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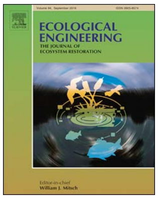

Modeling the effects of vegetation on fluid flow through an acid mine drainage passive remediation system

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ABSTRACT

The fluid dynamics of acid mine drainage (AMD) flow through Wingfield Pines passive remediation system is captured using a lattice Boltzmann model of shallow water flow. The retention time of fluid through the system is critical to the efficient treatment of these polluted waters and, therefore, the retention times in all five settling ponds and the wetlands are elucidated for both the system as it was built, and for when vegetation is present. The effects of vegetation growth is predicted to initially cause channeling, potentially decreasing retention times, but over longer times to increasingly spread the fluid flow throughout the system and increase retention times.

1. Introduction

Acid mine drainage (AMD) can be devastating to surrounding ecosystems, and have grave implications for both human and ecological health. However, it has been shown that water quality can be successfully remediated through the construction of engineered wetlands (Kleinmann, 1989). A long-term consequence of Pittsburgh Coal Seam mining in the Appalachian Basin, AMD has adversely affected approximately 10% of local waterways (Herlihy et al., 1990), and contaminated thousands of kilometers of streams and rivers in the Northern Appalachians (Kleinmann, 1989; Caraballo et al., 2011). However, this problem is not isolated to the United States, and is a global threat to water quality as a consequence of mining operations around the world (Williams and Turner, 2015; Ayora et al., 2013). Water which drains through active or abandoned mines can become contaminated through the oxidative dissolution of metals from sulphide ores, and subsequently have a deleterious environmental impact as a consequence of its acidity and toxicity (Johnson and Hallberg, 2005; Kelly et al., 2012; Gerhardt et al., 2004; RoyChowdhury et al., 2015). In particular, mining operations expose iron pyrite and similar sulfide-bearing minerals to water and oxygen, which through accelerated oxidation, and other chemical and biological processes, produce discharges with low pH and increases in dissolved metals (Johnson and Hallberg, 2005; Williams and Turner, 2015; Johnson, 2003; Akcil and Koldas, 2006; Jacobs et al., 2014; Obreque-Contreras et al., 2015; Bigham and Nordstrom, 2000; Younger et al., 2002; Chen et al., 2016). Furthermore, the mine drainage may be contaminated for hundred, if not thousands, of years after the mining site is abandoned (Ayora et al., 2013); the long term ecological consequences of which can be devastating.

The intention of engineering a treatment for AMD waters is to restore water quality, and ensure the biological recovery of ecological communities poisoned by mining operations (Kruse et al., 2013). The ecological impacts of AMD waters arise from low pH discharges, contamination with toxic metals and metalloids, and the sedimentation of particulate matter (Hallberg and Johnson, 2005). The impact of these conditions on the sustainability of rivers and streams can be dramatic; declines in the abundance and diversity of macroinvertebrates (Williams and Turner, 2015; Gerhardt et al., 2004; Van Damme et al., 2008; Alvial et al., 2012), reduced habitat and lower survival rates of fish (Kruse et al., 2013; Kimmel, 1988; Kimmel and Argent, 2010), impediments to fish migration (Henry et al., 1999), replacement of acid/metal sensitive species with acid/metal tolerant species (Gerhardt et al., 2004), and the reduction in the biological activity and structural stability of soils (RoyChowdhury et al., 2015; Hillwig et al., 2015) have all been observed as a consequence of AMD. Chartiers creek, a tributary of the Ohio River, is one of the most polluted watersheds in Pennsylvania and suffers from acid mine drainage, agricultural and industrial runoff, and storm sewer overflows. In particular, it is in the lower half of the watershed where the evidence for the discharge of heavily iron-laden AMD water is most apparent. This water is more alkaline than most AMD, as the acidic discharges from the abandoned mines have interacted with naturally occurring calcareous material, but still carries large amounts of iron resulting in waters stained bright orange with iron oxides. Wingfield Pines Conservation Area was built by Hedin Environmental, at the request of the Allegheny Land Trust, on a 80 acre strip-mined floodplain of Chartiers Creek with the purpose of cleansing iron oxide from polluted waters that were discharging into Chartiers

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Creek (Hedin, 2004).

