



# Regional groundwater flow and the future of hydrogeology: evolving concepts and communication

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Received: 1 March 2022 / Accepted: 20 November 2022 / Published online: 21 December 2022  
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## Abstract

Consideration of regional groundwater flow in aquifer systems allows for solving groundwater issues on a larger scale than single aquifers and contributes to all practical aspects of the UN's Sustainable Development Goals for water. The approach has been extended to a wide range of hydrogeological environments. However, it suffers from poorly constrained terminology and conceptualisation, compounded by the difficulties of interpreting complex groundwater flow systems. This essay aims to initiate a discussion on improving the application of regional groundwater flow approaches.

**Keywords** Groundwater flow · Aquifer system · Groundwater basin · Conceptual model · Hydraulic continuity

## Introduction

Recognition of how groundwater flow systems operate has opened ‘a new era in hydrogeology’ (Bredehoeft 2018). Following the slogan of the 2022 World Water Day “Groundwater: Making the invisible visible”, recognising regional groundwater flow helps not only hydrogeologists but also natural scientists, engineers, decision-makers, and members of society to better understand what happens to water in the subsurface and how it returns to the atmosphere, biosphere or hydrosphere.

Characterisation of regional groundwater flow started 60 years ago with analytical and numerical solutions for theoretical basins, first

assuming homogeneous aquifers, then later continuing with heterogeneous aquifers. Along with the development of regional groundwater flow theory, it became evident that so-called aquicludes or impermeable units that completely impede groundwater flow do not exist. Instead, hierarchically nested flow systems (local, intermediate or regional) evolve in the subsurface with complex water-table geometries in infinite variations depending on the climate, geological setting and topography. Groundwater flow on different spatio-temporal scales in three-dimensional terrains can be initiated not only by water-table differences but also by other driving forces acting on groundwater. One also has to consider the transient evolution of groundwater systems due to changing climate, driving forces, and boundary conditions during the geological history of their host crustal rocks.

Recognition of the topic ‘regional groundwater flow’ by the International Association of Hydrogeologists (IAH) led to the formation of the Regional Groundwater Flow Commission (RGFC) in 2011 to foster international research and practical applications of related methodologies. Evaluation of the future of groundwater science and research identified the need for new tools for modern hydrogeology and basin-wide studies of regional groundwater flow systems. The term ‘aquifer’, which suggests that groundwater flow and storage are properties of the rock itself, may be inadequate in some cases. In this sense, studying groundwater flow limited to ‘aquifers’ is an outdated concept, and the approach of ‘groundwater flow systems’ should be fully embraced.

This essay intends to outline the significance of groundwater flow systems in the context of current and future hydrogeological challenges. The concept is extended for interpreting complex aquifer systems in different hydrogeological environments. The essay reveals terminology issues and introduces the interpretation of complex aquifer connectivity as a framework. The focus here is on regional topography-driven groundwater flow systems induced by recharge or

This article is part of the topical collection “International Year of Groundwater”

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topography-controlled water-table gradients, and includes the evolution of these systems from human to geological timescales.

### **The regional groundwater-flow-system approach: facing future global challenges**

The increasing global population as well as industrial and agricultural development are degrading the natural environment and human health. The need for mitigation is recognised in the UN Sustainable Development Agenda for 2030, defining water-related goals, including those for groundwater. Groundwater issues, both quantity and quality, appear often at local scales but, in many cases, require basin or regional-scale solutions.

Climate change may significantly impact groundwater levels. A warming climate, for example, can lead to simplified hierarchical flow systems. Groundwater levels in recharge areas seem more sensitive to drying conditions, while discharge areas to a wetter climate. Analysis of the spatial-temporal variability of groundwater levels can therefore convey information about climate change. This approach provides a new tool for regional groundwater management and protection, which can contribute to food security and human health.

Increasing water production not only induces local changes in flow patterns but can also affect entire basins, causing storage loss and initiating cross-formational flow to compensate for the withdrawals. Increased recharge from surface water and reduced seepage to discharge areas also reflect basin-scale reactions of the flow system to groundwater withdrawals. Moreover, basin-scale effects of water exploitation by neighbouring countries can also extend to transboundary aquifer systems. Therefore, consideration of regional groundwater flow will be even more important in the future to prevent further multistakeholder conflicts.

