The Role of Geological Expertise in the Characterization of Regional Aquifer Systems

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Abstract

Characterization of the aquifer system is a prerequisite for the development of a hydrogeological model. Aquifer characterization includes the structuring of the model area in hydrostratigraphical units. A hydrostratigraphical unit possesses similar hydraulic properties in respect to its capability to transmit and to store groundwater. Usually point information, e.g. well data, is used for the zonation of the hydrostratigraphical units. Besides this data, geological expertise determines the quality of aquifer characterization. The expertise includes knowledge about the sedimentary facies and architecture, the tectonic settings, and the genesis of the aquifer.

Geological expertise is a source of knowledge independent from the field data. It helps to interpret the data, to fill data gaps, and to apply geological features to the model that are not represented by the data. Examples from Saudi Arabia and Germany show the enhancement of aquifer characterization through geological expertise.

Sedimentary facies and architecture: In siliclastic sedimentary bedrock aquifers the primary porosity is reduced by compaction or almost completely filled by cementation. The permeability and storability for groundwater is linked to a network of openings corresponding to bedding planes, joints, faults, and other fractures. Their shape, spacing, number and distribution are controlled by the sedimentary facies and architecture. Groundwater movement through pores is minimal. Spatial distribution of sedimentary facies and architecture is shown for the Paleozoic Wajid sandstone in Saudi Arabia. Based on this distribution, hydrostratigraphical units are identified. Tectonics: The spatial hydraulic conductivity distribution of an aquifer is often determined by the tectonic structure. Examples from the Upper Jurassic karst aquifer and Muschelkalk karst aquifer in Germany show two main areas of hydraulic conductivity: low conductivities in the plateau area and high conductivities in valleys. The valleys usually represent tectonic fracture zones. Spatial distribution of the hydraulic conductivities can only be explained considering these fracture zones. Another example shows the importance of tectonic features for the hydrogeology of the Umm Er Radhuma aquifer system in the eastern part of the Arabian platform. The aquifer system consists of the Aruma, Umm Er Radhuma, Dammam and

Neogene aquifer, which are hydraulically connected to each other. The hydraulic connection is not uniform. The highest vertical hydraulic conductivities can be found along anticline structures, e.g. the Ghawar anticline. These structures show a higher fracture density, and a reduction in primary thickness. These zones are important as they provide “hydraulic windows” between adjacent aquifers. Aquifer genesis: The Muschelkalk in Germany can be subdivided in 3 units. The Upper and Lower Muschelkalk consist mainly of limestones, whereas the Middle Muschelkalk consists of evaporites. Different stages of karstification occur. Sulphate karst in the evaporites of the Middle Muschelkalk prevails in the primary phase. In a second step, ongoing dissolution of evaporites causes irregular subsidence of the overlaying Upper Muschelkalk, accompanied by fracturing and karstification. The process is self-perpetuating, because fresh water has easy access to the evaporites through the collapsed and fractured overlying aquifers. In this stage all features of a mature karst terrain, e.g. sinkholes, missing surface drainage, and caves can be found. Finally, the underlying Lower Muschelkalk is affected by karstification. With the development in landscape and karstification, the aquifer characteristics change in space and time. In the initial phase the aquifer is represented by very low permeability. In the second phase the Upper Muschelkalk is the major aquifer. In the final stage the Lower Muschelkalk replaces the Upper Muschelkalk as main aquifer.

Conclusions: The need and importance of geological expertise is underestimated. This results in an incomplete or even wrong aquifer characterization, although numerous and good-quality field data are often available.

Keywords: Aquifer Characterization, Hydrogeological Model, Wajid, Umm Er Radhuma Aquifer system

Introduction

The description and prognosis of groundwater flow and transport processes in groundwater is always based on a model of the hydrogeological situation. Therefore, the characterization of the aquifer system is a prerequisite for the development of a hydrogeological, respectively conceptual model (Anderson & Woessner 1992, Kinzelbach & Rausch 1995). Aquifer characterization includes the structuring of the model area in hydrostratigraphical units (FHDGG 2002). A hydrostratigraphical unit possesses homogeneous hydraulic properties with respect to its capability to transmit and to store groundwater. Usually point information, e.g. well data, is used for the identification and zonation of the hydrostratigraphical units. Besides this data, geological expertise determines the quality of aquifer characterization. The expertise includes knowledge about:

- the sedimentary facies and architecture,
- the tectonic settings,

- and the genesis of the aquifer.

Geological expertise is a source of knowledge independent from the field data. It helps to interpret the data, to fill data gaps, and to apply geological features to the model that are not represented by the data. Examples from Saudi Arabia and Germany show the enhancement of aquifer characterization through geological expertise.

