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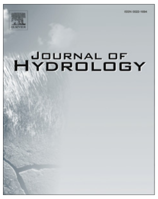

Impact of heterogeneous permeability distribution on the groundwater flow systems of a small sedimentary basin

Alraune Zech [a,*], Björn Zehner [b], Olaf Kolditz [a,c], Sabine Attinger [a,d]

[a] Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
[b] Federal Institute for Geosciences and Natural Resources, Berlin, Germany
[c] Technische Universität Dresden, Germany
[d] Friedrich Schiller University, Jena, Germany

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SUMMARY

Ground water flow systems of shallow sedimentary basins are studied in general by analyzing the fluid dynamics at the real world example of the Thuringian Basin. The impact of the permeability distribution and density differences on the flow velocity pattern, the salt concentration, and the temperature distribution is quantified by means of transient coupled simulations of fluid flow, heat, and mass transport processes. Simulations are performed with different permeabilities in the sedimentary layering and heterogeneous permeability distributions as well as with a non-constant fluid density. Three characteristic numbers are useful to describe the effects of permeability on the development of flow systems and subsurface transport: the relation of permeability between aquiclude and aquifer, the variance, and the correlation length of the log-normal permeability distribution. Density dependent flow due to temperature or concentration gradients is of minor importance for the distribution of the flow systems, but can lead to increased mixing dissolution of salt. Thermal convection is in general not present. The dominant driver of groundwater flow is the topography in combination with the permeability distribution. The results obtained for the Thuringian Basin give general insights into the dynamics of a small sedimentary basin due to the representative character of the basin structure as well as the transferability of the settings to other small sedimentary basins.

1. Introduction

Sedimentary basins are of special concern for both scientific and economic reasons, because they are potential aquifers. Thus, understanding the basin-scale flow of groundwater is important for water management, geothermal applications, hydrocarbon migration and for assessing the long-term transport behavior of pollutants dissolved in groundwater. Multiple groundwater systems and sub-systems have been investigated in the past in order to characterize and analyze their main driving force causing the flow (Toth, 1962, 1978; Ge and Garven, 1992; Bachu and Burwash, 1991; Bachu, 1995b; Zechner et al., 2011; Huggenberger et al., 2013). Various forces drive the movement of fluids within sedimentary basins like gradients in hydraulic head due to topography and fluid density variations, but also tectonic loading, seismogenic pumping and the production of diagenetic fluids (Person et al., 1996; Ingebritsen et al., 2006).

For small sedimentary basins, topography is in general the dominant driver for the movement of groundwater: precipitation infiltrates into the soils, partially percolates through the unsaturated zone and recharges the aquifer systems. It leaves the aquifer system usually at low topographic elevations and it returns as groundwater discharge or base flow to surface flow systems such as rivers and lakes. The overwhelming part of groundwater recharge enters shallow or local fluid systems (Toth, 1963). Only a small amount of recharge enters deeper aquifer units by intermediate or regional fluid systems.

Based on a simple mathematical model, Toth (1963) investigated the existence, intensity and potential co-existence of the three flow systems: local, intermediate and regional. The local system describes the flow between adjacent areas of topographic highs and lows. Intermediate flow systems link distinct topographic highs and lows. In regional flow systems, the distance between the areas of recharge and discharge is at basin scale.

According to Toth (1963), the existence and intensity of the flow systems depend on the geomorphological factors of (a) the ratio of depth to width of the basin, (b) the average slope and (c) the local

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* Corresponding author.
E-mail address: alraune.zech@ufz.de (A. Zech).

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relief. Basins with a general slope to the terrain of the terrain but negligible local relief exhibit only a regional flow system. If the basin has a well-defined relief, also local and intermediate flow systems arise, forming a flow system of three co-existing components. An increasing topographic relief tends to increase the depth and the intensity of local flow systems whereas an increasing slope helps the regional flow system to persist. As Toth (1963) emphasized, the theory only holds for basins down to depths at which basin-wide extended layers of contrasting low permeability are found, which implies that groundwater flow has been treated as an unconfined flow through a homogeneous medium.

As extension of Toth's work, Freeze and Witherspoon (1966, 1967, 1968) performed an extensive study on steady-state regional groundwater flow in a three-dimensional, stratified, anisotropic basin. Results are inferred from both analytical as well as numerical solutions, by making use of a finite difference model. Later on Zijl (1999) further developed Toth's idea by making use of Fourier analysis to study scale aspects of groundwater flow. However, these fundamental studies on the groundwater dynamics at basin scale are limited to idealized basin geometries with homogeneous permeability.

