in both groundwater and surface water research and practice. The amount of literature on both concepts is overwhelming. As neither groundwater recharge nor baseflow can usually be measured directly, a large number of indirect methods for their estimation exists (for overviews see, e.g., de Vries and Simmers, 2002; Ghasemizade and Schirmer, 2013; Jie et al., 2011; Scanlon et al., 2002; Tallaksen, 1995). The available methods are conceptually very different and often yield very different results.

Baseflow is usually determined using conceptual approaches (conceptual hydrological models and hydrograph separation (Levy and Xu, 2011)); however, recently it has often also included hydrochemical and isotopic methods (Ghasemizade and Schirmer, 2013) or numerical models (Levy and Xu, 2011). There is a lot of evidence originating from different studies worldwide that the results of most approaches to baseflow estimation are highly unreliable or at least only valid under very specific conditions (see, e.g., Halford and Mayer, 2000; Partington et al., 2012; Vogel and Kroll, 1996). Groundwater recharge estimation methods have an even wider spectrum of approaches (see, e.g., de Vries and Simmers, 2002). Some reasons why so many different methods were established – and thus often yield very different results – are contrasting catchment/groundwater system characteristics, different data availability and different scales of application. However, different approaches are also the result of *a difference in the understanding of recharge and baseflow*.

In the case of groundwater recharge, two different perspectives can be identified: from a groundwater-focused perspective, groundwater recharge is defined as the sum of in-flows *entering* the saturated groundwater zone from above, below and laterally. Surface hydrologists and soil scientists, in contrast, often assume that groundwater recharge is the amount of water *leaving* the soil or root zone vertically downwards (see Barthel, 2006; Scanlon et al., 2002). The basic assumption here is that when water leaves the domain influenced by vegetation and evaporation moving downwards, it will eventually have to reach the groundwater and therefore must be equivalent to groundwater recharge. An even simpler, but closely related, understanding of groundwater recharge is a water balance-based consideration, where recharge has to be what is left of precipitation after evapotranspiration, surface runoff, soil moisture storage, etc. have been subtracted. In general, this kind of consideration works well for approaches that are calibrated against observed river discharge. The question of whether or not water has actually entered the groundwater domain (see the recharge definition in the hydrogeological sense presented above) will then not have an influence on the quality of the calibration results.

It should, however, be immediately clear that groundwater recharge defined as "root zone percolation" and groundwater recharge defined as "water entering the saturated zone" cannot be fully identical because, depending on the distance between the root zone bottom and the groundwater surface, at least a temporal delay must occur. This delay can be ignored or at least easily determined when the groundwater table is close to the surface, which is often the case on *local scales* (see, e.g., hillslopes in Sect. 4.2). On a *regional scale* it is highly unlikely that shallow (and unconfined) groundwater tables are present everywhere. On a large scale, the relief and heterogeneity of the deep unsaturated zone will lead to considerable differences in temporal delay at different locations. Even more important is that on the regional scale, and with growing depth in the groundwater, domains of low permeability in the unsaturated zone will lead to the formation of local, independent saturated zones (perched water) and subsequently to horizontal flow. Water transferred horizontally may discharge at the surface at springs and thus does not reach the groundwater system (the mysterious "interflow"). Thus, with a growing scale the differences between the two recharge definitions start to grow (Barthel, 2006).

In the case of baseflow, the differences in conceptualization are even more pronounced. Again, two perspectives can be identified: standard hydrograph separation methods derive baseflow simply speaking as the slow component of a river discharge time series. The empirical methods mainly used cannot identify where baseflow actually originates. Baseflow becomes a portion of discharge measured/simulated at a gauging station, i.e., an integral measure for a catchment. From a groundwater perspective, however, "baseflow" is seen rather as "groundwater discharge", and for most practical applications it is important to know (exactly) where and when the groundwater enters the river.

Problems related to different definitions of groundwater recharge and baseflow typically occur when numerical groundwater models are driven by recharge that is calculated by conceptual hydrological models or when groundwater and surface water models are coupled using recharge and baseflow as linking processes. The spatial distribution of this recharge calculated by hydrological models often ignores the actual geological situation (Barthel, 2006; Götzinger et al., 2008).