Sedimentary Facies and Architecture

The permeability and storability for groundwater in sedimentary rocks is linked to the porosity of the rock and to a network of openings corresponding to bedding planes, joints, faults, and other fractures. Shape, spacing, number, and distribution of these are often controlled by the sedimentary facies and architecture (DI NACCIO et al. 2005, GROSS 2003, GROSS et al. 1995). Both small scale and large scale variations in sedimentary facies and architecture are of importance for the definition and zonation of hydrofacies units. This is shown by 2 examples from the Paleozoic Wajid sandstone, located in the south of the Kingdom of Saudi Arabia (BOCK et al. 2008).

The first example from the Jabal Dibsiyah outcrop shows small scale hydrofacies variations: Planar bedded sandstones intercalate with bioturbated layers. The permeability of the planar bedded sandstone is in the range from 50 to 400 mD, its distribution is isotropic. In contrast, the bioturbated layers show permeabilities of up to 1,000 mD (see Figure 1). The permeability distribution is anisotropic: vertical permeabilities are up to 5 times higher than horizontal permeabilities. The bioturbation is made by S*kolithos sp*.; this worm species penetrated the seafloor and left behind vertical burrows, which account for the anisotropy in permeability. The difference in permeability, especially the greatly enhanced vertical permeability in the bioturbated layers, influence the groundwater flow, and hence lead to different hydrofacies units within a few meters of rock. Note that the lithology – medium to coarse grained sandstone – remains the same.

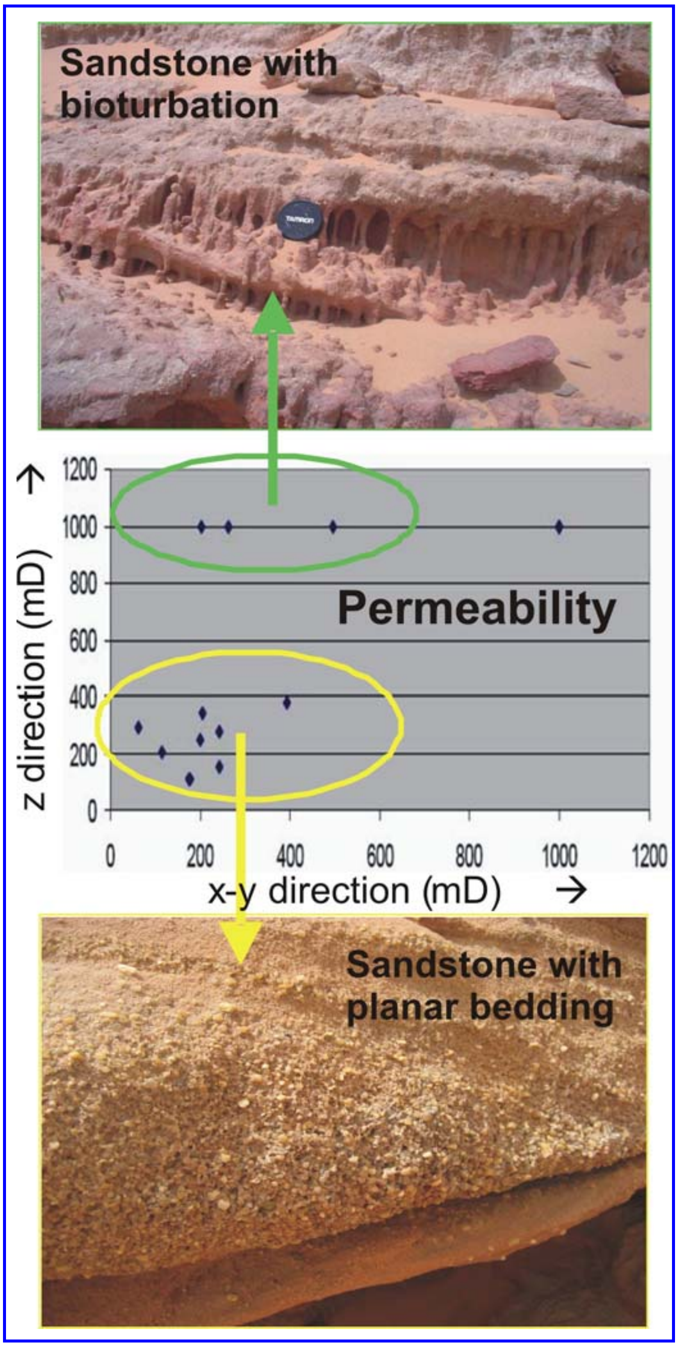

Figure 1: Examples for small scale hydrofacies units from the Lower Wajid sandstone in Saudi Arabia (location: Jabal Dibsiyah). The permeability distribution of the planar bedded sandstone (lower picture) is isotropic. The difference between horizontal and vertical permeability is small. The "*Skolithos*" sandstone (upper picture) is extremely anisotropic. Its vertical permeability is 5 times higher than its horizontal permeability. The vertical *Skolithos* burrows are produced by worms living in the sediment.

