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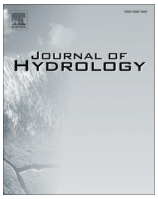

Riverbed Clogging Associated with a California Riverbank Filtration System: An Assessment of Mechanisms and Monitoring Approaches

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SUMMARY

An experimental field study was performed to investigate riverbed clogging processes and associated monitoring approaches near a dam-controlled riverbank filtration facility in Northern California. Motivated by previous studies at the site that indicated riverbed clogging plays an important role in the performance of the riverbank filtration system, we investigated the spatiotemporal variability and nature of the clogging. In particular, we investigated whether the clogging was due to abiotic or biotic mechanisms. A secondary aspect of the study was the testing of different methods to monitor riverbed clogging and related processes, such as seepage. Monitoring was conducted using both point-based approaches and spatially extensive geophysical approaches, including: grain-size analysis, temperature sensing, electrical resistivity tomography, seepage meters, microbial analysis, and cryocoring, along two transects. The point monitoring measurements suggested a substantial increase in riverbed biomass (2 orders of magnitude) after the dam was raised compared to the small increase (~2%) in fine-grained sediment. These changes were concomitant with decreased seepage. The decreased seepage eventually led to the development of an unsaturated zone beneath the riverbed, which further decreased infiltration capacity. Comparison of our time-lapse grain-size and biomass datasets suggested that biotic processes played a greater role in clogging than did abiotic processes. Cryocoring and autonomous temperature loggers were most useful for locally monitoring clogging agents, while electrical resistivity data were useful for interpreting the spatial extent of a pumping-induced unsaturated zone that developed beneath the riverbed after riverbed clogging was initiated. The improved understanding of spatiotemporally variable riverbed clogging and monitoring approaches is expected to be useful for optimizing the riverbank filtration system operations.

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1. Introduction and background

Riverbank Filtration (RBF) systems consist of high capacity pumping wells that are located adjacent to or beneath rivers. RBFs produce water by taking advantage of the natural processes that occur as surface water migrates through the riverbed (Jaramillo, 2012; Stuyfzand et al., 2006), such as adsorption, reduction, physicochemical filtration, sediment filtration, and biodegradation (Tufenkji et al., 2002). Riverbed clogging reduces hydraulic conductivity of the riverbed materials and thus limits infiltration of surface waters toward the collection wells. The clogging can impose a serious limitation to the rate and volume of water production associated with RBFs (Jaramillo, 2012; Schubert, 2006a, 2006b; Sophocleous, 2002; Stuyfzand et al., 2006; Treese et al., 2009).

Laboratory and field studies conducted over the last decade have linked clogging to a combination of mechanisms, including sedimentation of fine-grained particles (Cunningham et al., 1987; Hubbs, 2006; Ray and Prommer, 2006; Wett, 2006), and biological processes, including growth of microbes and algae as well as production of biogas (Battin and Sengschmitt, 1999; Engesgaard et al., 2006; Darnault et al., 2003; Nogaro et al., 2010; Seifert and Engesgaard, 2007). Although commonly recognized in practice, development of methods to monitor and distinguish between different types of clogging mechanisms remains a topic of research.

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This study has two primary objectives. The first objective is to investigate clogging mechanisms, their spatiotemporal evolution, and key controls at a RBF system in California. The second objective is to document the benefits and limitations of various methods for monitoring riverbed clogging and hydrological properties with an objective to identify which combination of methods is optimal. We consider a variety of both conventional and novel characterization and monitoring methods, including: grain-size analysis, temperature sensing, electrical resistivity tomography, seepage meters, microbial analysis, and cryocoring. To our knowledge, this is the first study to investigate the spatiotemporal clogging mechanisms at a RBF facility and to determine an efficient suite of methods to monitor clogging and associated riverbed hydrodynamics. After a brief description of the study site and related research (Section 2), we describe the monitoring methodologies (Section 3) and then present the results of the data analysis (Section 4). Section 5 presents a discussion of the methods and an interpretation of the clogging mechanisms at the study site.

1.1. Riverbed clogging mechanisms and hydrological responses

Riverbed clogging associated with sediment deposition has been investigated under both laboratory and field conditions for decades. Cunningham et al. (1987) conducted a flume study using sediments having grain-sizes (silt and clay) less than 0.063-mm diameter to investigate infiltration characteristics as a function of flow velocity. They observed deposition of fine-grained sediment at low flume flow velocities [<18 cm/s]; above a flume velocity of 18 cm/s they observed a steady degradation of the surficial fine-grained clogging layer. Schälchli (1992) conducted flume studies using riverbed sediments and found that hydraulic conductivity decreased by a factor of 9 within 100 h due to intrusion of fine sediments into the open pore space. Using seepage meters, and sediment cores, Nowinski et al. (2011) monitored the evolution of hydraulic conductivity on a riverbed point bar using slug tests and grain-size analysis. They observed a hydraulic conductivity decrease by a factor of 4; this decrease was associated with a 10% increase in fine-grained sediments.

