Groundwater dynamics

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Analytical solutions of groundwater dynamics in an elongated aquifer subjected to general time-dependent recharge are presented. The lateral boundaries are specified heads with the head variations governed by general time-dependent functions. General recharge function was not considered in previous works of this kind. Both single and double-porosity aquifers are considered. The solution is obtained using Fourier sine and Laplace transformations, followed by an inverse Fourier-Laplace transform involving residue theorem and convolutional integral. For the unconfined single-porosity aquifer case, the exact time-domain solution is obtained using the residue theorem; for the unconfined double-porosity aquifer case, the time-domain head is calculated using the de Hoog inverse Laplace algorithm. The presented solution can be used to estimate the hydraulic parameters of 1) groundwater head variation of a river basin aquifer subjected to general lateral head variation and recharge; 2) groundwater head variation in a double-porosity elongated fractured anticline; 3) groundwater depletion of an elongated fractured anticline subjected to recharge due to rainfall or snowmelt to its adjacent alluvial aquifer. In addition, the presented solution can be utilized to optimize the irrigation pattern in a cropland between two trench drains to control the groundwater mound.

Keywords: Analytical solution ; river basin aquifer ; recharge ; river level fluctuations ; anticline reservoir

1. Introduction

There are many river basin aquifers subjecting to river level fluctuations (Barlow et al., 2000; Moench and Barlow, 2000; Sedghi and Zhan, 2016; Serrano and Workman, 1998; Singh et al., 2018; Sophocleous, 2002; Workman et al., 1997). These fluctuations serve as natural stresses to aquifers of concern. Response of aquifers to theses stresses or controlled stream-stage variations can be used to estimate the hydraulic parameters of aquifers, if a proper mathematical model can be established between the stresses and aquifers (Bolster et al., 2001; Rötting et al., 2006). These methods are less expensive that the pumping test among other benefits (Trefry and Bekele, 2004). Groundwater dynamics in such aquifers can be used to estimate aquifer hydraulic parameters using appropriate mathematical models and their associated analytical solutions. Assumptions that are made to obtain such solutions, limit their application in real field situations. Therefore, eliminating some of those limiting assumptions to make the solutions applicable for more realistic situations becomes indispensable for better estimate of aquifer parameters. One of these limiting assumptions is ignoring time varying recharge to aquifers.

The stream-aquifer interaction have been the subject of many investigations by hydrogeologist (Intaraprasong and Zhan, 2009). These investigations are fallen into two categories. In many of these studies the stream depletion rate and drawdown due to pumping from a nearby well were explored (Sedghi et al., 2012; Sun and Zhan, 2007; Yeh et al., 2008; Zlotnik, 2004). In other researches, the hydraulic response of river basin aquifers to stream stage variations were investigated (Akylas and Koussis, 2007; Bansal, 2012; Barlow et al., 2000; Cooper and Rorabaugh, 1963; Hall and Moench, 1972; Haushild and Kruse, 1962; Jiang and Tang, 2015; Moench and Barlow, 2000; Sedghi and Zhan, 2016; Yeh, 1970). Sinusoidal function was considered by Cooper and Rorabaugh (1963) to simulate the stream stage fluctuation. Instant change in stream stage was considered in other researches (Akylas and Koussis, 2007; Haushild and Kruse, 1962; Yeh, 1970). Discrete time hydrograph (Barlow et al., 2000; Hantush, 2005; Moench and Barlow, 2000), uniform rate stage rising (Bansal, 2012) and exponentially decaying of stream stage (Bansal, 2013) were considered in other works. General approximate (Jiang and Tang, 2015) and exact (Sedghi and Zhan, 2016) function were also considered to simulate stream stage fluctuations.

2. Effect

The effects of natural and artificial recharge on groundwater head variation or groundwater mound have received attention in many researches. The growth and decay of groundwater mound due to uniform recharge from an infinite strip was investigated by Marino (1974). The Dupuit-Forchheimer assumptions were adopted by Amar (1975) to investigate the effects of recharge from an infinite strip. Comparing results with experimental data, Amar (1975) concluded that the Dupuit-Forchheimer theory was valid for relatively small water-table rises. Dupuit-Forchheimer assumptions were also adopted in many researches concerning groundwater recharge simulation (Anderson, 1976; Brock, 1976; Manglik et al., 2004; Rai and Singh, 1995; Singh and Jacob, 1977; Verhoest and Troch, 2000). Constant recharge from a circular basin to a perched aquifer was considered by Brock (1976). In above mentioned solutions uniform recharge in an infinite strip basin was considered and the aquifer was bounded by a constant-head boundary.

Periodic step functions were used by Singh and Jacob (1977) to simulate areal recharge. They utilized linearized Boussinesq equation to obtain their solution. The model domain was bounded by constant-head boundaries. Aquifer domain bounded by Cauchy boundary condition subjected to periodic recharge was considered by Latinopoulos (1986). Using exponential decaying (Rai and Singh, 1995) and piecewise linear functions (Manglik et al., 2004) were not uncommon to simulate groundwater recharge. Zlotnik and Ledder (1993) utilized the first-order free surface equation with a source term representing recharge to simulate the water table boundary condition. The same method was followed by Chang et al. (2016) to simulate the water table boundary condition to obtain three-dimensional (3D) time-domain solution of groundwater head in a rectangular aquifer with the Robin type lateral boundaries. They also presented a fairly intensive review on analytical solutions concerning groundwater recharge.

To our knowledge, there is no analytical model considering general time-varying recharge and time-varying lateral boundaries head variations. This model set up is not uncommon in field situations. In river basin aquifers, rainfall causes the river water level rise due to the surface runoff and recharge to the aquifer from its top boundary. Elongated fractured anticlines replenished by rainfall or snowmelt and recharge from their adjacent alluvial aquifers.

The presented solution can be used to determine the hydrodynamic parameters of 1) groundwater head variation of a river basin aquifer subjected to general time-dependent lateral head variation and recharge; 2) groundwater head variation in a double-porosity elongated fractured aquifer (i.e. an anticline with length higher than its width so that the groundwater flow is always along its width. This type of anticline is quite common in folding belts (Ashjari and Raeisi, 2006).); 3) groundwater depletion of an elongated anticline subjected to recharge due to rainfall or snowmelt to its adjacent alluvial aquifer. Furthermore, the presented solution can be used to optimize the irrigation amount and pattern in a cropland between two trench drains to control the groundwater mound. To sum up, the presented analytical model is applicable to many river-aquifer systems where there is no point source or sink.