4.2 Example 2: the hillslope

Mismatching perspectives are also related to the choice of study objects: it is quite interesting to see that when surface water hydrologists become more deeply involved with the saturated zone (groundwater), this is often done in the context of *hillslopes*, the sloping region adjacent to a river. Groundwater at such a location is often shallow and unconfined. Hillslopes are of great interest in surface hydrology as they, from a surface-oriented perspective, encompass almost all relevant processes. On the other hand, the hillslope situation is not of much particular interest to groundwater hydrologists, mainly because the spatial and temporal scales of hillslope processes are much too small to be of interest for "real" groundwater processes or because many local-scale groundwater problems are not situated in this special topographic condition. Not exactly a quantitative proof of this, but still interesting, are the results of a simple literature research: the Scopus database (www.scopus.com) lists only 18 papers containing "hillslope" or "hill-slope" under article title, keywords or abstract for the almost exclusively groundwater-oriented journals *Hydrogeology Journal* AND *Groundwater*, while 717 papers meet the same criteria in the *Journal of Hydrology* AND *Hydrological Processes*, which are more surface water oriented.

The reason to be interested in groundwater at hillslopes may be less the interest in groundwater system properties and processes itself than the contribution of groundwater to the discharge in the adjacent river. The most problematic aspect of this might be that the groundwater situation at hillslopes seems to have a big influence on the general perception of groundwater. Without being able to provide hard evidence of this, the author has made the observation that many surface water hydrologists tend to regard groundwater systems as shallow, undifferentiated systems, which form bucket-like sinks (or sources) for water that comes from the unsaturated zone or flows into rivers. If you have a hillslope (or floodplain) in mind, there will be many cases where the situation will be exactly like this, but there is a danger that this view of the connection between the unsaturated zone, surface water and groundwater will be extended to larger systems, where the groundwater situation is usually much more complex and the connections are less straightforward.

5 Interdisciplinary aspects of groundwater and surface water integration on the regional scale

The question asked at the beginning of this article was whether regarding groundwater hydrology and surface water hydrology as different disciplines and whether acknowledging this might help to integrate them better. The previous sections have indicated a number of strong differences and several fields with a lack of integration. To evaluate whether applying interdisciplinary concepts may lead to better integration, the following section will at first briefly review interdisciplinary approaches and discuss their relevance with respect to the integration of groundwater and surface water hydrology. Furthermore, this section will discuss the integration of groundwater and surface water in the wider context of interdisciplinarity, mainly with respect to the integration of the natural and social sciences and the interaction between science and society in general.

According to Repko (2011), "academic disciplines are scholarly communities that specify which phenomenon to study, advance certain central concepts and organizing theories, embrace certain methods of investigation, provide forums for sharing research and insights ... Each discipline has its own defining elements – phenomena, assumptions, epistemology, concepts, theories and methods". Looking at the differences derived in Sect. 3, a number of aspects can be identified that suggest that groundwater hydrology and surface water hydrology actually could be considered different disciplines. To prove this might actually be impossible, yet this applies generally to the delineation of disciplines (Abbott, 2001).

5.1 Interdisciplinarity and interdisciplinary methodology

If applying interdisciplinary methodology to the integration of groundwater and surface water research is considered beneficial, then first a clarification of "interdisciplinarity" is necessary. Some definitions of interdisciplinarity focus on how research is performed (e.g., Roy et al., 2013); others emphasize the problem context of research. Repko (2011) reviews several widely used definitions of interdisciplinary research, extracts the common elements of these definitions and finally condenses them into the following: "Interdisciplinary studies is a process of answering a question, solving a problem or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insight to construct a more comprehensive understanding".

Within the huge body of literature on interdisciplinarity, a large number of partly conflicting theories of how interdisciplinary research should be conducted are available. The author does not make an attempt to review and compare the different theories, but instead presents the one that comes closest to his own ideas: Szostak (2002) presents a twelve-step process for interdisciplinary research and discusses comprehensively the relevance of performing and the risks of omitting any of the steps. Some of the steps may at first seem trivial, yet it is the interdisciplinary context that makes them worth considering:

1. *Start with an interdisciplinary question*. This step can mean and encompass different things depending on the starting point of the research: either to explore whether or not a research question is suitable for an interdisciplinary approach, or to frame a research problem or question in an interdisciplinary way. In the context of the discussion presented in this article, this first step is difficult to define and maybe difficult to understand. To determine whether a question is interdisciplinary or in order to ask a question in an interdisciplinary way, iterations with steps 2–4 will be needed for clarification. Only the later steps in the workflow will help to decide whether or not an interdisciplinary approach adds new insights and gives better results than a disciplinary one.