The second example presents a large scale approach for the zonation of hydrogeological units on the basis of a regional basin facies model. Like the example for small scale hydrofacies variations, this approach is shown for the Dibsiyah member (Late Cambrian – Ordovician) of the Lower Wajid sandstone.

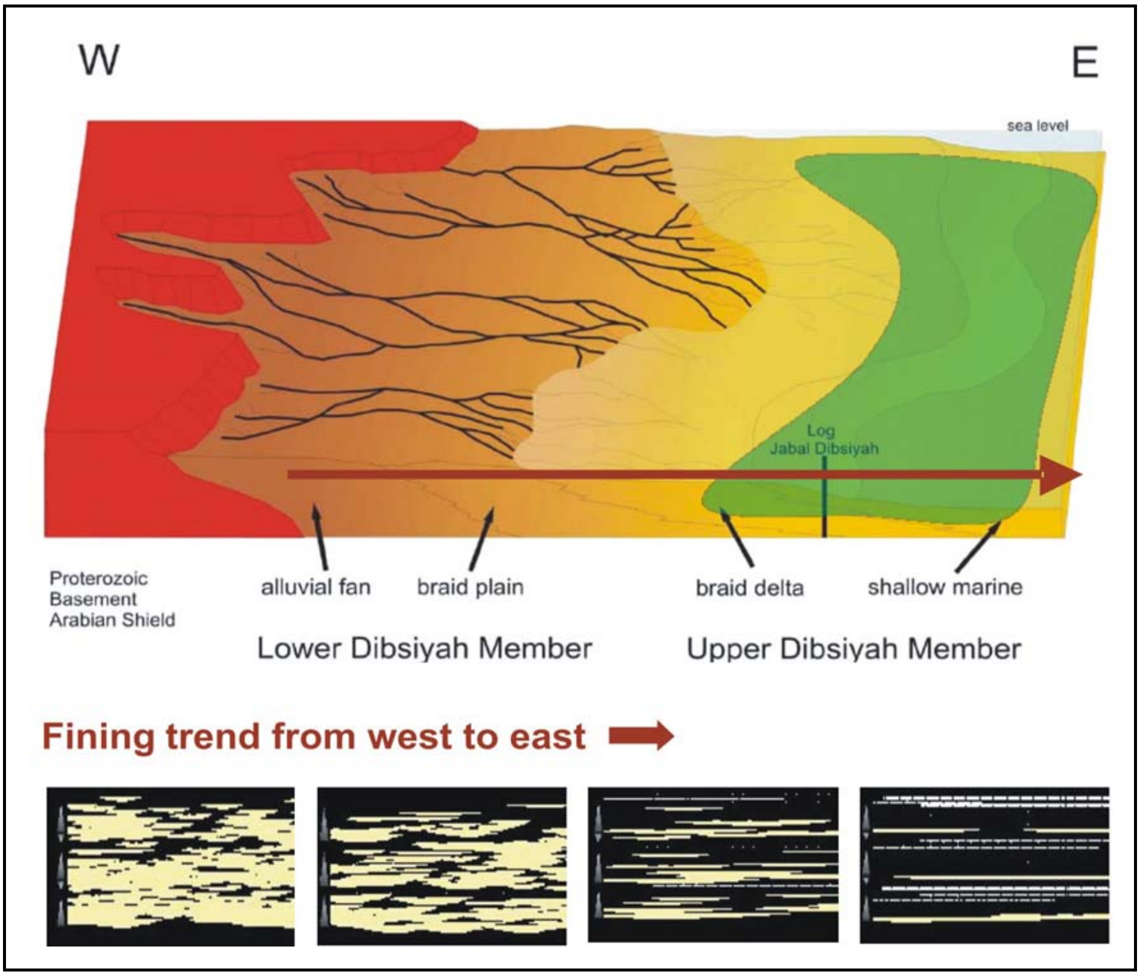

Figure 2: Basin scale facies model for the Cambrian Ordovician Dibsiyah member of the Lower Wajid Sandstone sequence. A fining trend from west to east can be observed, which leads to a decrease in hydraulic conductivity and aquifer storativity. In the western part the Dibsiyah member is developed as a principal aquifer. To the east it becomes less permeable forming an aquiclude or even an aquitard

The general basin facies model for the Dibsiyah formation is shown in Figure 2. It comprises a lateral extent of the Dibsiyah formation of about 50 km. In the West, at the depositional margin of the formation, mainly continental clastic sediments were deposited in an environment of alluvial fans and braided rivers. The lithological succession is made up of thick interconnected sandstone bodies, with only few intercalated silt or clay layers. To the east, this environment changes and becomes deltaic and shallow marine. As a result, more fine grained sediments are deposited. In the east, the lithological succession is made up mainly by clay and siltstones. This leads to a fining trend from west to east, accompanied by a change of hydrogeological properties: hydraulic conductivity and storativity decrease to the east. Based on this observation, different hydrofacies units can be distinguished.

