Journal of Hydrology 509 (2014) 115–131

Contents lists available at ScienceDirect

Journal of Hydrology

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

Analytical solutions for analysing pumping tests in a sub-vertical and anisotropic fault zone draining shallow aquifers

B. Dewandel [a,*], B. Aunay [b], J.C. Maréchal [a], C. Roques [c], O. Bour [c], B. Mougin [d], L. Aquilina [c]

[a] BRGM, Water Dept., New Water Resource & Economy Unit, 1039 Rue de Pinville, 34000 Montpellier, France
[b] BRGM, French Regional Geological Survey of Réunion Island, 5 Rue Sainte Anne, CS 51016, 97404 Saint-Denis Cedex, France
[c] OSUR Research Federation – Géosciences, UMR 6118, University of Rennes 1, CNRS, Av. du Général Leclercq, 35042 Rennes, France
[d] BRGM, French Regional Geological Survey of Brittany, Rennes Atalante Beaulieu, 2 Rue de Jouanet, 35700 Rennes, France

ARTICLE INFO

Article history:
Received 19 July 2013
Received in revised form 4 November 2013
Accepted 8 November 2013
Available online 22 November 2013
This manuscript was handled by P. Kitanidis, Editor-in-Chief, with the assistance of Christophe Darnault, Associate Editor

Keywords:
Pumping test
Compartmented aquifer
Fault
Crystalline aquifer
Groundwater dating

SUMMARY

We present new analytical solutions for examining the influence, during a pumping test in a well, of an infinite linear and anisotropic strip-aquifer that drains shallow aquifers of different diffusivity and thickness. The whole system is confined and the aquifer geometry can be represented by a 'T', an aquifer geometry resembling a sub-vertical fault or a sub-vertical vein cross-cutting shallower aquifers. The proposed solutions are based upon an unconventional application of well-image theory, without limitation of the diffusivity contrast between the three domains. Solutions for drawdown were developed for the three domains, i.e. the strip-aquifer and the two shallow compartments, and flow signatures are discussed in detail and compared to numerical modelling. The proposed solutions are not shown to be exact solutions to the appropriate partial differential equation, but very good and useful approximations. The solutions were applied to a 63-day pumping test in a steep fault zone in crystalline aquifer rock of Brittany, France. After that, the flow contributions of the fault zone and of the shallow aquifers deduced from groundwater dating were compared to analytical solutions. The solutions and theoretical type-curve examples can help in understanding flow processes from tests conducted in settings that are similar to such a conceptual model.

1. Introduction

In hydrogeology, the oil-and-gas industry, and geothermal activities, well testing is a critical element for assessing the hydrogeological properties of the rock. The evaluation of these properties, as well as their variability in space, is essential for improving the management of the resource (e.g., Raghavan, 2004; Dewandel et al., 2012), or because detailed groundwater-flow data are required for sophisticated pressure and transfer modelling, as for instance when studying nuclear waste deposits, geothermal energy, or contaminant transport.

In discontinuous aquifers, determination of an adequate conceptual model prior to quantification of the hydrogeologic parameters by modelling of the tests, is a particular challenge because the hydraulic signature can be non-unique (Rafini and Larocque, 2012). Well-test data are extensively used in numerical models for evaluating hydraulic conductivity and storativity fields. Though different approaches have been used, the problem is particularly difficult to tackle in fractured media because of system heterogeneity (Neuman, 2005). For instance, numerical models can be deterministic (e.g. Walton, 1987; Rathod and Rusthon, 1991), based on a stochastic continuum (e.g. Neuman, 1987; Molz et al., 2004; Illman and Hughson, 2005, etc.) or based on discrete fracture networks that explicitly consider the complex geometry of fracture networks (e.g. Long et al., 1982; Cacas et al., 1990a,b; de Dreuzy et al., 2002, etc.). Various approaches are also used for developing inverse methods in fractured media (Zimmerman et al., 1998; Lavenue and de Marsily, 2001; Franssen and Gomez-Hernandez, 2002; Illman et al., 2009), or for testing on numerical models our ability to image the properties of heterogeneous media from well tests (Tiedeman et al., 1995) or hydraulic-head data (Le Goc et al., 2010). Among these methods, hydraulic tomography has shown very promising results (e.g. Gottlieb and Dietrich, 1995; Butler et al., 1999; Yeh and Liu, 2000; Huang et al., 2011; Illman et al., 2007, 2008, 2009; Yin and Illman, 2009). Although these approaches may provide a detailed site characterisation (Meier et al., 1998; Sánchez-Vila et al., 1999), such high-resolution techniques required intensive field work, such as several hydraulic tests, collection of numerous pressure-head data, and detailed geological knowledge. Such data are generally only available for experimental sites, but not where most of tests

