Marine and Petroleum Geology 78 (2016) 690–700

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Hydrodynamics of porous formations: Simple indices for calibration and identification of spatio-temporal scales

M. El-Rawy [a, b], F. De Smedt [b], O. Batelaan [c], U. Schneidewind [d], M. Huysmans [b], W. Zijl [b, *]

[a] Department of Civil Engineering, Faculty of Engineering, Minia University, Minia 61111, Egypt
[b] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[c] National Centre for Groundwater Research and Training, School of the Environment, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia
[d] Department of Engineering Geology and Hydrogeology, RWTH Aachen University, Lochnerstr. 4-20, 52064 Aachen, Germany

ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form
2 August 2016
Accepted 22 August 2016
Available online 25 August 2016

Keywords:
Absolute permeability
Basins
Characteristic indices
Double constraint methodology
Groundwater hydrodynamics
Hydraulic conductivity
Spatial and temporal scales

ABSTRACT

This paper proposes simple indices to characterize the hydrodynamic conditions of groundwater flow systems and parameters of a basin on different space-time scales, i.e., quantities characterizing a complex phenomenon in a relatively simple way. It focuses especially on the identification of hydraulic conductivity in relation to the space-time scales. Two indices, decay time and penetration depth, are derived on the basis of Fourier flow systems. For the determination of parameters, especially hydraulic conductivities, on the scales of such flow systems, simple Flux/Potential (F/P) ratios are obtained from two hydrodynamic models: a flux model (F), in which measured fluxes (flow rates) are specified, and a potential model (P), in which measured potentials or pressures are specified. The F/P ratios are the basis for the double constraint method (DCM), which is shown to be applicable as a simple and efficient calibration methodology for hydraulic conductivity in single phase flow and absolute permeability in multi-phase flow. The index approach is exemplified using a hydrogeological case study of an aquifer-aquitard system in Belgium, which shows sufficient similarity to larger-scale basin hydrodynamics. It is shown that the indices allow to identify the scale of the relevant parameters, mainly hydraulic conductivity, while the F/P ratios indicate where and how measurement of potentials or pressures and flow rates can be used to determine the hydraulic conductivity on that scale.

1. Introduction to basin hydrodynamics

At the basin scale, groundwater hydrodynamics shows extremely complex flow patters. Time-dependent and spatially variable multi-scale undulations of the water table induce a hierarchy of continually growing and disappearing nested flow systems. The water moves rapidly through the local shallow flow systems, while it moves slowly through the regional deep ones (Foster and Hirata, 1988; Tóth, 2009). The different residence times of the water in the different flow systems strongly influence its chemical composition (Tóth, 2009). Fourier decomposition of the spatial multi-scale undulations of the moving water table leads to a superposition of time-dependent Fourier flow systems, in which each flow system is characterized by its orientation, phase and wavelength. The spatial extent of each flow system can then be characterized by its penetration depth, while its temporal behavior can be characterized by its decay time (Stolwijk et al., 1996; Meekes, 1997; Zijl, 1999; Tóth, 2009).

Two parameters, absolute permeability and hydraulic conductivity, play a major role in the fluid dynamic models that are used by the "oil and gas community" and the "groundwater community." This common interest has a great potential for constructive overlap between the two communities. The growing interest in basin hydrodynamic systems in relation to their contained resources may be considered as an important step, not only in the field of research and development related to modeling, but also for applied studies as, for instance, carbon capture and storage, and exploration and production of natural gas to replace coal, lignite, peat and wood as producers of energy (Verweij, 1993; Tóth, 2009).

This paper deals with (i) the characterization of spatial and temporal scales of groundwater hydrodynamics in basins and (ii) the identification of parameters - especially hydraulic conductivity and/or absolute permeability - in relation to these space-time scales. Characterization of the hydrodynamic scales is based on

* Corresponding author.
E-mail address: VUB@zijl.be (W. Zijl).

http://dx.doi.org/10.1016/j.marpetgeo.2016.08.018

indices, i.e., on quantities characterizing complex phenomena in a relatively simple way. For the identification and quantification of parameters at the scale relevant to the flow system under consideration, simple Flux/Potential (F/P) ratios obtained from two hydrodynamic models are used: (i) a flux model (F-model), in which measured fluxes (flow rates) are specified and (ii) a potential or pressure model (P-model), in which measured potentials or pressures are specified. This concept is based on Darcy's law and can simply be summarized as: 'conductivity/permeability' is equal to the 'flux from the F-model' divided by the 'potential/pressure gradient from the P-model' (El-Rawy et al., 2015).

Earlier work on penetration depth and decay time to characterize flow systems by Stolwijk et al. (1996), Meekes (1997), Zijl (1999) and Tóth (2009) deals only with incompressible flow (shallow flow systems). Here we extend their work to compressible flow (deep flow systems). The theory on determination of conductivity/permeability extends earlier work by Brouwer et al. (2008), Trykozko et al. (2008), El-Rawy (2013) and El-Rawy et al. (2015) by including theory how to determine storage coefficients and how to handle multi-phase flow (water-oil-gas). Because the F/P index approach is relatively new, exemplifications related to hydrodynamics in large-scale basins are not yet available. For that reason we present an application of a relatively large-scale aquifer-aquitard system in North-East Belgium that can be considered as a "small-scale basin."

