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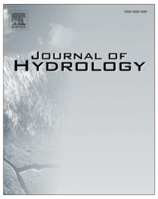

Research papers

Modeling karst spring hydrograph recession based on head drop at sinkholes

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ABSTRACT

Spring discharge often responds to rainfall with a rapid increase followed by a slower recession, and the mode of recession is often exponential-like. We propose a new model of the response of spring discharge to rainfall based on the square law for turbulent conduit flow. The new non-exponential model is compared against the exponential model under specific constraints. A hydrograph of St. Marks River in Florida is used to illustrate that when the change in "sinkhole head" (defined as the hydraulic head at the upstream end of the karst conduit connected to the spring) is relatively small, the solution of the new model is close to that of the exponential model, which extends the validity and application of the exponential solution. When the change in sinkhole head is very large, the solutions from the two models clearly differ from each other. Limitations of the non-exponential model are analyzed by simulation of a hydrograph observed downstream of Wakulla Springs. It is concluded that both solutions are applicable when spring response is smaller than or comparable to the base flow, but are nonphysical when the response is much larger than the base discharge.

1. Introduction

Karst landscapes and karst aquifers are formed by the dissolution of carbonate rocks by water rich in carbon dioxide. Karst aquifers can be described as a network of solutional conduits and caves embedded in, and interacting with, a rock matrix with intergranular pores and fissures. Therefore, karst aquifers can be described as double-porosity (conduits vs. matrix) or even triple-porosity (conduits, fissures, pores) hydraulic media (Worthington, 2007). Karst landscapes are characterized by solutional landforms, such as karren or dolines, that are genetically related to the aquifer system underneath. Sinkholes and swallow holes are places where surface water sinks underground, into the network of conduits (Ford and Williams, 1989).

Karst aquifers are a precious resource because they provide drinking water to about one quarter of the world's population (Ford and Williams, 1989), and because they are habitats for many rare and endemic species (e.g. Mahler and Bourgeai, 2013). In the United States, over 20% of the land is karst, and the underlying karst aquifers provide about 25% of the country's freshwater supplies (Elliot, 2000). In some European countries, such as Austria or Slovenia, karst water even contributes about 50% to the total freshwater supply (Hartmann et al., 2014). Karst is also extensive in southwest China, where people living in rural areas are typically subjected to untreated water from karst springs for drinking (Guo et al., 2013).

Karst aquifers are typically very productive, because of their ability to convey water through a network of interconnected conduits. These conduits are also preferential pathways for pollutants which can travel rapidly over long distances, making karst aquifers highly vulnerable to contamination, particularly microbial contamination (Field and Nash, 1997; Goldscheider et al., 2010; Lauber et al., 2014). For example, over the last few decades Wakulla Springs in northwest Florida have been impacted by municipal wastes entering Ames Sink, south of Tallahassee, causing widespread reproduction of algae, which in turn consumes oxygen in water and results in anoxic conditions and the decrease of fishes (Li, 2004). Besides their vulnerability and variable water quality, karst aquifers are also characterized by rapid and marked variations of water table and spring discharge, which further complicates their use as water sources (Bakalowicz, 2005).

In karst aquifers, solution conduits in which rapid and turbulent flow is common are clearly distinctive from the pores and fissures of the matrix in which storage and laminar flow predominates.

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These two flows can interact with each other, depending on the pressure difference between them (Screaton et al., 2004). Many karst hydrogeology studies focus primarily on qualitative investigations of flow and geochemical analyses (e.g., Martin and Dean, 2001; Moore et al., 2009). Quantitative studies of the physical processes associated with karst aquifers are still challenging because karst aquifers and their conduit networks are complicated systems that are difficult to explore, characterize, and quantify. However, quantitative studies of the physical processes of flow and transport are indispensable for calculating water budgets, predicting climate change impacts and understanding the fate and transport of contaminants. For these reasons, simulations of physical processes are essential for understanding karst-aquifer functioning and for sustainable karst aquifer management.

The linear reservoir model, originally proposed by Maillet (1906), linearly links the discharge at the outlet of a reservoir to its water level. When applied to karst aquifers, the model predicts that a spring's flux is proportional to the aquifer volume. An essential aspect of the model is the assumption that spring discharge must behave linearly with respect to water-table fluctuation, an essential element of laminar flow (i.e., flux is proportional to pressure difference), because the area of an aquifer is almost fixed and is a quasi-constant. Flow inside pores, relatively tight fractures, and in some instances, very small conduits is typically laminar due to large shear/friction forces caused by the walls such that the linear reservoir model works well for non-karst aquifers. In the case of karst aquifers with large solution conduits that are not well interconnected, flow may be constrained by narrow passages and remain laminar, which would allow application of the linear reservoir model (Rimmer and Hartmann, 2012). However, flow in large solution conduits, such as the coastal karst aquifers in Florida, have been shown to be interconnected (e.g., rammiform), and have been observed to be turbulent, and feed one or more first-magnitude springs. Unfortunately, the difference between laminar- and turbulent-flow dynamics is not always adequately reflected by the exponential model.