2. *Identify the key phenomena involved, but also subsidiary phenomena*. This will help to identify the degree of interdisciplinarity needed. Subsidiary phenomena might be regarded negligible from one disciplinary view point, but they might be the key phenomena of another.

3. *Ascertain which theories and methods are particularly relevant to the question at hand ... Be careful not to ignore casually theories and methods that may shed some lesser, but significant light on the question*. While disciplinary research often focuses on a few established methods in the field, the key to true interdisciplinarity is openness to any theory or method.

4. *Perform a detailed literature survey*. This means a review of the literature describing a problem from *all* possible disciplinary perspectives. This step thus also requires a review of the different terminology and how terms are used by different disciplines.

5. *Identify relevant disciplines and disciplinary perspectives*. This step could be seen as a conclusion of steps 1–4 and may require several iterations of those.

6. *If some relevant phenomena (or links between these), theories, or methods identified in (2) and (3) have received little or no attention in the literature, the researcher should try to perform or encourage such research*.

7. *Evaluate the results of previous research*. The goal is to identify key phenomena that may have been excluded from previous analyses and to evaluate the impact that this may have had on results. It is important to identify disciplinary perspectives and the biases resulting from this.

8. *Compare and contrast results from previous disciplinary or interdisciplinary research*. If different disciplines reach differing conclusions, it should be checked whether these differences are merely semantic or real. If differences are real, the question needs to be asked: what would have to change in order to generate similar (unique) results?

9. *Develop a more comprehensive/integrative analysis*. This step encompasses a wide range of activities. In addition to understanding the parts, the interdisciplinary researcher must attempt to understand how multiple causation and feedback loops interact. It is necessary to check whether one unifying theory or methodology is possible or whether different phenomena within the problem in question require different methodologies.

10. *Reflect on the results of integration*. How and why do the results of interdisciplinary research differ from previous disciplinary research? What is the added value of integration? What degree of integration is truly necessary and what could be omitted?

11. *Test the results of integration*. That results should be validated or verified does not require justification in the field of natural sciences; however, as Szostak (2002) points out, one has to be careful of biasing such tests and one should also be prepared to adjust the analysis in the face of new information.

12. *Communicate the results*. Again, this is an obvious part of any research, yet interdisciplinary research faces the great challenge of having to communicate to both an interdisciplinary audience and to various disciplinary audiences.

A good example of where and when research could benefit from such an interdisciplinary approach is the example of groundwater recharge on the regional scale presented in Sect. 4.1. The author leaves it to the interested reader to do this exercise. For example, such an analysis could reveal that flow and transport through the deeper vadose zone have hardly received any attention (see step 6) but have a significant impact on the results (step 8). In general, the question of where and when integration is feasible and useful is discussed in excellent books like the one by Bronstert et al. (2005).

5.2 The regional scale as a platform for broader inter- and trans-disciplinary research

Integration of groundwater and surface water is an important step towards holistic research in water resources, but truly integrated research has to go far beyond these first efforts. The best integrated groundwater–soil–surface water model still requires meaningful inputs and boundary conditions, i.e., meteorological input and information on water demand, land-use changes, hydraulic structures, etc. In particular, on the regional scale, anthropogenic impacts and processes in neighboring compartments require integration of a much wider range of aspects, in particular also those of a socio-economic nature. Detailed evaluations of the different usages of the term "integration" are provided by Kelly et al. (2013) and Jakeman and Letcher (2003).