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Tectonics

Many groundwater pathways through rocks are related to tectonic features. Fractures, fissures, and joints determine hydrogeological properties and enable or limit the groundwater flow. Yet differences in the tectonic characteristics are often neglected in aquifer characterization, e.g. when zones of different tectonic exposure are statistically combined.

An example from the Upper Jurassic karst aquifer of the Swabian Mountains in Germany shows two main areas of transmissivity (see Figure 3). The limestones in the plateau areas have low transmissivities while the limestones in and along the valleys have significantly higher transmissivities (Rausch 2002). The valleys are characterized by a higher primary fracture density compared to the plateau areas, which leads to a more intense karstification, respectively higher hydraulic permeability and storativity. Within a relatively homogenous lithology, zones of different tectonic stress determine hydrogeological properties.

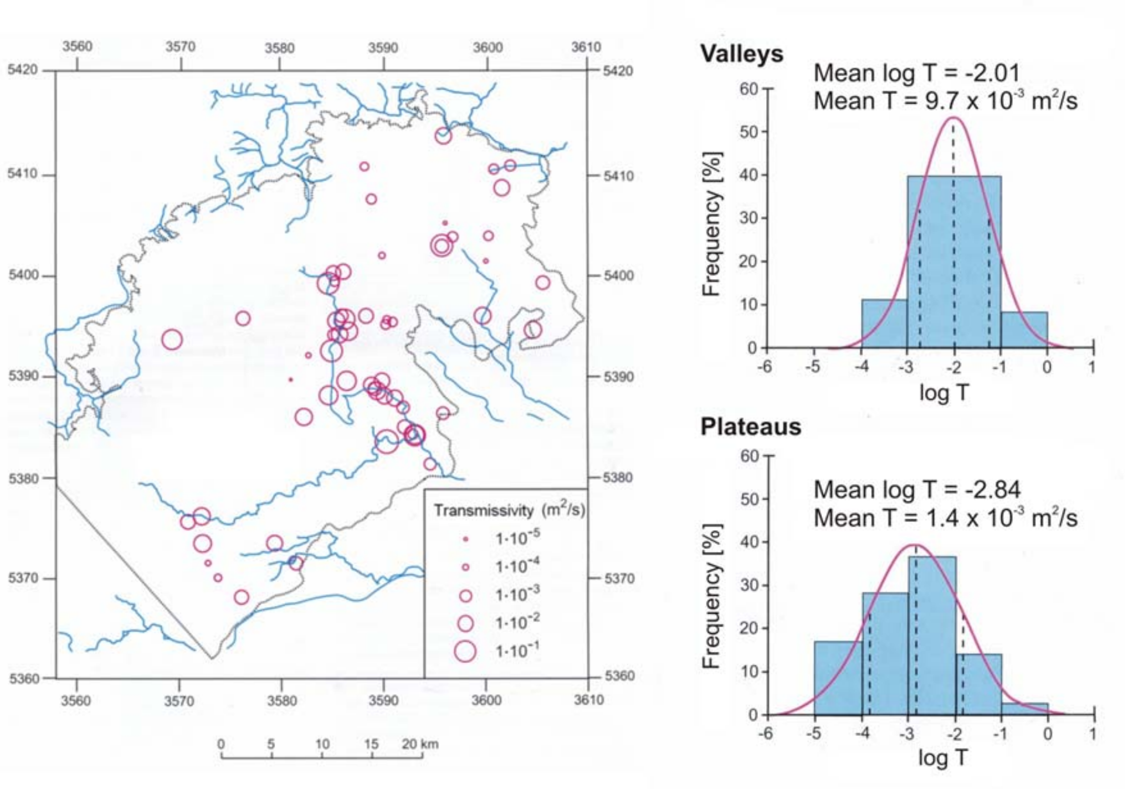

Figure 3: Map showing the spatial distribution of transmissivity in the Upper Jurassic karst aquifer of the Swabian Mountains in southern Germany. Transmissivities in the valleys are significantly higher than in the plateau areas and show a smaller range. The average transmissivity for the valley area is $T = 9.7 \cdot 10^{-3}$ m^2/s. Compared to the average transmissivity of the plateau areas ($T = 1.4 \cdot 10^{-3}$ m^2/s) it is about 7 times higher (modified after Rausch 2002).