The growing global population and industrial/agricultural activity are increasing groundwater pollution and influencing the local groundwater composition and its natural chemical evolution. Groundwater flow system characterisation can therefore aid in identifying sources of pollutants, such as nitrate, and help determine their fate in groundwaters of large basins. Potential threats to groundwater, especially in karst systems, by emerging organic contaminants (EOCs) have been increasing, but their significance as natural tracers for detecting storage properties and for characterising flow systems is also possible. Hydraulic connections between recharge and discharge areas are underpinned by network analysis between clusters of common microbes representing groundwaters with similar geochemical conditions. Indeed, combining microbial data with hydrologic, geologic, and water-chemistry information can open new directions to characterise groundwater flow systems.

Groundwater-dependent ecosystems (GDEs) are found in discharge areas fed by different flow paths depending on the scale of the associated flow systems (local or regional), with high- or low-seasonal-variability feeding streams, springs and wetlands. Groundwater discharge feeds GDEs, but physical hydrology also affects the type and distribution of GDEs. Climate change and potentially reduced recharge, especially in already dry regions, increase the importance of water retention and replenishment with the investigation of groundwater flow.

Understanding groundwater flow systems is important for both shallow zones and deeper regions. Deep-infiltrated meteoric water

can increase in temperature, creating geothermal systems that can be utilised for heat and power production. Sustainable development of geofluids (groundwater, hydrocarbons and hydrothermal fluids) requires collaborative planning.

### **Extension of the regional flow concept to complex aquifer systems in different environments**

Since regional groundwater flow theory was initially developed for sedimentary basins, much interest has been focused on aquifers in siliciclastic environments. Consequently, hydrogeological studies in complex mountainous regions mainly focus on alluvial valley aquifers while considering mountain-front zones impermeable, which is erroneous. Perennial springs can reveal groundwater flow in fractured rock, indicating that basement faults can be discrete high-permeability structures, possibly conducting groundwater across mountain-front zones as far as adjacent alluvial aquifers. Consequently, bedrock aquifers can contribute to streamflow through shallow, weathered bedrock, higher-order streams, and central valley aquifers through deep fracture flow.

Regional groundwater flow theory has also been extended to carbonate aquifer systems. Groundwater flow pattern is characterised by local fast conduit flow, intermediate fracture flow and regional slow matrix flow. In a nonmagmatic orogenic basement, regional thermal-hydraulic-chemical simulations prove that surface topography is sufficient to produce the regional flow conditions. The extent of regional groundwater flow in mountain belts can be analysed using hydraulic features of springs in addition to a statistical analysis of their elevation, discharge and temperature. Finally, the analysis of springs in the high mountains indicated their atmospheric origin and that the penetration depth of meteoric flow was around 2 km.

Permafrost thawing due to climate warming impacts ecology, mass transport and infrastructure. Groundwater flow can accelerate climate-warming-induced thaw, and heterogeneity and topography strongly affect thaw rates and patterns.

On an extended scale, numerical groundwater flow simulations determined long-range flow pathways from continental interiors to the oceans. Their highly scalable numerical framework can display the effect of increasing water extraction from the continent, influencing long pathways. Nowadays 'coastal hydrogeology' is an important zone of interaction of different origins of water and driving forces, i.e. regional groundwater flow and density-dependent flow.

Meteoric water and advective fluid transport in orogenic crystalline basements may reach the brittle-ductile transition zone. Although this is beyond the present discussion, different fluid driving forces, including topography and temperature gradients or topography and salinity gradients, in such basement zones can also be treated as energy flow systems of the upper crust.

### **Framework for interpretation of regional groundwater flow**

Extension of the regional flow system concept for different environments is based on several theoretical and practical developments over the last few decades. However, there are often misunderstandings of

regional groundwater flow processes and inconsistencies in defining conceptual flow models developed to help manage groundwater resources. This is partially due to the misuse of associated terminology. These issues can lead to uncertainty in evaluating regional groundwater flow.

The first issue is the need to replace the term ‘aquifer’ with ‘aquifer system’, as initiated by Kreamer et al. (2021). The term ‘aquifer’ is often used synonymously with ‘aquifer system’. Van der Gun (2022) presents definitions that refer to more than one aquifer or intercalated permeable and less permeable material (i.e. aquifers and aquitards), but most do not invoke the context of spatial dimensions and lithology. As a result, even different parts of the same general aquifer can form ‘aquifer systems’. On the other hand, spatially distinct aquifers can also behave as an aquifer system, like the four horizontal compartments in the Guarani Aquifer (Argentina, Paraguay, Uruguay, Brazil) and three separate aquifers in North Africa.

