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Natural recovery of infiltration capacity in simulated bank filtration of highly turbid waters

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ABSTRACT

As a consequence of the suspended sediments in river water, cake formation on the streambed and clogging of the aquifer may occur, leading to a decline in the production yield of riverbank filtration systems, particularly in highly turbid river waters. However, naturally occurring flow forces may induce sufficient scouring of the streambed, thereby self-regulating the thickness of the formed cake layer. This study assessed the recovery of the infiltration capacity in a simulated physically clogged riverbank filtration system, due to self-cleansing processes. A straight tilting flume, provided with an infiltration column at the bottom, was used for emulating clogging, infiltration and self-cleansing. Based on the presented research it may be concluded that the infiltration of a mixture of different sediments, as found in natural water bodies, can already be recovered at low shear stresses. Clay and silt behaved very differently, due to the difference in cohesiveness. Clay was found to produce a persistent sticky cake layer, whereas silt penetrated deeper into the bed, both resulting in an absence of infiltration velocity recovery. A cake layer of fine sand sediments was easiest to remove, resulting in dune formation on the streambed. However, due to deep bed clogging by fine sand particles in a coarser streambed, the infiltration velocity did not fully recover. The interaction between mixed suspended sediments (5% clay, 80% silt, and 15% fine sand) resulted in uneven erosion patterns during scouring of the streambed and recovery of the infiltration velocity is low. Altogether it may be concluded that natural recovery of infiltration capacity during river bank filtration of highly turbid waters is expected to occur, as long as the river carries a mixture of suspended sediments and the sand of the streambed is not too coarse.

1. Introduction

Riverbank filtration (RBF) is a surface water treatment method for drinking water, using extraction wells located near the river in order to ensure direct aquifer recharge. As the surface water travels through the sediments, contaminants, such as pathogenic microorganisms, are removed (Schubert, 2003). RBF systems, like other filters, are, to some degree, vulnerable for clogging. Suspended particles in river water can affect the hydraulic conductivity of the bed and limit aquifer recharge (Caldwell, 2006). Streambed clogging may occur on the surface (external clogging) or within the porous media (internal clogging). Experience from the Netherlands has suggested that streambeds primarily consisting of gravels are at a far greater risk of clogging than those consisting primarily of finer grade materials (Stuyfzand et al., 2006). Also, the properties of the suspended particles in the river, such as particle size, affect the extent and clogging degree of the streambed and aquifer (Pavelic et al., 2011; Veličković, 2005).

External clogging corresponds to the cake build-up on the surface of the streambed due to the deposition of suspended solids, which reduces its permeability. Internal clogging, or deep bed clogging, occurs when the suspended particles enter the porous media and get stuck in the subsurface before abstraction (Du et al., 2014). Once a cake is built-up, penetration of particles into the porous media is prevented, and external – or cake clogging - rather than internal clogging will dominate (Fallah et al., 2012;

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Sacramento et al., 2015). Cake and deep bed clogging may also happen simultaneously (mixed clogging), caused by the movement of particles within the porous media and the accumulation of sediments in the upper layer (Du et al., 2014). With this mixed clogging, the hydraulic conductivity of the soil decreases over time, but it decreases much faster in the top layer (Du et al., 2014). Cake clogging may be reversible, but this is typically not the case for deep bed clogging (Pholkern et al., 2015; Seiler and Gat, 2007).

Physical, mechanical, chemical and biological clogging are the main obstruction mechanisms occurring in the streambed. The physical clogging occurs when inorganic and organic suspended solids in the river (e.g., clay, silt particles, algae cells, microorganisms, flocs) become trapped in the streambed pore channels as water flows from the river and through the aquifer (Bouwer, 2002; Caldwell, 2006; Hubbs, 2006a; Pavelic et al., 2011; Schubert, 2002). Particle size distribution and suspended solids concentration in the river water are considered the main factors affecting the physical clogging process (Blaschke et al., 2003; Bouwer, 2002; Pavelic et al., 2011; Platzer and Mauch, 1997). Mechanical clogging refers to air entrainment during recharge from vadose zone to the phreatic aquifer or gas binding from microbiological activities (e.g., methane) (Martin, 2013). Chemical clogging is the loss of hydraulic conductivity of the streambed due to the precipitation of initially soluble water constituents, due to changes in redox potential and pH values caused for example by mixing with native groundwater (e.g., carbonate precipitates, iron hydroxides) (Bouwer, 2002; Caldwell, 2006). The accumulation of precipitates in pores might lead to chemical clogging in the aquifer and nearby the abstraction well (Schubert, 2002). Biological clogging is caused by the accumulation of bacterial cells in the streambed (Baveye et al., 1998; Bouwer, 2002; Engesgaard et al., 2006). The growth of these bacterial cells is dependent on physical-chemical factors associated with both soil and water (Pavelic et al., 2011).