Basin hydrodynamics is important for both the geo-energy community, among which the oil and gas sector (e.g., see Verweij, 1993), and for the hydrogeological community (e.g., see Tóth, 2009). To profit from the insights in the different communities, the issue of "different languages" of the experts in the different communities has to be overcome; communicating specialist knowledge effectively is an essential aspect for successful overlap. Therefore, this paper pays some attention to such aspects. For instance, to quantify the perviousness of a geological material, the oil and gas community uses the concept of permeability while the groundwater community uses the related concept of hydraulic conductivity. A similar difference holds for the quantities pressure and potential/head.

2. Basic equations setting the scene

This section presents the basic equations that govern groundwater flow through porous formations. They can be found in numerous textbooks (Bear, 1972, 1979; 1980; Bear and Corapcioglu, 1985; Bear and Verruijt, 1987; Strack, 1989; Zijl and Nawalany, 1993; Bear and Cheng, 2010)

$$\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}=q_t, \tag{1}$$

$$q_x=-k_x\frac{\partial\varphi}{\partial x},\ q_y=-k_y\frac{\partial\varphi}{\partial y},\ q_z=-k_z\frac{\partial\varphi}{\partial z},\ q_t=-s\frac{\partial\varphi}{\partial t}. \tag{2}$$

In equation (1) only flow rates occur, while equation (2) relate the flow rates to the "driving forces." The first three expressions in equation (2) represent Darcy's law relating the flux densities $q_\bullet$ to the *spatial* potential gradients $(\partial\varphi/\partial\cdot)$, $\bullet=x,y,z$, under the assumption that the principal directions of the conductivity tensor are in the Cartesian x, y and z directions. The last expression in equation (2) relates the volumetric flow rate q_t (out-flowing water volume per unit time and per unit volume) to the "*temporal* potential gradient" $\partial\varphi/\partial t$. In this paper, we do not consider steady flow $(\partial\varphi/\partial t=0)$. However, in unsteady flow the specific storage term $s\partial\varphi/\partial t$, which accounts for the storage caused by the compressibility of the water and the pore space, is often be negligibly small and will be denoted as incompressible flow.

The potential φ is defined as

$$\varphi=\int_{p'=p_{atm}}^{p}\frac{dp'}{\rho(p',T,c)g}-z, \tag{3}$$

where p is the water pressure; p_{atm} is the atmospheric pressure, which is assumed to be constant in space and time; ρ is the water density which depends on pressure p, temperature T and concentration c; g is the gravitational acceleration; and z is the vertical depth coordinate with respect to a horizontal reference level $z=0$ (generally the mean sea level (MSL)). The parameters in equation (2) are: (i) the specific storage (Bear, 1972); and (ii) two horizontal hydraulic conductivities k_x, k_y and one vertical hydraulic conductivity k_z. Darcy's law in the form of equation (2) holds under the condition that the density gradient is in the same direction as the pressure gradient. This is exactly the case if the density depends on only pressure. Consequently, under conditions where the pressure gradient as well as the temperature and concentration gradients are mainly in the vertical direction, density-driven flow may be neglected and equation (2) is a good approximation of Darcy's law. In the shallow subsurface, where the density may be considered as spatially constant (negligible $\partial\rho/\partial\bullet$), potential φ is equal to the well known hydraulic head $h=(p-p_{atm})/\rho g-z$. However, under these conditions $\partial\rho/\partial t$, a component of specific storage s, is not always negligible; also see section 3.

The hydraulic conductivities are related to the intrinsic or absolute permeabilities of the porous medium $(\kappa_x,\kappa_y,\kappa_z)=(\mu/\rho g)(k_x,k_y,k_z)$, where μ is the dynamic viscosity of water. The absolute permeability is generally used in the oil and gas community, while the hydraulic conductivity is used in the hydrogeologic community, as is shown in the last paragraph of section 4.2 on permeability calibration for multiphase flow. The absolute permeability of a porous medium is generally expressed in the unit darcy defined as 1 darcy $=10^{-12}$ bar m^2/atm, in which bar and atm are pressure units. By definition 1 atm $=1.01325$ bar which leads to the approximation 1 darcy $\approx 10^{-12}$ m^2. At a temperature of 20 °C (68 °F) a permeability of $\kappa=1$ darcy corresponds to a hydraulic conductivity of $k\approx 10^{-5}$ m/s $=0.864$ m/day, and at a temperature of 30 °C (86 °F) a permeability of $\kappa=1$ darcy corresponds to a hydraulic conductivity of $k\approx 1$ m/day $=1.16\times10^{-5}$ m/s. In realistic situations, also the influence of salinity and other dissolved matter, as well as the pressure has to be taken into account (see section 4.3).

The height of the water table above MSL is given as a function of the horizontal coordinates x,y and the time coordinate t

$$z=-h_w(x,y,t). \tag{4}$$

The temporal evolution of this height is governed by two boundary conditions: (i) the dynamic boundary condition expressing the force (the dynamics) exerted on the boundary, and (ii) the kinematic boundary condition expressing the motion (the kinematics) of the boundary. The dynamic condition states that the force on the water table is caused by the atmospheric pressure, i.e., $p(x,y,-h_w(x,y,t),t)=p_{atm}$, and from equation (3) it follows that this condition can be written as

$$\varphi(x,y,-h_w(x,y,t),t)=h_w(x,y,t). \tag{5}$$

The kinematic boundary condition governing the temporal evolution of the water table is