If one assumes regional groundwater flow in aquifer systems, the next issue is the interpretation unit, which can be a basin. It is clear that aquifer systems are part of ‘basins’ and constitute natural units and environments for regional groundwater flow. In this sense, an ‘aquifer system’ consisting of two or more hydraulically connected aquifers would be part of a groundwater basin allowing water movement between the aquifers under cross-aquifer hydraulic gradients. Note that the term ‘aquifer system’ represents the rock framework of the basin with stratigraphic and tectonic elements of the area but does not imply anything about the flow system. Flow patterns also involve information about driving forces influenced by climate and topography (Fig. 1).

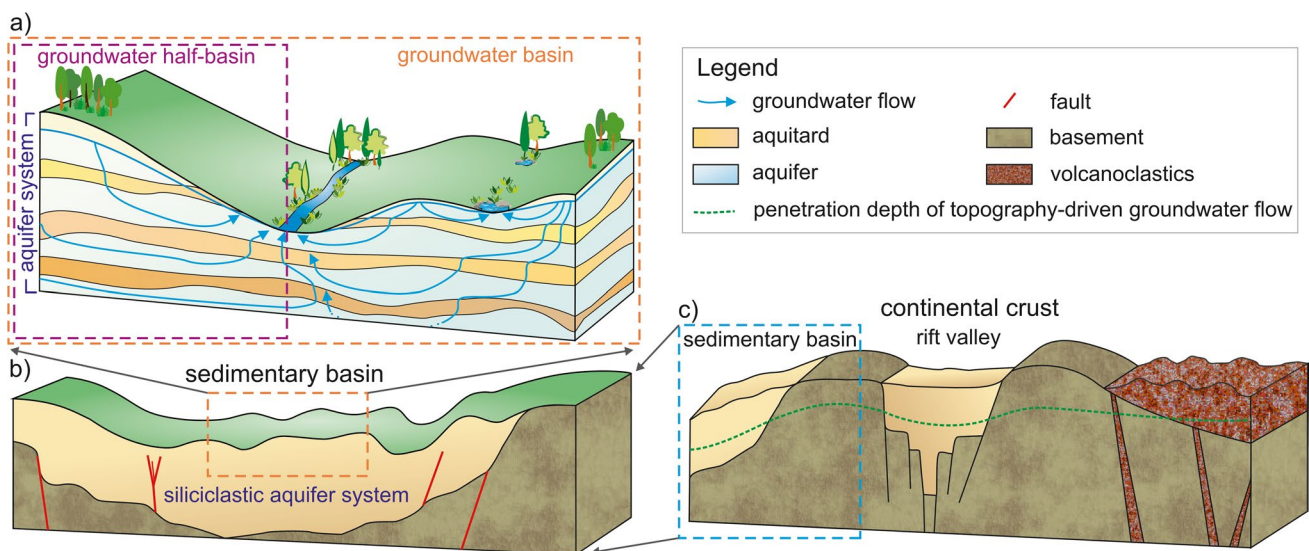
The confusion is that the term ‘basin’ is used in hydrogeology in different contexts, including artesian, groundwater, surface watershed and sedimentary basins, without a clear definition. In so-called ‘artesian basins’, hydrogeologists assume simplified plug flow in confined and separated unconfined aquifers. However, ‘artesian flow’ is possible without confining layers in an unconfined system; therefore, the term ‘artesian basin’ has become obsolete. Nevertheless, the term ‘artesian

flow’ is still widely used in hydrogeology, which can be confusing when interpreting groundwater flow systems.

Cross-formational flow across unconfined and confined aquifers and aquitards in basins has been recognised since the late 1960s. The term ‘groundwater basin’ is a three-dimensional closed hydrologic unit which contains the entire flow paths. In the low-lying parts of groundwater basins, the hydraulic-head increase with depth is greater than the hydrostatic value, even without aquitards, and can create flowing wells if the potentiometric surface is higher than the well casing. However, in some cases, the interpretation of a basin refers to only a half-basin extending from a water divide to a valley. Because such a half-basin does not fulfil the groundwater basin definition, it often confuses hydrogeologists; therefore, interpretations of ‘complete’ groundwater basins are required even in two-dimensional simulations (Fig. 1).

Another issue is that water management decisions are usually made on a catchment scale or in areas bounded by water divides. These areas are defined only by surface topography, but they actually extend underground and the groundwater can change due to pumping. Hence, aligning a surface catchment with a groundwater basin defined by its geological and hydraulic boundaries becomes difficult.

