Chapter 1

Introduction

Population growth and expansion of irrigated agriculture put increasing demands on current water resources management. Combined with anticipated increases in the frequency and intensity of drought and precipitation due to climate change, these pressures may render existing surface water storage insufficient (Barnett and Pierce 2008), if not impractical in arid and semi-arid areas subject to lower streamflows and excessive evaporation (Gleick 2002, Brikowski 2008). Alternative water resources management, if able to take advantage of water reuse and to reduce the capital- and energy-intensity of water treatment, promises to improve sustainability and reliability in light of these pressures.

One form of alternative water resources management with a long history in Europe is bank filtration. In this system, groundwater is extracted from a well adjacent to a river or lake, thereby inducing infiltration from the surface water body into the shallow groundwater. The natural processes along the infiltration flow path lead to nutrient, organic carbon, and pathogen removal, thereby improving the quality of the water recovered (Schwarzenbach et al. 1983, Dillon 2005). Active in some locations for more than 100 years (Eckert and Irmscher 2006), current estimates suggest that 27 million people, approximately 23% of the population, in Slovakia, Hungary, Germany, Switzerland, and the Netherlands rely on bank filtration for their drinking water supply (Hiscock and Grischek 2002).

An operational limitation of bank filtration is the release of iron (Fe) and manganese (Mn) as the infiltrating water passes from oxic to reducing conditions in the river- or lake-bank. High concentrations of Fe and/or Mn often necessitate post-extraction treatment in bank filtration sites in Germany (Massmann et al. 2008b), the Netherlands (de Vet et al. 2010), and Canada (Petrunic et al. 2005). However, re-introduction of dissolved oxygen to the shallow groundwater along the infiltration path could potentially precipitate Fe and Mn oxides *in situ*. Furthermore, the stability of Fe and Mn oxides is known to control the release of other trace metals in groundwater (Davranche and Bollinger 2000). A bank filtration site in Berlin, Germany, with Fe and Mn concentrations above WHO guidelines (5 μM and 2 μM, respectively) was selected to study the processes controlling these two key trace metals in further detail.

Scope and Objectives

The objective of this research is to quantify the rates and mechanisms controlling Fe and Mn behavior in bank filtration systems. Specifically, it will address the following questions:

- How do the rates of reductive dissolution, the predominant mobilization pathway for Fe and Mn, vary with depth in the bank sediments?
- Do water table fluctuations in the vicinity of the production wells provide sufficient dissolved oxygen to enable *in situ* Mn oxidation?

- What ambient conditions lead to the presence or absence of significant *in situ* Mn and Fe oxidation?

A critical review of the inorganic geochemistry of bank filtration systems, in light of the relevant physical and transport processes, is presented in Chapter 2. This chapter, along with an additional section in Chapter 7 on future research needs, has been submitted to *Environmental Science and Technology* for publication. A Mn-oxide-doped gel probe sampler was developed to measure *in situ* rates of reductive dissolution in shallow (< 50 cm) sediments. The laboratory development of this method, including experiments with model reductants (ascorbic acid and *Shewanella oneidensis* MR-1) and modeling to account for diffusion, is presented in Chapter 3. Gel probes were deployed in the sediments of Lake Tegel (Berlin, Germany) in July, and in Chapter 4, the subsequent reductive dissolution rates were paired with sequential extraction of nearby sediment cores to understand the relevant diagenetic processes in this setting. Chapters 3 and 4 were published as companion papers in *Environmental Science and Technology* in January 2010.

Anoxic microbial medium was flowed through a quartz-sand-filled column inoculated with *Pseudomonas putida* GB-1 (a well-characterized Mn oxidizing bacterium) and subjected to 1.3 m water level changes every 30–50 h for 600 h. The frequency and amplitude of the water level fluctuations, as well as the flow conditions, were designed to simulate the conditions present in the shallow groundwater at the Lake Tegel bank filtration site. Analysis of the Mn removal rates in the column and the solid-phase Mn at the end of the experiment are detailed in Chapter 5. Aquifer sediments up to 25 m depth were collected during the drilling of a borehole 3 m away from a production well at Lake

Tegel. In Chapter 6, the results the solid-phase characterization for Mn and Fe are discussed in terms of the general conditions necessary for *in situ* Mn and Fe accumulations in bank filtration settings. Chapter 7 presents the conclusions of this work, including further commentary on Chapters 3 and 4 in light of more recent publications, and a section on future research needs in bank filtration settings. Additional field and experimental data can be found in the appendices; data are organized such that Appendices A, B, and C provide supporting information for Chapters 3, 4, and 5, respectively.