* Corresponding author. Address: 1039 Rue de Pinville, 34000 Montpellier, France. Tel.: +33 (0) 4 67 15 79 82; fax: +33 (0) 4 67 15 79 90.

E-mail addresses: b.dewandel@brgm.fr (B. Dewandel), b.aunay@brgm.fr (B. Aunay), jc.marechal@brgm.fr (J.C. Maréchal), clement.roques@univ-rennes1.fr (C. Roques), Olivier.Bour@univ-rennes1.fr (O. Bour), b.mougin@brgm.fr (B. Mougin), luc.aquilina@univ-rennes1.fr (L. Aquilina).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.11.014

Nomenclature

List of symbols

a	distance to discontinuity in m
e^x	exponential function
k	hydraulic conductivity in m/s
L	half-width of the pumped compartment (e.g. Domain 1; strip aquifer), in m
Q	pumping flow-rate, in $m^3\ s^{-1}$
r	distance to pumping well, in m
r_w	well radius, in m
S_1, S_2, S_3	storage coefficients of the strip aquifer, right- and left side compartments respectively, dimensionless (–)
Ss_1, Ss_2, Ss_3	specific storage coefficients of the strip aquifer, right- and left-side compartments respectively, m^{-1}
s_1, s_2, s_3	drawdown of the strip aquifer, right- and left-side compartments respectively, in m
s_D	dimensionless drawdown
t_{DL}	dimensionless time according to the distance to the boundary, isotropic case
t_{DLx}	dimensionless time according to the distance to the boundary, anisotropic case
t	time in seconds
T_1, T_2, T_3	transmissivity of the strip aquifer, right- and left-side compartments respectively, in m^2/s
T_{xx} and T_{yy}	principal axes of transmissivity anisotropy in the horizontal plane of the strip aquifer, in m^2/s
x, y	coordinates of a Cartesian system, in m
η_1, η_2, η_3	diffusivity of the strip aquifer, right- and left-side compartments respectively, in m^2/s
$W(u_r) = \int_u^\infty \frac{1}{y}\exp(-y))dy$	with y variable of integration. Well function

are conducted. For example, for water-supply purposes generally just data from one well and one test are available. Analytical solutions for analysing pumping-test data, such as the ones developed here, are thus still of wide interest. They are useful for evaluating averaged properties of the media (e.g. hydrogeological properties, flow behaviour, geometry), and can help in constraining the numerical models particularly in fractured aquifers where field data may not be sufficient, if they exist, to justify the use of a detailed numerical model.

We present new analytical solutions for examining the influence in a well test of an infinite linear and anisotropic strip-aquifer that drains shallower aquifers of differing diffusivity and thickness with a geometry that resembles a 'T' (the 'T-aquifer'; Fig. 1). However, the thickness of the shallow aquifers on the sides of the strip aquifer can be the same as that of the strip one. The flow behaviour, i.e. flow signature, has also been examined in detail. This conceptual model may represent the main features of several geological conditions, such as a fault zone cross-cutting shallow aquifers, or dykes and veins intruding igneous rock, which are favourite discontinuities for borehole siting in crystalline aquifers (Sander, 2007; Dewandel et al., 2011). It may also represent a buried channel embedded in other materials, two faults separating a central strip with dissimilar hydraulic properties, cut and filled paleo-valleys of lava flows, etc.