The discharges occur because of the flow of rain water through a network of mines that can cover large areas. Therefore, it is not practical to inhibit the formation of AMD and treatment of polluted discharges is the only option (Hallberg and Johnson, 2005). There are two general strategies for remediating AMD: active and passive treatment. Active treatment generally consists of adding an alkaline material (such as lime) to AMD to raise the pH of the discharge, which in turn accelerates chemical oxidation and causes many of the metals present in the solution to precipitate as hydroxides (Johnson and Hallberg, 2005; Hallberg and Johnson, 2005). However, this requires a steady supply of alkaline material to be quarried and transported to the site, and can be labor intensive (Johnson and Hallberg, 2005). This is economically unviable, especially for abandoned mines (Ayora et al., 2013; Johnson and Hallberg, 2005; RoyChowdhury et al., 2015) and there has been a large amount of interest in developing passive remediation systems that are based on wetland ecosystems (Johnson and Hallberg, 2005; Kleinmann, 1990; Hedin et al., 1994). Therefore, while active treatment of AMD may be used if there is a requirement to remediate large amounts of water at an active mine site, a passive treatment approach is more appropriate for AMD from abandoned mine sites (Caraballo et al., 2011; Hallberg and Johnson, 2005).

The majority of early passive remediation systems were implemented in the Appalachia region of the eastern USA (Kleinmann, 1990; Hedin and Nairn, 1992, 1993; Hedin et al., 1994) to mitigate the environmental impact of AMD from Pittsburgh Coal Seam mining. As opposed to active remediation systems, passive remediation systems do not require chemical additives or mechanical pumping, and require only very limited maintenance (Dempsey et al., 2001). A passive remediation system is typically situated before the polluted water is discharged into streams or other waterways (Johnson and Hallberg, 2005). Such a system might first consist of small sedimentation or settling ponds, where oxidation and solid settlement can first occur prior to the fluid flowing into a constructed wetland (Johnson and Hallberg, 2005); this extends the useful life of the system by reducing the amount of sedimentation in the wetland. The fluid is then discharged into a wetland which consists of a shallow body of water, and appropriate vegetation, in order to provide sufficient retention times to further oxidize iron and precipitate iron oxides. These wetlands are ideal for mildly acidic waters containing elevated iron concentrations, such as is found at the Wingfield Pines Conservation Area. Passive remediation systems are cost-effective, environmentally friendly, and can remain effective despite large seasonal variations in temperature and flow rates (Hedin, 2008; Hedin et al., 2010). Furthermore, the precipitated iron sludge can be extracted and have commercial value (as a raw material in pigment production) (Hedin, 2008, 2003). This makes passive remediation systems the most cost effective solution for AMD, and was the system implemented by Hedin Environmental at the Wingfield Pines Conservation Area (Hedin, 2004).

Wingfield Pines Conservation Area treats AMD which is neutral, with a pH between 6.7 and 6.8, and allows approximately 43 tonnes of iron oxide solids to be removed annually from the discharge into Chartiers Creek (Hedin, 2004). Metal-rich groundwater enters the first settling pond (the orange pond on the left of Fig. 2a), before going around a series of 4 settling ponds arranged in a circle (going around clockwise, the decrease in iron oxide in the water is clearly visible through the reduction in orange), and finally being discharged into a meandering wetland (on the right of Fig. 2a). The settling ponds are designed to retain the water long enough for oxidation to occur, and the solid iron oxides to settle out of the solution (Hedin et al., 2013). The wetland removes residual suspended solids (while also providing a scenic exhibit of ecological rehabilitation and environmental education) (Hedin, 2004). The oxidation and sedimentation of iron oxide in both the settling ponds and the wetlands require a sufficient retention time and, therefore, one aspect of the design of such passive remediation systems that is crucial to their performance is the hydrodynamic efficiency; the purpose of this study is to consider the hydrodynamic efficiency of the Wingfield Pines Conservation Area passive remediation system in the presence of vegetation.