Besides the hydraulic gradient, the permeability determines the ground water flow systems of a sedimentary basin by Darcy's law. The distribution of permeability is subject to a high degree of uncertainty. On the one hand, the amount of available measured data is very low. On the other hand, permeability is heterogeneously distributed in space. To cope with the resulting uncertainties, permeability is in general described using a stochastic model. A random description of natural variability allows the limitation of homogeneous permeability to be overcome and the effect of natural heterogeneity in hydraulic parameters to be included. There is an abundant literature on the stochastic aspect of groundwater flow, e.g. early work by Freeze (1975), Gutjahr et al. (1978) and text books by Dagan (1986), Gelhar (1993), Rubin (2003). Smith and Freeze (1979b) published a study on the impact of stochastic heterogeneity in permeability on groundwater flow. They performed statistical analysis of hydraulic head distributions for multiple aspects like boundary conditions as well as different statistical parameter distributions. The benchmark character of the flow domains allowed to determine the impact of different statistical parameters like variance, correlation length and anisotropy ratio on the mean behavior of the flow and the spatial variations from expected head gradients.

Whereas the analysis of Toth (1963) focused on aspects influencing the hydraulic gradient only, this study aims to investigate the impact of the permeability on the distribution of local, intermediate and regional flow systems at an representative basin structure. The analysis is not restricted to an artificial and homogeneous basin, but include complex topography, realistic sedimentary layering, fault zones and local heterogeneities using the stochastic approach. Like Toth (1963), the groundwater flow system of a basin is investigated with a mathematical model but solving the model requires numerical solvers due to the complexity and non-linearity of the equations. In contrast to studies like Smith and Freeze (1979b), which focus on regionalizing the equivalent field of permeability, the focus of this study is on giving a qualitative description of the flow pattern as affected by random heterogeneities.

Areas of stagnant flow are of particular interest in small sedimentary basins (Toth, 1963). Where flow velocities are very small, mineralization and salt dissolution take place. Therefore, it is investigated how permeability distribution impacts on the fluid dynamics in combination with salt and heat transport. In turn, the latter processes can impact on fluid velocity by density variations due to temperature and concentration gradients. If density differences are sufficiently large, they initiate flow due to gradients in hydraulic head (Johannsen et al., 2006). This often occurs in deep basin regions, where the impact of topography driven flow is reduced. For large sedimentary basins, like the North East German Basin, Magri et al. (2005, 2008) and Kaiser et al. (2011) showed that salinization is presumably caused by the interaction of hydrostatic and thermal forces, leading to thermohaline convection. Bachu (1995a) presented two case studies illustrating the importance of accounting for variations in water density and viscosity when analyzing the flow of formation waters in deep sloping aquifers in sedimentary basins. The interest here is in density depending flow in combination with heterogeneous permeability distribution, which has been a recent topic of research interest (Held et al., 2005; Simmons et al., 2010; Zidane et al., 2014).

The Thuringian basin is an ideal real world example of a relatively small drainage basin: it is bounded by topographic highs, drained by a low order stream and has similar physiographic conditions over the whole of its surface. However, it has a much more complex geometry due to local geological structures than the idealized basin of Toth (1963). The real world basin structure affords different combinations of the topographical factors average slope and local relief at different locations of the basin. The permeability distribution of the basin is highly heterogeneous, with several geological layers of different hydraulic character. A salt containing sedimentary layer is present at the bottom of the basin, where salt is dissolved constantly. Tracing the salt transported by groundwater allows regions of stagnant flow with increased salinization to be identified.

The paper is organized as follows: In Section 2 the study area is hydrogeologically characterized, including briefly the geological and sedimentological features as well as the hydrodynamic regime and the temperature distribution. Section 3 is dedicated to the numerical groundwater flow and transport model, its settings, processes, boundary conditions and parametrization. Furthermore, the different numerical experiments are introduced of which results are presented in Section 4. In the last two sections the results for all simulated scenarios are discussed and the conclusions are drawn.

2. Hydrogeological characterization of the study area

2.1. Geological overview

The Thuringian Basin is located in the center of Germany. It stretches in an oval shape approximately 150 km from north-west to south-east and 80 km from south-west to north-east (Fig. 1). The basin borders on the Harz and Kyffhäuser mountains in the north, on the Eichsfeld Swell in the west, and on the Thuringian Forest mountains as well as Thuringian shale mountains in the south (Hoppe, 1959; Jordan and Weder, 1995; Seidel, 2003; Kober, 2008).

Over much of its geological history the Thuringian Basin was part of the North German Basin. It became separated in the Late Cretaceous by the nearly 100 km long Finne fault zone, which symbolizes the morphological and geological north-east border (Malz and Kley, 2012). Several north-west south-east striking faults subdivide the synclinal structure (Seidel, 2003; Malz and Kley, 2012). Their influence on the groundwater flow pattern can be significant on a local up to a regional scale, acting as barriers or preferential pathways.

The basin is filled with Permian and Triassic sediments, while the overlying layers of Jurassic and Cretaceous age are eroded. Tertiary and Quaternary deposits are restricted to river valleys. The internal structure of the basin is strongly influenced by the Upper Permian Zechstein salt deposits. In the center of the basin the