Valley orientation is also often linked to tectonic features. An example from the Upper Muschelkalk karst in Hohenlohe in southern Germany shows the interrelation between fracture and valley orientation (see Figure 4). The directions of fractures correlate highly with the valley directions. It must be mentioned, that this relation is only valid for short parts of the valleys (Rausch 1976, Zander 1973).

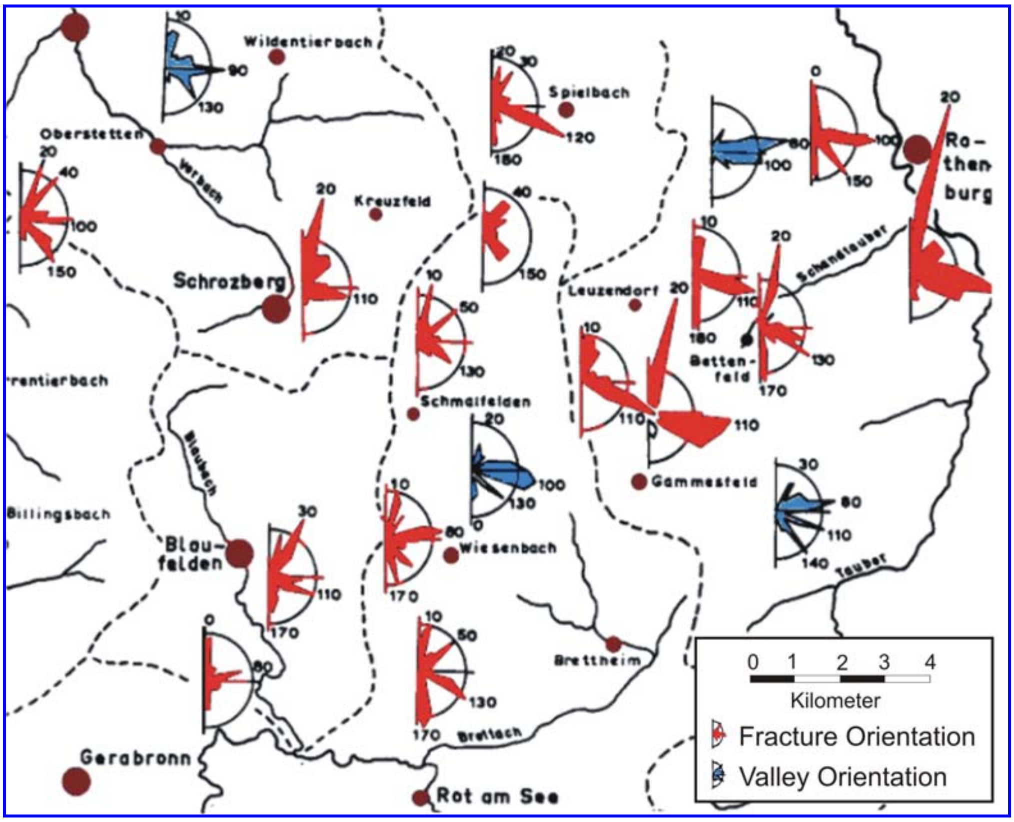

Figure 4: Relation between fracture and valley orientation. The map shows rose diagrams for fractures (red) and valleys (blue). It can be seen that the maximum of the fracture direction coincides with the valley direction. Example from the Upper Muschelkalk karst in Hohenlohe in southern Germany (modified after Rausch 1976, Zander 1973).

Besides the lateral heterogeneities in transmissivity distribution, also vertical changes of transmissivity occur in homogenous lithologies. In both sandstones and limestones, hydraulic conductivity and storativity decrease with depth. This is due to higher fracturing of the rocks at shallower depth. The higher fracturing is caused by weathering, ground relaxation, and carbonate dissolution in case of limestones or dolomites. In contrast, fractures deeper in the aquifer are reduced by compaction. The higher fracturing in shallow depths often leads to a preferential flow zone in the upper part of an aquifer (Lloyd 2004).

In Central Europe, the permafrost during the ice ages altered the width of fractures significantly: up to a depth of 30 m fracturing is enhanced. Figure 5 shows an example from the ‘Keuper Bergland’ in southern Germany. The Triassic Upper Keuper (‘Stubensandstein’) is made up of sandstones, interbedded with siltstones and claystones. It forms an inhomogeneous fractured bedrock aquifer. The caliper log shows the higher fracturing in the upper zone, the flow meter log the corresponding enhanced hydraulic conductivity (see Figure 5). In this example the higher fracturing in the upper zone is due to the impact of permafrost during the ice ages and ground relaxation from erosion.

