

**Integration of  
groundwater and  
surface water  
research**

R. Barthel

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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 resources 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 specialisations of hydrology with different focus, yet similar theory, concepts, 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 focusses on the regional scale (areas of approx.  $10^3$  to  $10^6$  km<sup>2</sup>), which is identified as the scale where integration is most greatly needed, but ironically 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 conceptualisation of integration schemes. It is also discussed that integration of GW and SW research on the regional scale necessarily must move beyond the hydrological aspects, by collaborating with social sciences and increasing the interaction between science and the society in general. The typical elements of an ideal interdisciplinary workflow are presented and their relevance with respect to 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 different theory, methodology and terminology. Yet, 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

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integration and consequently the development of truly unifying, interdisciplinary theory and methodology. Thus, despite having the ultimate goal of creating a more holistic approach, we should start integration by analysing 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 (truly) interdisciplinary methodology because this is tedious and few, immediate incentives are experienced.

## 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 for a regional-scaled catchment with a long tradition in integrated research (Blackmore, 1995), but still, as Ross 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 from a foremost 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 for the lack of truly integrative approaches. The present article strives to look at this separation of communities as a cause for the lack of integration more closely:

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- 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 better integrate them 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 requires of course much more. Interdisciplinarity has long become a buzz-word in the scientific world. Hydrology maybe was not always at the forefront of their respective related activities, but more recently, more and more authors argue 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 of 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, they do not say much about the practical ways to implement this.

## 1.2 Why the regional scale?

As pointed out before there is an overwhelming consensus among scientist and practitioners in the entire water sector that the pressing problems in water resources management can only be solved in an integrated way (Savenije and Van der Zaag, 2008).

5 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<sup>2</sup>. This choice was made mainly because from a practical management (or societal) view point, 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  
10 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.

## 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 better integrate groundwater and surface water research. This implies the assumption that the current state of integration of these two topics requires improvement. To see if this assumption  
20 is appropriate, three major domains of integrated research on groundwater and surface water are briefly evaluated:

1. integrated regional field studies;
2. integrated regional modelling;
3. integrated regional management and assessment.

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*Integrated regional field studies* use field observations from both compartments to analyse 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 for the following statements without citing a huge number of individual references. Most readers might still agree that from the overwhelming number of scientific studies that use regional hydrological data sets (be it proprietary measurements or from public observations 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 to generate status reports, thereby often separating groundwater and surface water in different chapters) than oriented at analysing 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 at local scales: hill slopes, riparian systems, the hyporheic zone, flood plains, etc.

*Integrated regional modelling*: in comparison to integrated field studies, models are not immediately constrained by the size of the study area and the costs of observations. In 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 regional 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, (ii) loosely coupled models – iterative solution methods, where models are linked by using the results of one model as an input to another (for a more detailed description of the available schemes and the respective differences see Barthel and Banzhaf (2014). 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

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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 modelling 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 managing the technical, environmental, social and economic aspects of groundwater and surface water resources and their interaction. While field studies and modelling can be carried out at any scale, the regional scale is the typical scale for integrated water resources management and assessment. The lack of integration of groundwater and surface water in water resources management was already pointed out in the very beginning of the article. While IWRM is a by now 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, 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 modelling described above as it necessarily bases on those. Additionally, it is facing 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 manifestation 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 perspective 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<sup>1</sup>, 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), glaciers (glaciology) are not in 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

<sup>1</sup><http://www.merriam-webster.com/dictionary/hydrology> (last access: 10 January 2014).







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have thus led to entirely different sets of mathematical formulations. In ground-  
water 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, rather  
than pressure gradients.

- Catchments and aquifers have different dynamics. Catchments are flow domi-  
nated, with typically relatively short residence time in the domains that are most in-  
teresting to surface water hydrology. It is often possible to close the water balance  
within one year and inflow and outflow 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 outflows. This difference, however, is an  
apparent one created by different perception.

*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  
characterise river catchments and groundwater systems and a wide variety of prop-  
erties and processes therein. To simplify, this discussion disregards 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. But  
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 sum-  
marizing the processes that occur within the catchment. In contrary, groundwater  
level observations are representative for a certain location and a certain depth  
only. This is a consequence of subsurface heterogeneity and hydraulic barriers or

connections both in horizontal and vertical direction paired with the fact that those structures are often hidden in the inaccessible subsurface.

- While typically most discharge hydrographs show cyclic behaviour with recurring features (wet, dry seasons occurring every year with only moderate long-term fluctuations), a groundwater hydrograph can be completely dominated by low-frequencies without any significant seasonal behaviour as a result of the long residence and response time of groundwater systems.
- Measurements of river discharge and river levels at a gauge can be directly interpreted with respect to consequences (risks, water availability). In 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 is required and conceptually difficult transformations need to be carried out. The meaning of a hydraulic head is always specific for the specific location and the geological/hydrogeological conditions there.