The fluid dynamics of the settling ponds and wetland have a direct influence on the residence times of the water (the amount of time water spends within the system) (Kjellin et al., 2007). In other words, a longer residence time allows more time for oxidation and sedimentation to occur, which obviously improves the treatment efficiency and results in a clearer discharge into Chartiers Creek. The hydrodynamic efficiency is determined by how efficiently the flow is distributed throughout the pond (Persson et al., 1999); for example, the most efficient flow is plug flow which refers to the case where the entire flow is spread out equally, all fluid spends an equal time flowing through the pond, and all flow travels at a similar velocity that is evenly distributed over the width of the pond (Persson et al., 1999). Under these ideal conditions, the fluid would flow through the pond with a nominal residence time, defined as the ratio between the volume of the pond and the flow rate through the pond. This, of course, assumes that there is no dispersion present which is not the case in real ponds (and especially wetlands) where the velocity of the fluid varies considerably and the fluid can spend more or less time in the pond than the nominal residence time (Lightbody et al., 2008). This can have a significant effect on the efficiency of passive remediation systems (Wörman and Kronnäs, 2005). In particular, short circuiting can decrease both the hydrodynamic and treatment efficiency (Persson et al., 1999). Short circuiting is the presence of preferential pathways or channels for the fluid, which results in the fluid flowing along these preferential paths at higher velocities (a process referred to as channelization) and spending appreciably less time in the pond than the nominal residence time (Persson et al., 1999; Lightbody et al., 2008). The opposite of short circuiting can also occur; that is fluid can become trapped in dead zones, where the flow is stagnated or recirculates separate from the main channels of flow. Dead zones typically occur around corners or behind obstructions, or around vegetation in wetlands.

There has been a substantial interest in the effects of vegetation on fluid flow. For example, Jimènez-Hornero et al. (2007) have used the standard two-dimensional lattice Boltzmann model to capture the flow in an open and vegetated straight channel. The vegetation was captured using a drag force on the fluid, that took into consideration the density of vegetation and was proportional to the velocity squared (appropriate for rigid cylindrical stems). Recently, Yang et al. (2017) simulated the flow-vegetation interactions in an open channel, using a lattice Boltzmann shallow water equations model to capture the flow around discrete vertical cylinders. Similar to Jimènez-Hornero et al. (2007), a drag force proportional to vegetation density and the fluid velocity squared was adopted. Here, we capture the growth of the vegetation as a consequence of the flow profile and the subsequent effects of the vegetation on the fluid flow. The flow through vegetation can be influenced by the length scale of the vegetation, from individual branches and blades of a single plant to a canopy of plants, and is strongly influenced by the rigidity and density of the plants (Nepf, 2012). On the lengthscale of the pond, the plants can help disperse the flow of water throughout the wetland, decreasing channelization, and increasing retention times (RoyChowdhury et al., 2015). Furthermore, the vegetation can grow heterogeneously throughout the pond, resulting in complex flow fields and different distributions of residence times (although, as mentioned, the vegetation is thought to generally increase residence times) (Kjellin et al., 2007). However, the interactions between vegetation and flow goes both ways, and not only is the fluid flow influenced by vegetation, but the growth of vegetation is also dependent on the local fluid dynamics. When fluid flow is too slow vegetation may not be supplied with sufficient nutrients and when the fluid flow is too fast the vegetation can become damaged (Chambers et al., 1991). Vegetation, therefore, plays a crucial role in the hydrodynamics of ponds and wetlands and can influence the efficiency of passive remediation systems, such as found at the Wingfield Pines