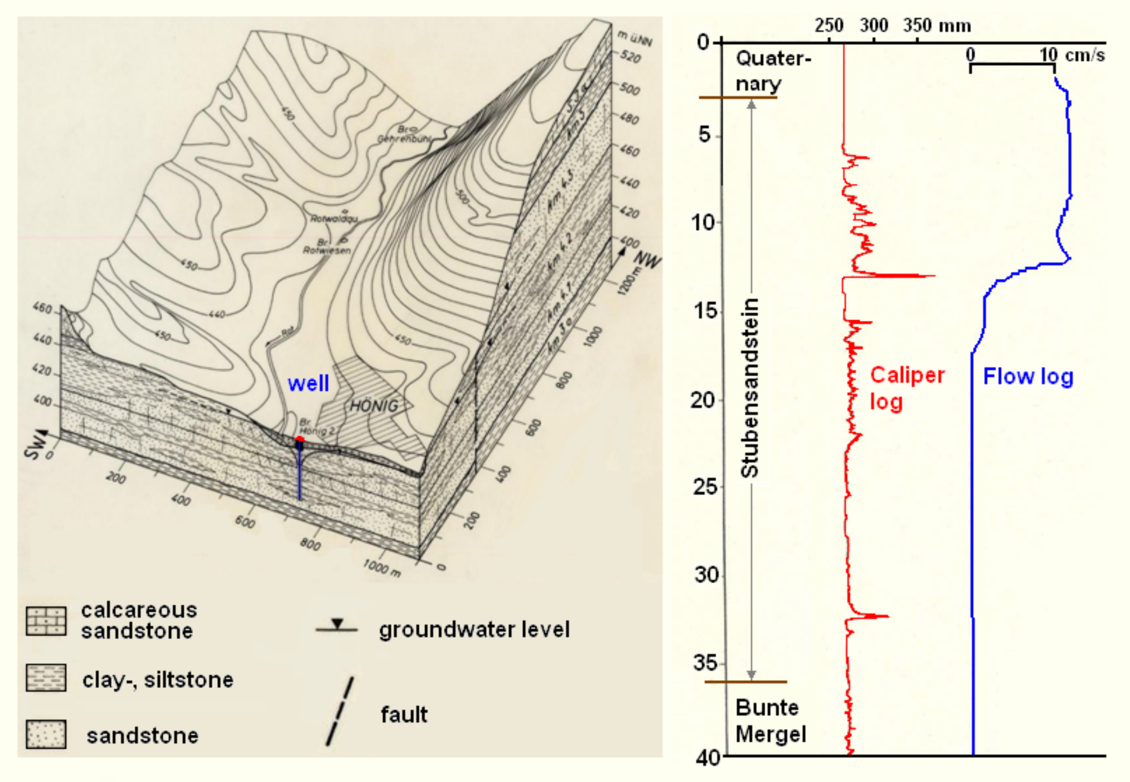

Figure 5: The 3D-view depicts a well location in the 'Keuper Bergland' in Southern Germany. The aquifer consists of a sedimentary succession of sandstones, subordinate clay- and siltstones. The caliper log of the well shows intense fracturing up to a depth of 22 m below ground. The corresponding flow log shows that the main groundwater inflow corresponds to the main fracture zone (modified after Koziorowski & Rausch 1988, unpublished).

Another example shows the importance of tectonic features for the understanding of the hydrogeology of the Umm Er Radhuma aquifer system in the eastern part of the Arabian Platform (GDC 1980, Bakiewicz et al. 1982, MoWE 2007). The aquifer system consists of the Aruma, Umm Er Radhuma, Dammam, and Neogene aquifers, which are hydraulically connected to each other. The hydraulic connection is not uniform (see Figure 6). The highest vertical hydraulic conductivities between the different aquifer units can be found along anticline structures, e.g. along the Ghawar anticline. These structures show a higher fracture density and a reduction in primary thickness. They are important, as they provide 'hydraulic windows' between adjacent aquifers, and lead to a cross-formation flow between the aquifers.