The connectivity of aquifers in an aquifer system is another critical topic. ‘Hydraulic continuity’, a phenomenological property of a rock framework, is one of the crucial principles in interpreting groundwater flow. In so-called ‘artesian basins’, one assumes a priori isolation, whereas in groundwater basins, one can assume a priori connection due to hydraulic continuity. Analysis of hydraulic data (potential anomalies) can also reveal if some parts of a basin are isolated due to sedimentary or tectonic reasons or geological evolution. Consequences of any natural or human activities are, therefore, influenced by the hydraulic connection between the aquifers through aquitards (i.e., the rock framework of a basin), in addition to the hydraulic properties of the aquifers and aquitards themselves. Thus, the hydraulic conductivity of aquifers and aquitards is not as deterministic as their hydraulic connectivity and their response to hydraulic changes over different spatial and time scales.



**Fig. 1** Relation of different frameworks to groundwater flow interpretation: **a** groundwater basins; **b** sedimentary basin; **c** terrestrial crustal aquifer system (modified after Yardley and Bodnar (2014))

The term ‘groundwater basin’ relates to hydrogeology, while ‘sedimentary basin’ is a geological term. The lateral boundary of a sedimentary basin can be interpreted as the lateral boundary of a siliciclastic aquifer system, i.e. coinciding with the top of the basement aquifer system. A sedimentary basin potentially contains more than one groundwater basin. The advantage of referring to groundwater basins (for basin-scale interpretation) is their fractal behaviour: small and large basins behave similarly. Flow systems of aquifers with different basement rocks and basin types represent the complex terrestrial crustal aquifer systems.

### Risk of developing conceptual models without testing

By developing hydrogeological conceptual models, one tries to visualise the ‘invisible’, i.e., the groundwater flow system, via the conceptualisation of physical and spatial structures. Nevertheless, these conceptual models are often a collection of vague hypotheses without solid support and can be a significant source of uncertainty if they are not tested. Consequently, hydrogeologists need standard methods for testing alternative conceptual models related to groundwater flow. One can develop such standards by reviewing the great variety of numerical models of regional flow in the literature, including those applicable to basin-scale groundwater systems.

Large-scale groundwater flow systems that extend to greater depths are often data-scarce for the deeper regions. Many approaches are available for evaluation, including measurements of dynamic fluid properties (e.g. pressure, hydraulic head), as well as recharge estimates, groundwater discharge, geochemical, isotopic proxies and borehole temperature data. These are complemented by hydrograph analysis and by artificial and natural tracers, including those in carbonate karst aquifers. However, if one ignores the direct evaluation of the flow field by measured data (hydraulic head and pore pressures), one risks missing direct physical evidence of flow systems.

As a complementary approach, one can interpret manifestations caused by the systematic spatial features of groundwater flow, including water-related surface features (springs, wetlands) and a multitude of processes and characteristics, including those related to hydraulics (e.g. deep or shallow water tables in recharge or discharge areas, respectively), chemistry (e.g. transport of dissolved solids; chemical evolution along flow paths), mineralogy (e.g. accumulation of mineral deposits), vegetation (ex. phreatophytes in discharge areas), and soil and rock mechanics. Although their integration is highly desirable, one must keep in mind that these methods for groundwater flow evaluation have not yet been standardised.

### Concluding remarks

Although the theory of regional groundwater flow was initially developed for sedimentary groundwater basins, it has since been extended to different environments in the Earth’s crust. Regional groundwater flow analysis in aquifer systems provides a comprehensive approach suitable to solve problems on a larger scale than single aquifers and provides a framework for practical application. However, the developed terms are

often not clarified, which causes difficulties in interpreting complex hydrogeological flow systems.

In this sense, several conclusions can be drawn: (1) use of the term ‘aquifer system’ is preferable for regional groundwater flow evaluation; (2) the term ‘artesian basin’ has become obsolete; instead, the use of ‘groundwater basin’ is preferred; (3) more than one groundwater basin can be contained in a sedimentary basin; (4) groundwater basins are characterised by siliciclastic basin fill and/or basement aquifer systems; (5) interpretation of a (full) groundwater basin is required; (6) hydraulic continuity can be assumed in groundwater basins across multiple aquifers, aquitards and faults, as long as one has no contradicting evidence; and (7) multiple conceptual groundwater flow models need to be developed and tested with specific field data, numerical simulations and groundwater flow-related manifestations.

Good governance of aquifer systems requires an understanding of regional groundwater flow and clear communication of concepts and terms. To this aim, the RGFC-IAH Commission is initiating future discussions to promote scientific and practical advancements. There are already many papers relevant to this discussion, which are detailed in the electronic supplementary material (ESM).

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10040-022-02577-3>.

**Acknowledgements** The authors thank Marco Petitta and editor Jean-Christophe Comte for their valuable suggestions. We also appreciate the comments of two reviewers.

**Funding** Open access funding provided by Eötvös Loránd University.

### Declarations

**Conflicts of interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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