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Optimum experimental design of a monitoring network for parameter identification at riverbank well fields

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SUMMARY

A steady-state flow regime in riverbank well fields is often violated by fluctuations in river stages and variations in groundwater extraction. In this study, a criterion of quasi-steady flow during filtration processes at riverbank well fields was introduced. Under the assumption of steady-state flow, an analytical approach for determining the key hydraulic parameters (aquifer transmissivity and riverbed filtration resistance) between a stream and a hydraulically connected aquifer during riverbank filtration was presented. An optimal regular observation network (consisting of the locations of monitoring wells and the observation regime), which is based on the model-oriented approach using an example of a riverbank well field near the Kuybyshev Reservoir, Russia, was designed to minimise the uncertainty in the estimates of hydraulic parameters. The analyses showed that the initial recession in the surface water levels for the simplest constant groundwater withdrawal patterns can be used to determine the key hydraulic parameters; the error in these estimated parameters was less than 7% or 12%, depending on the designed monitoring network. When comparing the two typical monitoring networks, observation line A–A that passes midway through the water supply wells performed better than observation line B–B that passes through the water supply wells when estimating the hydraulic parameters. The results of this study can be used as a reference for designing and optimising a monitoring network that aims to determine the key hydraulic parameters at riverbank well fields.

1. Introduction

Riverbank filtration (RBF) is a managed surface–groundwater interaction process in which surface water is forced to flow downward through porous media into production wells that are installed on the banks of rivers and lakes under pumping stress (Dillon et al., 2002; Grischek and Ray, 2009; Ray et al., 2002). RBF, which is an important part of managed aquifer recharge (MAR) systems (Rauch-Williams et al., 2010), has been used for water supplies in Europe along the Rhine, Elbe, Danube, and Seine Rivers for over a century (Schubert, 2002; Tufenkji et al., 2002) and it has provided the majority of the drinking water for large cities in Russia (Filimonova and Shtengelov, 2013), the USA (Hoppe-Jones et al., 2010; Roy et al., 2012), China (Wu et al., 2007) and other countries (Hamdan et al., 2013; Lee et al., 2009; Polomčić et al., 2013; Shamsuddin et al., 2014) over the last few decades. The obvious advantage of RBF is the conjunctive use of infiltrated surface water and groundwater from the alluvial catchments of intake structures (Polomčić et al., 2013), which ensure long-term productivity and stability of the water supply (Sprenger et al., 2011). Additionally, surface water contaminants can be significantly removed or degraded as the infiltrating water moves from the river/lake to the production wells due to a combination of physico-chemical and microbiological processes (Hiscock and Grischek, 2002; Maeng et al., 2010; Singh et al., 2010; Weiss et al., 2005).

However, as noted by Doussan et al. (1998) and Schubert (2002), poor surface water quality, heavy clogging of the riverbed, and accidental pollution have already greatly threatened RBF systems. Importantly, the sustainability of RBF is affected by particulate organic matter, which intensifies physical or chemical clogging of riverbed (Baveye et al., 1998; Henzler et al., 2014;

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Hiscock and Grischek, 2002; Yong et al., 2013) and significantly reduces the hydraulic conductivity of riverbed as well as well yield (Schubert, 2002). Moreover, the hydraulic relationship between surface water and aquifers may be transited from connected to disconnected systems (Brunner et al., 2011) due to the increasing hydraulic resistance of riverbed sediments during RBF processes (Wiese and Nützmann, 2009). Thus, sustainable water management at riverbank well fields requires fundamental investigations into the hydraulic properties of riverbed, which are considered an important indicator of riverbed clogging processes.

Numerous approaches have been developed to investigate the hydraulic properties of riverbed, including grain-size distribution analysis (Alyamani and Sen, 1993), in-stream methods (Cardenas and Zlotnik, 2003; Chen, 2000; Landon et al., 2001; Rosenberry, 2008), environmental tracer experiments (Anderson, 2005; Constantz, 2008; Roshan et al., 2012; Vogt et al., 2012), a vadose zone monitoring system (Dahan et al., 2007, 2009), water balance techniques (Fleckenstein et al., 2010; Kalbus et al., 2006; Shanafield and Cook, 2014), and integrated surface–groundwater numerical modelling (Boano et al., 2013; Brunner et al., 2010; Doppler et al., 2007; Lautz and Siegel, 2006). The hydraulic properties of the riverbed, which are estimated using the aforementioned methods, are mostly assumed to be constant over time in studies on riverbank filtration processes and the related surface–groundwater interactions (Baveye et al., 1998). However, field investigations have documented both spatial and temporal variability in the hydraulic properties of riverbed (Chen et al., 2010; Genereux et al., 2008; Leek et al., 2009), particularly in riverbank well fields, which are mainly associated with dynamic hydrological processes, such as groundwater extraction and changes in surface water levels (Levy et al., 2011; Zlotnik and Huang, 1999). Therefore, as indicated by Schubert (2002), the hydraulic properties of riverbed are principal factors for determining the volume of the bank filtrate, which cannot be regarded as constant during RBF investigations.