Naturally occurring flow forces may induce sufficient scouring of the streambed, thereby self-regulating the thickness of the formed cake layer and restoring its hydraulic conductivity. Vertical sedimentation forces induce the deposition of particles on the streambed. Horizontal forces onset the resuspension of the deposited particles. The extent of scouring is determined by the magnitude of the shear stress and the properties of the streambed and cake layer, deposited onto the streambed. Scouring or self-cleansing capacity of RBF systems is commonly assessed in terms of streambed particle size (considering critical shear stress) and the shear stress exerted by the river flow. Reported shear stress values typical for river streambeds range between 1 and 100 N/m^2, considering a value of 20 N/m^2 as reasonable (Hubbs, 2006b). However, van Rijn et al. (2007) reported shear stress values for individual sediments ranging from 0.08 to 0.4 N/m^2. The shear stress for the mobilization in porous media of colloidal particles, such as clay, have been reported to range from 0.1 to 1 N/m^2 (Manga et al., 2012; Mays, 2013). Thus, the incipient motion of sediments depends on critical shear stress, which is a function of streambed-armor layer characteristics. For particles finer than 62 μm, the critical shear stress increases as particle size decreases due to the cohesive effects (van Rijn et al., 2007).

Erosion and deposition exhibit dissimilar behavior for cohesive and non-cohesive sediments (Winterwerp and van Kesteren, 2004). Cake layers composed from the deposition of cohesive materials, carried by the rivers, will increase the resistance to erosive processes, meaning higher shear stresses to move the sediments deposited on the streambed. In addition, cohesive sediments have a different shear stress for deposition than for erosion (Krishnappan, 2007). The cake layer may affect the surface water/groundwater interaction and therefore may influence the abstraction capacity yield by altering the permeability of the streambed (Packman and MacKay, 2003). The mechanisms affecting the infiltration velocity based on the movement and settlement of particles on streambeds and the streambed–aquifer clogging are represented in Fig. 1.

The streambed infiltration velocity (q) thus depends on the characteristics of the streambed sediments and the suspended sediments being transported by the river, and it is expected to vary according to the characteristics of the flow (i.e., streambed velocity and flow velocity profile across the river), leading to the deposition and resuspension of particles. The minimum shear stress, τ_c, is defined by the gravitational and cohesive forces that resist particle motion in ideal conditions. When the friction velocity on the sediment bed is greater than the threshold velocity, sediment particles on the bed will become mobilized. The variables that influence the infiltration velocity in the porous media considering the clogging and self-cleansing processes are (e.g., Cunningham et al., 1987; Wang, 1999; Winterwerp and van Kesteren, 2004; Huang et al., 2006; Pugh, 2008; Al-Madhhachi et al., 2013; Zheng et al., 2014): initial infiltration velocity (q_o), density of the fluid (ρ_w) and suspended particles (ρ_s), dynamic viscosity of the water (μ), suspended particle diameter (d_s), d_{50} particle size of the streambed media, surface water depth, bed slope, flow velocity (u), suspended particle concentration ($\varnothing_{sed}$), porosity of streambed, and particle attachment and detachment coefficients.

The main purpose of this study is to evaluate the effect of the concentration of suspended solids and different compositions of the suspension on physical clogging and recovery of the infiltration capacity by subsequent self-cleansing for highly turbid waters. To the authors' knowledge, this has not yet been studied previously. To achieve this, physical modeling with an experimental RBF set-up was conducted in order to assess the effect of flow velocity, particle size of the streambed media, suspended particle diameter, and suspended particle concentration on the infiltration velocity during clogging and self-cleansing. Special attention was paid in this study to differentiate between cake and deep bed clogging.

2. Materials and methods

2.1. Experimental setup

A straight tilting flume with two channels (duplicate) was used for simulation of the river flow (Fig. 2). Infiltration columns placed at the bottom were used to determine the effect of variable shear stress conditions on self-cleansing and infiltration. The channels had dimensions of 500 cm length by 19 cm width and were constructed of smoothed wood. The lateral walls were made of wood and Plexiglas. The infiltration columns were made of transparent Plexiglas (50 cm long and 10.8 cm ID). The columns were equipped with four piezometers for the monitoring of head loss over the height of the porous media and four sampling ports (placed 10 cm from each other). The bottom of the channels was roughened by gluing 0.2–0.8 mm sand onto them, leaving the sides smooth. Flow characteristics were measured with an electromagnetic flowmeter (EM). Turbidity was measured at the different ports of the columns using a turbidity meter (HACH 2100P). The infiltration velocity ($q = Q/A$, where $Q = V/t$ and A is the area of column perpendicular to the water flow) and pressures were monitored for the duration of the experiments to assess porous media clogging and infiltration recovery. The experiments were conducted at room temperature (about 20 °C).