The research reported in this article is based on a large body of earlier works in hydrogeology and petroleum literature. Numerous works (e.g. Maximov, 1962; Bixel et al., 1963; Nind, 1965; Fenske, 1984; Raghavan, 2010) have examined the effects of well tests performed near a single linear discontinuity separating materials of dissimilar properties, or the case of two arbitrarily intersecting boundaries (van Poollen, 1965). Others focused on the behaviour of a semi-permeable fault separating aquifers with similar properties (e.g. Yaxley, 1987; Abbaszadeh and Cinco-Ley, 1995; Shan et al., 1995) or with dissimilar properties (e.g. Ambastha et al., 1989; Rahman et al., 2003; Charles et al., 2005; Anderson, 2006), the behaviour of two intersecting leaky faults (Abdelaziz and Tiab, 2004), or the behaviour of pumping well located in an infinite conductive vertical or horizontal fracture (Gringarten and Ramey, 1974; Gringarten et al., 1974). Much work was also done on the behaviour of pumping in a strip aquifer of permeable material limited by at least two impermeable or constant-head boundaries (e.g. Muskat, 1937; Ferris et al., 1962; Earlougher et al., 1968; Lennox and Vandenberg, 1970; Chan et al., 1976; Strelsova and McKinley, 1984; Ehlig-Economides and Economides, 1985; Larsen and Hovdan, 1987; Yeung and Chakrabarty, 1993; Kuo et al., 1994; Onur et al., 2005), or the behaviour of composite radial systems (e.g. Bixel and van Poollen, 1967; Butler, 1988; Abbaszadeh and Kamal, 1989; Bratvold and Horne, 1990; Butler and Liu, 1993; Acosta and Ambastha, 1994), or that of composite linear systems (Bourgeois et al., 1996).

However, few works have investigated the influence on a pumping test of a strip aquifer bounded laterally by aquifers of different diffusivity and thickness, such as in a 'T-aquifer'. Boonstra and Boehmer (1986, 1987) proposed a solution that assumed a high contrast in transmissivity between the inner and the two outer regions, while Butler and Liu (1991) proposed a solution without limitations of aquifer diffusivity between the three regions. Others have investigated trough numerical modelling the flow induced by a pumping test carried out in a fault embedded in low-permeable

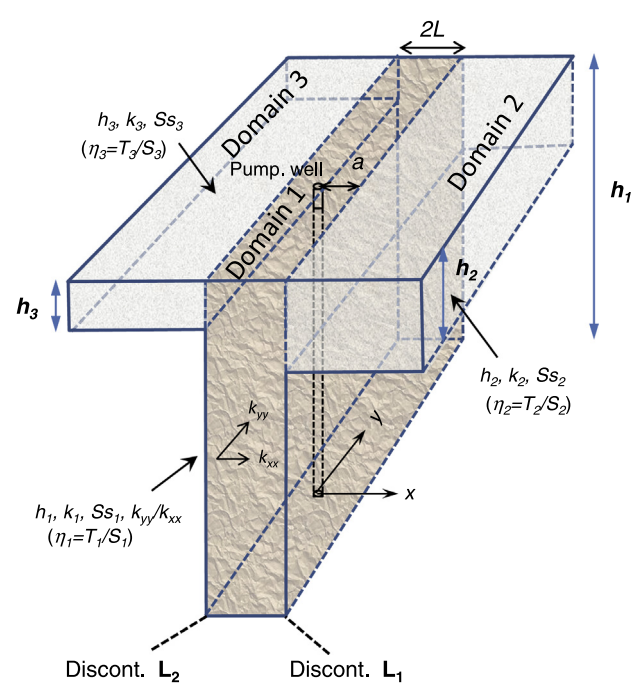

Fig. 1. The 'T' aquifer. Conceptual sketch of the infinite anisotropic linear-strip aquifer, Domain 1 (D1; width 2*L*), separating two semi-infinite half-spaces of dissimilar properties (domains 2 and 3).