An important aspect of linear reservoir model is based on the hydrological mechanism that spring discharge results directly from non-point sources (i.e., areal infiltration), but recharge to karst aquifers often occurs primarily at point locations (e.g., sinkholes). Point recharge in which surface runoff converges very quickly in the horizontal direction results in a response (i.e., change) in spring flux that is caused by transient point recharge. Point-like or localized recharge cannot be replaced by the concept of area-averaged infiltration nor water-table fluctuation because individual recharge locations are singular points from a mathematical perspective.

Hydrologically active sinkholes provide direct recharge to the solution conduits in karst aquifers. Although a water table in these surface features may not be observable in many instances, they actually constitute and represent the direct and quick inlets to the aquifers, because surface runoff can convey large amounts of precipitation to them and then to the conduits at much higher rates than percolation through the epikarst and vadose zone. In this paper, the term "sinkhole head" (h_S) refers to the hydraulic head at the upstream end of the conduit networks, taking the level of the spring as the reference level ($h = 0$), while the term "sinkhole base head" (h_{SB}) describes the hydraulic head prior to an intense precipitation event.

Spring hydrographs provide a classic approach for analyzing hydrodynamics in karst aquifers that are difficult to access and instrument (e.g., Kovács et al., 2005; Geyer et al., 2008). An intense precipitation event over a short period of time causes a rapid rising limb followed by a slower falling limb in spring hydrographs. The recharge signal can be conceptualized as the Dirac delta function, and thus the resulting spring hydrograph may be treated mathematically as the Green's function (Strauss, 1992). Green's function is powerful in that, for linear hydrology, a spring hydrograph resulting from any amount of precipitation with any kind of recharge history can be predicted through the convolution of the input mode with the Green's function. This has been shown by theory on linear and shift-invariant systems in signal processing (Lathi, 2000), which is the basis of Black-Box models, also referred to as Lumped Parameter Models (Hartmann et al., 2014).

Numerical or distributed models are often capable of producing more detailed results, but they invariably require *a priori* knowledge of the spatial distribution of relevant hydraulic parameters, particularly concerning the spatial configuration and properties of the conduit network. Furthermore, numerical karst aquifer models require substantial efforts to develop the model, to compute the solutions and to conduct uncertainty analyses, which greatly increases the cost of computational efforts (Hartmann et al., 2014).

In this paper, we shall focus on the response of spring discharges to precipitation. The approach adopted is to emphasize the dominant physical processes and simplify the complicated mathematical equations. Li and Field (2014) developed a simple mathematical model to simulate spring discharge and estimate "sinkhole porosity" in a karst aquifer (defined as the ratio of the area of all sinkhole cross-sections to the watershed area in the horizontal plane), based on the assumption of small changes in sinkhole head and the resulting linearization of the flow equation in the conduits. The purpose of this paper is to extend that model and to conduct analysis of a general situation in which the change in sinkhole head is comparable to or much larger than the sinkhole base head. Two spring hydrographs measured in the St. Marks Karst Watershed in northwest Florida are used to test the new model.

2. A physical model of spring discharge and its mathematical solution

Without heavy precipitation, base-level karst springs typically have a base flow originating from the (nearly) steady seepage from the matrix (consisting of fissures and pores) into the conduits. In addition, in many karst systems, the main water storage may occur in the epikarstic zone that allows water to percolate down to the aquifer matrix and to the conduits. The sustainability of base-level springs is due to groundwater in the aquifer matrix draining into the conduits, because rainfall entering a sinkhole and being transmitted down into a conduit bounded by impervious wall is ephemeral. In this ordinary scenario, sinkhole head is almost stable or decreases very slowly. During large precipitation events, however, the sinkhole head can rise very rapidly due to increased inflow from nearby runoff, causing a nearly instantaneous increase in spring discharge because of the high velocity of the compressional (or acoustic) wave in the water. The compressional wave transmits a change of pressure downstream to rebuild a new pressure gradient between the upstream sinkholes and the downstream spring, resulting in a change of conduit flow and, this, spring discharge. The increased head at sinkholes can also displace water and pollutants from the conduits into the surrounding matrix, which eventually flow back into the conduits when the hydraulic pressures decreases (Goldscheider, 2005; Li et al., 2008). The process and effects of "bank storage" (or "gradient inversion") in karst aquifers is very complicated but may not be as significant as was once thought (Peterson and Wicks, 2005). For this reason and for the sake of simplicity, we neglect this mechanism and attribute the response of spring discharge to the abrupt flooding of sinkholes and the following natural drop in sinkhole head. Fig. 1a and b illustrates the basic processes of low flow and high flow, respectively, as described above and Fig. 1c

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