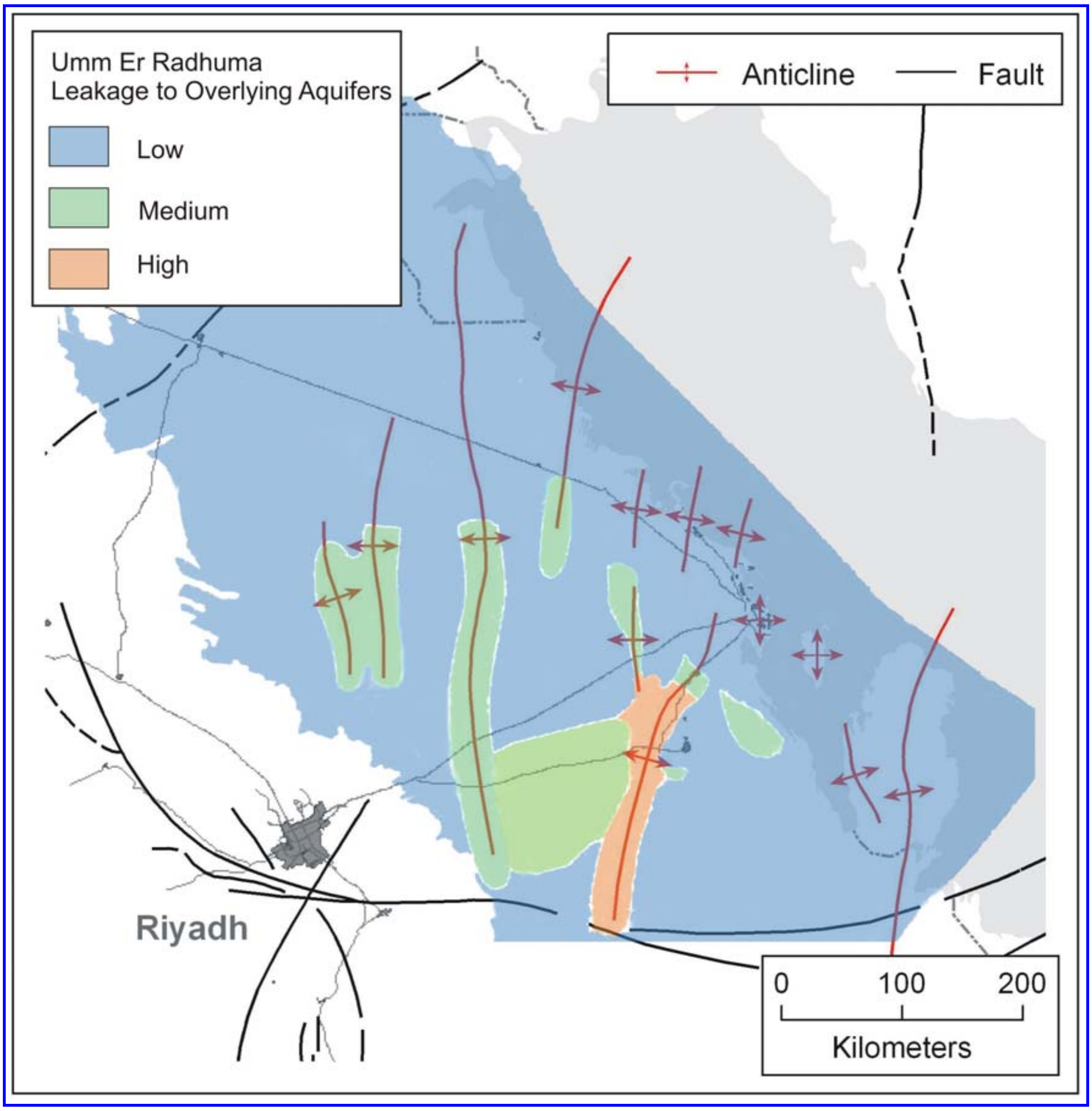

Figure 6: Map showing the main anticline structures and faults within the Umm Er Radhuma aquifer system in the eastern part of the Arabian Peninsula. ‘Hydraulic windows’ between Umm Er Radhuma and overlying aquifers correspond to the anticline structures. In these areas, anhydrite respectively gypsum is dissolved, which usually limits vertical flow between Umm Er Radhuma and its overlying aquifers.

Aquifer Genesis

The Triassic Muschelkalk in Germany can be subdivided in 3 units. The Upper and Lower Muschelkalk consist mainly of limestones, whereas the Middle Muschelkalk consists of evaporites like halite, anhydrite, and gypsum (see Figure 7). Different stages of karstification occur. In the beginning of the aquifer genesis the complete Muschelkalk is overlain by a thick sequence of Keuper sediments. The aquifer possesses a very low hydraulic conductivity and storativity. The groundwater velocity is very slow (about 1 m/d), and the average residence time is several thousand years.

In a second step, ongoing dissolution of evaporites causes irregular subsidence of the overlaying Upper Muschelkalk, accompanied by fracturing and karstification (Simon 1998, Rausch & Simon 2004). This process is self-perpetuating, because fresh water has easy access to the evaporites through the collapsed and fractured overlying aquifers. In this stage, all features of a mature karst terrain, e.g. sinkholes, missing surface drainage, and caves can be found in the Upper Muschelkalk (see Figure 8). The hydraulic conductivity is very high. Groundwater velocities along preferential flow paths are up to 400 m/h.