*Differences of practical problems and applications:* leaving water quality/chemistry aspects aside again, much research in groundwater hydrology is centred on the question of what is the influence of pumping/infiltration on groundwater systems, both locally (“aquifer testing”) and regionally (“water resources 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 the most important water quantity related issue is the prediction of discharge, often in relation to floods. The temporal dynamic is often more interesting than average conditions. Differences of 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

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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 process, the different objects of interest, different types of observations and different sets of problems led to the development of different methodology. Many approaches to predict the behaviour of groundwater systems follow mechanistic continuum approaches, with the aim to describe 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 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 behaviour of a catchment, as it is done for example by deriving flood return periods from past data, is a concept hardly known in groundwater hydrology. 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 modelling approaches and strategies in surface and groundwater hydrology is clearly beyond the scope of this paper. The huge amount of modelling concepts and codes in both the groundwater and the surface water field makes even a brief description of this subject difficult different. What adds to the problem is the different use of modelling terminology – even within groundwater or surface water hydrology respectively (see next section). In general, one could say that 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

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domain that is accordingly discretized in 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, 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. 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 relies on the hope that most readers have experienced 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 modelling. A specific example for 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:

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- 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 into 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 make it again difficult to cover this field in a few sentences. A good proxy to indicate difference and separation of education might be the relatively clear distinction of 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.

*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, organisations and networks. This might differ from country to country as a result of different scientific traditions (see above), but even if the existence of different communities might not be considered 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 over more than a decade in (surface water) hydrology, have not found much recognition in groundwater hydrology (see Barthel, 2014).



## 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 practical implications of these using two examples.

### 4.1 Example 1: different perspectives on groundwater recharge and baseflow

Within the hydrological cycle, groundwater, surface waters 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 of properties and processes at relatively distinct locations – forming *conceptual boundaries* in a less strict sense. Fully coupled approaches to describe groundwater–unsaturated zone–surface water systems as a continuum are feasible, but difficult to implement at 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 to 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 zone. 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, hydrograph separation, Levy and Xu, 2011), however, recently it often also includes 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). One reason 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 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 inflows *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: 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

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subtracted. In general, this kind of consideration works well for approaches which are calibrated against observed river discharge. The question, whether or not water has actually entered the groundwater domain (see 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, 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 to 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 conceptualisation 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

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rather “shallow” both in a conceptual and spatial sense. 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. Many hydrogeologists complain about surface water hydrologists, who tend to see groundwater systems as undifferentiated, shallow systems, which form bucket-like sinks (or sources) for water that comes from the unsaturated zone or flows into rivers.

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

The question asked in the beginning of this article was if regarding groundwater hydrology and surface water hydrology as different disciplines and if acknowledging this might help to integrate them better. The previous sections have indicated a number of strong differences and several fields with 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 integration of groundwater and surface water hydrology. Furthermore, this section will discuss the integration of groundwater and surface water in a wider context of interdisciplinarity, mainly with respect to the integration of 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 actually prove this might be impossible, yet, this applies generally to the delineation of disciplines (Abbott, 2001).

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## 5.1 Interdisciplinarity and interdisciplinary methodology

If applying interdisciplinary methodology to the integration of groundwater and surface water research is considered beneficial, than 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 12-step process for interdisciplinary research and discusses very 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 which makes them worth considering:

1. *Start with an interdisciplinary question.* This step can mean and encompass different things depending on the starting point of 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. Iterations with steps 2–4 will be needed for clarification.
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.

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3. *Ascertain what 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 focusses 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 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 among 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 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 if different phenomena within the problem in question require different methodology.

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.

## 5.2 The regional scale as a platform for broader inter and transdisciplinary 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 of water demand, land use changes, hydraulic structures, etc. In particular on the regional scale, anthropogenic impacts and processes in neighbouring compartments require integration of a much wider range of aspects, in particular also those of socio-economic nature. A detailed evaluation of the different usage of the term “integration” is 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

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an applied component to justify the efforts and they can hardly ignore existing problems and demands of practical management. Stakeholder involvement, participatory modelling 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”, “trans-disciplinarity” (see e.g., Brugnach et al., 2007; Carr et al., 2012; Croke et al., 2007; Pahl-Wostl et al., 2007; 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 trans-disciplinarity) is needed to tackle the challenges of water resources 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., two disciplines work together on one problem yet stay in their own disciplinary tradition without creating new unifying theory,





## 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 of 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-SW should be called different disciplines, sub-disciplines or just specialisations 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 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. Yet, even if it is highly desirable that in the future all problems in water resources management are solved in a holistic effort, we still need to face the fact that knowledge, expertise and perspectives are distributed

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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 (truly) interdisciplinary methodology because this is tedious and few incentives are provided.

5 The key to tackle 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. The growing number of 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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