Furthermore, it is difficult to imagine integrated GW–SW research on the regional scale that is purely driven by scientific interest. Research will quite often need to have an applied component to justify the efforts and they can hardly ignore existing problems and the demands of practical management. Stakeholder involvement, participatory modeling approaches and communication strategies are thus also an essential part (see Carmona et al., 2013 for a comprehensive discussion). Any researcher who wants to become involved in integrated water research on the regional scale should thus become acquainted with the idea (and challenges) of working together with social scientists and a wider non-scientific public. A good starting point for this are the discussions presented by Strang (2007), Fischer et al. (2011) or Jahn et al. (2012), who discuss the collaboration between natural and social scientists in general. A large body of literature is also available on the interaction between science and the non-scientific world. Keywords are the "science policy interface", "participatory research", and "transdisciplinarity" (see, e.g., Brugnach et al., 2007; Croke et al., 2007; Pahl-Wostl et al., 2007; Carr et al., 2012; Pohl, 2008, 2010; Schoot Uiterkamp and Vlek, 2007). Highly recommended discussions on the role of science in society are provided by Naustdalslid (2011), Weber et al. (2011) and Weichselgartner and Kasperson (2010).

5.3 Interdisciplinary challenges

The preceding sections have provided arguments why regional-scale research in general should be carried out from an interdisciplinary perspective or at least that such research should start with a careful evaluation of the potentially interdisciplinary aspects involved (see items 1–8 in Sect. 5.1). The consensus that interdisciplinarity (and transdisciplinarity) is needed to tackle the challenges of water resource management is overwhelming. To mention interdisciplinary components of research seems to be seen as important when describing individual research profiles or strategies and visions of research institutions. However, scientific evaluation of interdisciplinary research shows a different reality. Much of the research that is considered interdisciplinary by those who perform it is at best multi-disciplinary, i.e., more than one disciplines work together on one problem yet stay in their own disciplinary tradition without creating new unifying theories, concepts and methodologies (Roy et al., 2013). Moreover, the majority of research remains strictly disciplinary.

So why are there these differences between proposed plans and actual outcomes? Among the obstacles to interdisciplinary research that are usually mentioned first is the traditional disciplinary organization of educational systems and research institutes. Related to this is the observation that interdisciplinary research limits career advancement and funding possibilities (Froedeman et al., 2010; Vasbinder et al., 2010). This might be difficult to believe in view of the overwhelming consensus on the importance of interdisciplinarity. A reason might be that both career advancement and research funding is still mainly based on strictly disciplinary review processes. “Good research” is defined differently in different disciplines, but few reviewers will have an overview of what “good interdisciplinary research” is (see Fischer et al., 2011; Froedeman et al., 2010; Heberlein, 1988; Vasbinder et al., 2010). Publishing a (truly) interdisciplinary manuscript is tedious and still a great challenge (Schoot Uiterkamp and Vlek, 2007; Wood, 2012). Planning a (truly) interdisciplinary research proposal with a careful evaluation of all aspects (see Sect. 5.1) requires great effort. To design such research in a way that satisfies all the biased disciplinary reviewers is challenging. The most crucial aspect is the tediousness of interdisciplinary research. There is overwhelming consensus on the fact that interdisciplinary research requires much more time than disciplinary research (e.g., Campbell, 2005; Lerner et al., 2011; Strang, 2007). Collaboration requires a significant amount of time to be spent in communication between the participants, so that all achieve at least a basic understanding of the types of theory, methods, data and analysis used by the others. Collaboration also requires commitment and an openness to acknowledging and understanding differences (MacMynowski, 2007; Strang, 2007). Marzano et al. (2006) and Bell et al. (2005) show that the majority of researchers are not particularly excited about this side of interdisciplinarity. In particular, researchers in the early career stages are discouraged by the disadvantageous time-consuming publication record, limiting aspects of interdisciplinary research (Bruhn, 2000).

6 Discussion and conclusions

The discussion presented in this article is inspired by the recently published concept of the new IAHS scientific decade “Panta Rhei” (Montanari et al., 2013), which emphasizes the necessity for a more holistic perspective of hydrological research. The integration of groundwater and surface water hydrology is thereby particularly interesting in retrospect of the previous scientific decade on PUB. The assumption here is that PUB might not have been entirely successful in integrating groundwater, and the groundwater community might not have taken adequate notice of the PUB activities.