Finally, the underlying Lower Muschelkalk is affected by karstification. In this third stage, the Upper Muschelkalk acts no longer as a principal aquifer, because ongoing karstification leads to breakdown and filling of fractures and caves with clay and silt. With the development in landscape and karstification, the aquifer characteristics change in space and in time. In the initial phase the aquifer is represented by very low permeability. In the second phase the Upper Muschelkalk is the principal aquifer. In the final stage the Lower Muschelkalk replaces the Upper Muschelkalk as principal aquifer. That means that regarding a geological time scale an aquifer is dynamic and not static. It shows a development with different stages of maturity. In the area of investigation in southern Germany, all three stages of this aquifer development can be found next to each other. According to aquifer maturity, three different hydrofacies zones can be distinguished.

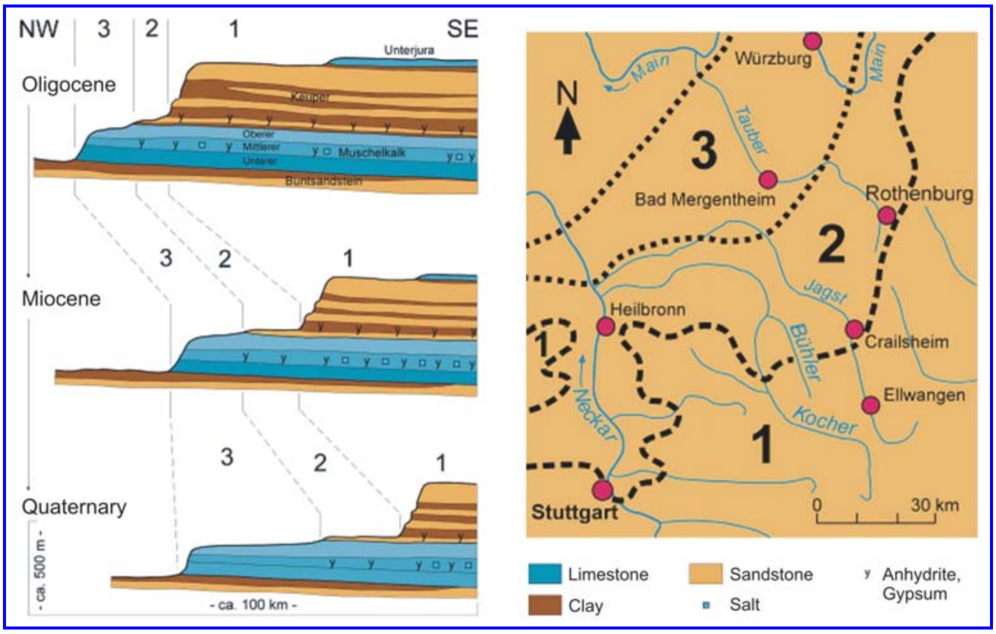

Figure 7: Landscape development from Oligocene to Quaternary and spatial distribution of Muschelkalk aquifers in Northern Baden-Württemberg (southern Germany). The areas 1 - 3 represent different development stages of the Muschelkalk aquifer. Area 1: the complete Muschelkalk aquifer has a very low hydraulic permeability and storativity. Area 2: karstification of the Upper Muschelkalk takes place, forced by subsidence due to the Sulphate dissolution in the Middle Muschelkalk. The Upper Muschelkalk forms the principal aquifer. Area 3: karstification affects the Lower Muschelkalk, making it the principal aquifer.

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Figure 8: Typical karst landforms of the Upper Muschelkalk in area 2. A: sinkhole.
B: dry valley, C: karst pipe, D and E: caves

Conclusions

Hydrogeological models generally have to deal with a lack of data. This is due to the nature of the studied object, the aquifer: it is mostly inaccessible for direct investigation, only penetrated by few punctual drillings, and heterogeneous in its composition. Indirect methods, such as geophysical investigations, can amend the punctual field data. However, using geological 'a priori' knowledge of sedimentology, tectonics or aquifer development contributes significantly to the quality of the hydrogeological model.

The examples from Germany and the Kingdom of Saudi Arabia show the many parameters that influence the spatial distribution of aquifer characteristics. The need and importance of geological expertise is often underestimated. This results in an incomplete or even wrong aquifer characterization, although numerous and good-quality field data are available. Main contributions of geological expertise – or so called geological 'a priori' knowledge – to aquifer characterization are the assessment of:

- Hydrogeological heterogeneities in homogeneous lithology (lateral, vertical, linear).
- Local features with a regional impact on groundwater flow.
- Regional scale lithological variations within the aquifer.
- Genesis and state of aquifer development.

For aquifer characterization and the development of a hydrogeological model on regional scale geological expertise is a must.

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