Clogging of riverbeds can also be caused by biological mechanisms, including the colonization of algae, diatoms, bacteria, extracellular polymeric substance (EPS), and subsequent biofilm build-up at the sediment–water interface and in the sediment pore spaces. Many different parameters affect biofilm development, including concentrations of organic matter and oxygen, nutrient flux, temperature, bacterial abundance and type, water depth, stream velocity, and pumping rate (Baveye et al., 1998; Engesgaard et al., 2006; Flemming et al., 2007; Jaramillo, 2012; Nogaro et al., 2010; Schijven et al., 2003; Seifert and Engesgaard, 2007). Both Engesgaard et al. (2006) and Vandevivere and Baveye (1992) investigated biotic clogging in column experiments, and reported that bioclogging decreased relative bulk hydraulic conductivity by a factor of 100 within 30 days. Naranjo et al. (2012) reported a reduction in both hydraulic and thermal properties as a result of streambed clogging (internal colmation) in the down welling areas of a riffle-pool sequence. Flemming et al. (2007), who also investigated biotic clogging in column experiments, reported a decrease in hydraulic conductivity by a factor of 7.5 after 15 days.

Under natural systems, biofilms can develop into mats or flocs (Seifert and Engesgaard, 2007). Battin and Sengschmitt (1999) investigated the spatiotemporal variation of bioclogging on the Danube River and documented a decrease in leakage coefficient (ratio between the hydraulic conductivity and sediment layer thickness) of a factor of $\sim$3.8 within the top 20 cm of the riverbed. They attributed clogging in this study to be due to the accumulation of dead bacterial assemblages associated with algae. Hoffmann and Gunkel (2011) investigated the effect of bioclogging and particle retention at the surface of a lakebed bank filtration site in Germany. They found up to 48% of the pore space in the upper 10 cm of riverbed sediments was occupied by particulate organic matter (diatoms, biofilms, benthic algae, and detritus), which led to a hydraulic conductivity decrease by a factor of 100 in late autumn. Thullner et al. (2002) numerically modeled homogeneous versus heterogeneous pore size distributions with biomass growth (colony vs. biofilm) in sediments of various grain-sizes and sorting. Their simulations suggested that poorly sorted sediments experienced the greatest clogging, revealing a hydraulic conductivity decrease up to a factor of 100. Using a sand–gravel sediment in laboratory flume studies, Salant (2011) found that both bacteria and algae biomass are equally capable of surficial clogging.

Clogging at RBF facilities can be further exacerbated by the development of a pumping-induced unsaturated zone beneath the riverbed or lake bed. This occurs when the pumping rate exceeds the infiltration rate, at which time the piezometric (groundwater) head drops below the riverbed elevation and air is drawn below the bed from the shore margin (Hubbs, 2006; Zhang et al., 2011). Creation of an unsaturated zone beneath the riverbed can entrap air in the pore space, resulting in decreased hydraulic conductivity, infiltration and water production (Hubbs, 2006; Su et al., 2007; Zhang et al., 2011). Hubbs (2006) indicated that unsaturated zones beneath a river have a reduced ability to support the overburdened weight of the river, which can also result in sediment compression and permeability reduction.

1.2. Methods for monitoring riverbed clogging and hydrological responses

Many methods have been used to investigate riverbed clogging mechanisms and associated hydrological responses. In this section, we provide a short summary of traditional as well as less conventional approaches, many of which are used in our study.

Seepage meters have been used for over four decades to estimate riverbed infiltration. Seepage meters, which often consist of an open 55 gallon drum, utilize the natural movement of water to estimate seepage through riverbeds (Lee and Cherry, 1979). The basic mechanics of a seepage meter entail inserting the open end of a seepage meter $\sim$10 cm into the riverbed. A bag filled with a known volume of water is attached by a hose to the seepage meter. Water flux across the sediment–water interface alters the volume of water in the bag (Lee and Cherry, 1979); calculation of the change of volume over time yields seepage rate and direction. Rosenberry and Pitlick (2009), Rosenberry et al. (2012) and others have successfully used seepage meters to quantify spatiotemporal variations of hyporheic exchange in riverbeds.

Heat as a tracer (temperature flux) methods are commonly used to monitor seepage and hyporheic exchanges. In riverine systems, surface water is heated by daily cyclical radiant heating and cooling (Blasch et al., 2007). The propagation of temperature from river water into the subsurface is assumed to be governed by conduction, advection, and/or dispersion (Battin and Sengschmitt, 1999; Constantz, 2008). As the oscillating temperature signals propagate, the temperature signal is attenuated from interaction with sediments and, where present, upwelling and/or downwelling water (Battin and Sengschmitt, 1999). The degree to which thermal gradients propagate in the subsurface also depends on the thermal properties of water and sediments (Hatch et al., 2006). Highly sampled logs of daily temperature variations at different riverbed depths are used to measure temporal changes. Shifts in the temperature amplitude and peak-lag (phase) between vertical temperature sensors have been used to estimate hydraulic properties (Constantz et al., 2004; Cox et al., 2007; Gordon et al., 2012; Hatch, 2007; Hatch et al., 2006; Lautz, 2012). When combined with