To understand the dynamic behaviour of the hydraulic properties of riverbed sediments during RBF processes, monitoring concepts that include continuous measurements of the surface–groundwater level and well productivity over long periods (Shestakov, 1993) must account for the dynamic hydrological processes of the entire riverbank system (Hiscock and Grischek, 2002; Schubert, 2002). The ultimate configuration of the monitoring network aims to determine the key hydraulic characteristics of the groundwater flow systems (Heath, 1976; Hudak and Loaiciga, 1993; Zhou et al., 2013), which are based on the parameter estimations using monitoring materials (Loaiciga, 1989). Nevertheless, the interpretation of the monitoring data, which targets the understanding of surface–groundwater interactions under induced filtration (e.g., riverbed clogging processes), remains a challenge due to the non-steady-state flow conditions under RBF. A reliable estimation of hydraulic parameters is highly dependent on the design of the monitoring network (Alzraiee et al., 2013), which includes two important components: the network density and the sampling frequency (Zhou, 1996). Conversely, such interpretation should also serve as a guide for optimising the existing monitoring network for further changes in hydrological and other conditions after a long period of RBF (Hudak and Loaiciga, 1993; Shestakov, 1993). In this study, we provide an analysis of the hydrological conditions that formed during RBF at the riverbank well fields near the Kuybyshev Reservoir, Russia. The primary objectives of this study are to (i) reveal the filtration processes under the non-steady flow regime induced by surface water level fluctuations and by the instability of water withdrawal at the riverbank well fields; (ii) present methods for interpreting monitoring data at riverbank well fields using a steady-state assumption; and (iii) provide a numerical, model-based design of a monitoring network that aims to identify hydraulic parameters under induced filtration.

2. Theoretical foundation: analytical solution for parameter estimations under quasi-steady flow

Under steady-state flow conditions, the hydraulic properties of an aquifer and a semipervious riverbed are two key parameters that determine the surface–groundwater interaction at the riverbank well fields. The hydraulic properties of a semipervious riverbed that partially penetrates a horizontal non-leaky water table aquifer can be determined by the coefficient of the vertical leakage through the semipervious riverbed, χ_0 (Shestakov, 1995):

$$\chi_0 = \frac{k_0}{m_0}, \tag{1}$$

where k_0 and m_0 are the hydraulic conductivity [L/T] and thickness [L], respectively, of the semipervious layer of the riverbed. To quantify the water exchange between the surface water and groundwater at riverbank well fields, Hantush (1965) and Shestakov (1965) proposed the concept of hydraulic resistance, which is defined as the equivalent loss through a horizontal semipervious layer of an insignificant storage capacity located between the aquifer and the river.

Consider the typical conditions of a two-layer structure of groundwater flow for an aquifer underlying a semipervious layer beneath a river with width N (Fig. 1). The aquifer below the riverbed, which has a transmissivity T_0, is covered with a semipervious layer that has a thickness m_0 and a vertical hydraulic conductivity k_0. The effective length of additional hydraulic resistance in aquifer ΔL, which has the same hydraulic resistance as the riverbed, can be calculated by the following equation (Pozdniakov and Shestakov, 1998; Shestakov, 1965):

$$\Delta L = \frac{T}{\sqrt{T_0\chi_0}} \coth\left(N\sqrt{\frac{\chi_0}{T_0}}\right), \tag{2}$$

where T is the transmissivity of the main aquifer at the riverbank [L^2/T]. By introducing the effective length ΔL, which refers to the general hydraulic resistance of the riverbed, the riverbank is virtually shifted this distance and the river is changed from a semipervious-bottom river to a river that is perfectly connected with the aquifer (Fig. 1); this newly shifted river is used with the steady-state analytical boundary conditions with a constant head at the riverbank.

$T_0 = T$ is usually assumed when calculating ΔL with Eq. (2). If a river has an infinite width, for example, an artificial reservoir or a large river where $N > 3\Delta L$, then a simplified relationship between χ_0 and ΔL would be produced (Pozdniakov and Shestakov, 1998; Shestakov, 1965):

$$\chi_0 = T/(\Delta L)^2. \tag{2a}$$

We assume that the flow in the main aquifer is essentially horizontal; therefore, the flow in the top semipervious layer is essentially vertical. As an approximation, we ignore the storage in the upper semipervious layer. The simplest and most common method of determining the parameter ΔL is to use the analytical solution that is widely used for steady (quasi-steady) flow regimes within single-layer aquifer systems. Systematic measurements of the river-water stages and the groundwater levels from the observation wells provide essential data needed to evaluate the interaction between groundwater and surface water. The observation line consists of six OWs, which are located in the direction of the groundwater flow and are installed in the aquifer with heads of H_1, H_2, H_3, H_4, H_5, and H_6 (Fig. 1). Note that the nearest OW to the riverbank is no closer to the shoreline than the equivalent thickness of the aquifer (Shestakov, 1995).

Observations of the steady-state flow regime from the two wells along the observation line (OW1 and OW2) in the aquifer