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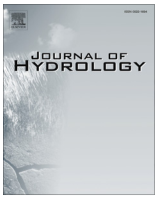

Review papers

Identifying turbulent flow in carbonate aquifers

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ABSTRACT

Turbulent flow has a different hydraulic response compared to laminar flow and so it is important to be able to identify its occurrence in an aquifer, and to predict where it is likely to be found. Turbulent flow is associated with large apertures and rapid velocities, and these occur most frequently in carbonate aquifers. Methods for identifying turbulent flow include correlating spring discharge with head variation, calculating Reynolds numbers from spring discharge and tracer velocity, and plotting the spatial variation of head differences between high flow and low flow. The probability of turbulent flow increases as a function of permeability and of spring discharge, and the probability increases in a downgradient direction in an aquifer. Spring discharge is a key parameter for evaluating the presence of turbulent flow, which is likely to occur where a spring with a discharge > 1 L/s is fed by a single channel. Turbulent flow appears to be a major contributing factor to the occurrence of groundwater flooding in carbonate aquifers.

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1. Introduction

Groundwater models have become an increasingly important part of hydrogeology in the last fifty years. Traditionally, finite difference and finite element models have only simulated laminar flow, but in recent years the capability to simulate turbulent flow had been added in programs such as CAVE (Liedl et al., 2003; Hubinger et al., 2016), MODFLOW DCM (Sun et al., 2005), MODFLOW CFP (Shoemaker et al., 2008a; Gallegos et al., 2013), KFM (Loper and Chicken, 2011), CTFC (Reimann et al., 2011), DisCo (de Rooij et al., 2013), MODFLOW NLFP (Mayaud et al., 2015), and MODFLOW USG-Beta (GSI, 2017). The pipe flow model SWMM has also been used to simulate turbulent groundwater flow (Chen and Goldscheider, 2014). This raises the question of where turbulent flow is likely to be found in aquifers.

The major consequence of the difference between laminar flow and turbulent flow is that the head/discharge relationship is linear in the former case and non-linear in the latter case. This is relevant to the calibration of numerical models and is especially relevant to head changes in transient models. In addition, turbulent flow can mobilize sediment grains and transport them through aquifers, and such suspended sediment impacts water quality.

The earliest testing of whether flow in an aquifer is laminar or turbulent was by Darcy (1856). He considered whether flow to artesian wells and to springs better fitted his non-linear flow law (the Darcy-Weisbach equation) or his linear flow law (Darcy's law). He concluded that flow to artesian wells fitted his linear flow law in most cases and that flow to a large spring in a limestone aquifer fitted his non-linear flow law (Darcy, 1856, pp. 137–157, 182–183). The conclusions of Darcy were largely confirmed by later studies. For instance, Hubbert (1940) showed that turbulent flow is rare in granular aquifers where grain size is 1 mm or less, and Smith et al. (1976) showed that flow is generally turbulent in the major channels in carbonate aquifers. The permeability of carbonate aquifers is higher on average than other bedrock aquifers (Gleeson et al., 2011), so large apertures, rapid groundwater velocities, and thus turbulent flow are more likely to occur than in other lithologies. Consequently, this paper will focus on carbonate aquifers.

It has long been known that continuous, large-aperture channels are common in carbonate aquifers. Caves represent the most striking manifestations of such channels. Some cave passages have been mapped for distances exceeding 10 km, and tracer tests with velocities exceeding 1 km/d provide evidence for channels over even longer distances (Worthington, 2015a). Turbulent flow in past conditions has been deduced from bedform-erosional features and sediments in cave passages (Gale, 1984), and turbulent flow under current conditions has been deduced from the combination of tracer velocity and spring discharge (Atkinson, 1977), and from the combination of head measurements and spring discharge (Bonacci, 2001; Jeannin, 2001; Sepúlveda, 2009). Despite such studies, there has been no comprehensive discussion of the range of different methods for identifying turbulent flow in aquifers, nor of the likelihood of turbulent flow occurring in a given carbonate aquifer. These issues will be addressed in this paper. Section 2 outlines the theory and methods used to identify turbulent flow, with examples in Section 3, practical applications in Section 4, and a discussion in Section 5.

2. Theory and methods

2.1. Laminar and turbulent flow

The transition between laminar flow and turbulent flow is determined by the dimensionless Reynolds number R, which for pipes is defined as

$$\mathrm{R} = \frac{\rho v d}{\mu} \tag{1}$$

where ρ is the density of water, v is groundwater velocity, d is pipe diameter, and μ is the dynamic viscosity of water. In engineering, the critical Reynolds number that defines the transition from laminar to turbulent flow is about 2100 for straight pipes and 1000 for openings with parallel walls (Street et al., 1996, p. 233). In the latter case, d in Eq. (1) refers to fracture aperture. In granular aquifers, mean grain diameter is often used for d, and the critical Reynolds number ranges from 1 to 60 (Shoemaker et al., 2008a). Natural channels in bedrock aquifers present an intermediate case between smooth, straight manufactured pipes and the tortuous pathways in granular aquifers and so will have intermediate critical Reynolds numbers. For instance, measurements have shown that turbulent flow in fractures and channels can occur at Reynolds numbers well below 1000 (Qian et al., 2005; Shoemaker et al., 2008b; Chen and Qian, 2009). Fig. 1 shows how Reynolds numbers vary as a function of channel aperture and groundwater velocity.

Laminar flow in a porous medium is described by Darcy's law

$$Q = -KiA \tag{2}$$

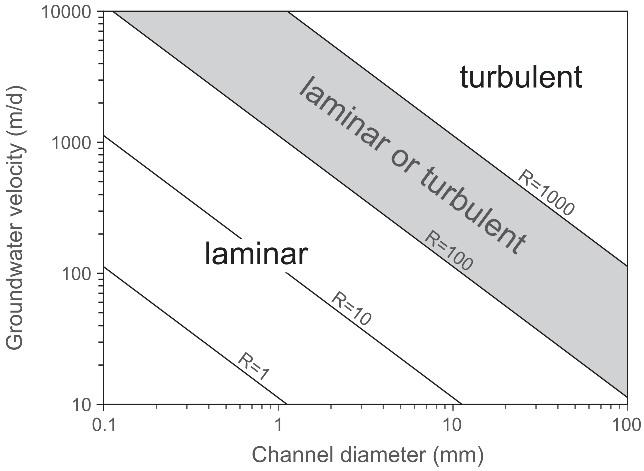

Fig. 1. Groundwater velocity as a function of channel diameter, showing the range of laminar and turbulent flow regimes, assuming transition from laminar to turbulent flow at Reynolds numbers (R) between 100 and 1000 (modified after Sundborg, 1956).