As mentioned earlier in this paper, the question of whether GW and SW should be called different disciplines, subdisciplines or just specializations within one common field is not considered important. What is important though is the *awareness* that substantial differences exist. It seems that difficulties in collaboration and mutual understanding between surface water hydrologists and groundwater hydrologists arise often because the fundamental differences between the two subjects are not acknowledged. The *apparent* closeness of the two disciplines leads to the result that partners in a collaboration often *assume* that they fully understand what the others are doing (and how they do it, why they do it, what their perspectives on problems and processes are), because they use very similar terminology and seemingly similar concepts. The danger is that this assumption is not questioned and the actual dissimilarity of terms and concepts goes undiscovered. This could not happen if such a collaboration would be designed using an interdisciplinary methodology, where determining and understanding the differences in research concepts is always the first step (see Sect. 5.1 as well as MacMynowski, 2007 and Strang, 2007).

It might seem contradictory to the goal of more holistic research in the water field (see, e.g., Galloway, 2010; Wagener et al., 2010) to focus on differences rather than on the commonalities of research fields. However, even if it is highly desirable in the future that all problems in water resource management are solved in a holistic effort, we still need to face the fact that knowledge, expertise and perspectives are distributed irregularly amongst individual researchers, who, in turn, have rather limited possibilities to share and communicate their full knowledge and viewpoints. Each contribution to integrated research will thus be biased by individual expertise and constrained by different backgrounds. The key to successful integration might lie not so much in the attempt to make everyone a universal scientist (or practitioner, decision maker, etc.), but rather in the attempt to enable better communication, i.e., sharing of knowledge between disciplinary experts. An essential step in communication is to make sure that there is a common understanding about the different individual perspectives on the subject. This requires awareness of difference: we need to acknowledge that there are (surface water-oriented) hydrologists and (groundwater-oriented) hydrogeologists. This does not mean that there is a sharp insuperable boundary between these groups, nor does it mean that there are no scientists that are located somewhere in between. Collaboration between individuals or groups of either affinity should be considered interdisciplinary and based on a workflow as presented in Sect. 5.1. Good collaboration requires knowing *what* the collaboration partners deal with, *how* they deal with it and *why* they do it in a specific way. One of the referees who reviewed this article provided a nice analogy by mentioning that the discussion presented in the opinion paper reminded him of the famous book by John Gray “Men Are from Mars, Women Are from Venus”. I have not read this book and do not want to judge its quality and the opinions it conveys, but the title makes it easy to assume what is meant: even if men and women are from the same species, the assumption that their behavior and thinking are motivated by the same reasoning might not be helpful in the attempt to achieve good “integration”. Back to hydrology: a workflow, as presented in Sect. 5.1, will help to identify gaps and overlaps and eventually to develop an appropriate new theory and methodology.

Four essential findings result from this discussion:

1. Groundwater hydrology and surface water hydrology are significantly different and have developed a different theory, methodology and terminology.

2. A lack of awareness of these differences hinders detection of the existing interdisciplinary aspects of GW–SW integration and thus the application of an interdisciplinary methodology that would help to identify a unifying theory and methodology.

3. Most hydrologists (groundwater and surface water) are not sufficiently involved in truly interdisciplinary research, have a lack of understanding of what interdisciplinarity is and how it works. They are not sufficiently involved in developing interdisciplinary strategies and do not usually regard the process of integration as such as a research topic of its own.

4. There seems to be a general reluctance to apply a (truly) interdisciplinary methodology because this is tedious and few incentives are provided.

The key to tackling the resulting problems seems to be that scientists at all levels need to be educated in interdisciplinary thinking and in understanding the benefits, but also the challenges, of interdisciplinarity. Interdisciplinary educational programs (for a compilation of further references see Seibert et al., 2013) are a good start. It is probably inevitable to follow a bottom-up approach, i.e., to start in early undergraduate training to establish the awareness that each problem can be viewed from different perspectives. It seems to me that the focus of interdisciplinary education should be not so much about trying to make each student a universal scientist but to establish knowledge on how highly specialized experts can combine their knowledge in a meaningful way: "It appears clear to us that, within interdisciplinary projects, as much conscious effort and time has to be put into 'making it work' as is required for the scientific research itself and that relational issues are of crucial importance." (Marzano et al., 2006).

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