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Source and migration of dissolved manganese in the Central Nile Delta Aquifer, Egypt

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A B S T R A C T

Dissolved metals in waters in shallow deltaic sediments are one of the world's major health problems, and a prime example is arsenic contamination in Bangladesh. The Central Nile Delta Aquifer, a drinking water source for more than 6 million people, can have high concentrations of dissolved manganese (Mn). Standard hydrochemical analyses coupled with sequential chemical extraction is used to identify the source of the Mn and to identify the probable cause of the contamination. Fifty-nine municipal supply wells were sampled and the results compared with published data for groundwaters and surface waters. Drill cuttings from 4 wells were collected and analyzed by sequential chemical extraction to test the hypothesized Mn-generating processes. The data from this research show that the Mn source is not deep saline water, microbial reduction of Mn oxides at the production depth, or leakage from irrigation drainage ditches. Instead, Mn associated with carbonate minerals in the surficial confining layer and transported down along the disturbed well annulus of the municipal supply wells is the likely source. This analysis provides a basis for future hydrogeological and contaminant transport modeling as well as remediation–modification of well completion practices and pumping schedules to mitigate the problem.

1. Introduction

In the Nile Delta of Egypt over the last 50 years, groundwater has replaced contaminated or less reliable surface waters. However, dissolved manganese (Mn) is widespread in Delta groundwater and commonly exceeds WHO and Egyptian water quality standards (Atta et al., 1993), particularly in Tanta and the western and northern areas of El Gharbiya Governorate. Commonly, new wells have low concentration of Mn, ([Mn]) but, with time, concentrations typically increase until the well must be abandoned (Atta et al., 1993; Khalil et al., 1992). This pattern of increasing dissolved metal concentration with pumping resembles reports from Bengal (e.g., Harvey et al., 2005; Mukherjee and Fryar, 2008) and suggests that the presence of the well, or the production of water from the well, may trigger or contribute to Mn mobilization.

The toxicity of ingested Mn from drinking water is not well established, but there are reports of Parkinson's type symptoms in populations consuming water with [Mn] of 1.8–2.3 mg/L (e.g., Kondakis et al., 1989); although no direct causal links have been established. In the Nile Delta region it is not the specific toxicity, but rather the response of the population to the manganese that is the issue. The drinking water limits on Mn are based on taste threshold, and the presence of Mn in the water imparts a distinctive and unpleasant flavor to the water (Habib, 2010; Gemail et al., 2011). According to the water authority, this has the effect of making the ground water less attractive, and the potentially contaminated surface waters more attractive to the population, thus increasing the risk of exposure to water-borne disease. A safe groundwater supply that is also attractive to the people at risk is essential for this region (Atta et al., 2006; Elewa, 2010).

There has been a global effort to assist developing nations to obtain safe drinking waters in part by developing groundwater resources. While successful in reducing water borne diseases (e.g., cholera and diarrhea) (Briscoe, 1978), there have been unexpected consequences due to mobilization of naturally occurring toxic elements (Caldwell et al., 2003). The prime example is the Bengal Basin (Bangladesh and India), where tube wells installed to supply clean drinking water can also produce water contaminated with arsenic (BGS and DPHE, 2001; Caldwell et al., 2003, Smedley and Kinniburgh, 2002). In fact, this has been described as the major failure of "hydrophilanthropy" (Sharp et al., 2010). Other regions may encounter similar problems (e.g., South and East Asia, Bengal Basin, Irrawaddy Delta, Mekong River Valley, Indus Plain, Yellow River Plain) (Smedley, 2005a,b; Buschmann et al., 2007; Sthiannopkaoa

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et al., 2008). Understanding manganese mobilization may contribute to a broader understanding of redox element speciation and mobility in groundwater in these settings. It should be noted that in this paper, Mn is the general abbreviation for manganese and [Mn] is the abbreviation for dissolved manganese.

This study tested five working hypotheses for the source of [Mn] contamination in the Nile Delta Aquifer:

1. Widespread but discontinuous natural [Mn] controlled by groundwater flow and sediment variability in Nile River paleochannels.
2. Upward mixing (upconing) of deeper (saline) reduced water with high [Mn].
3. Localized microbial reductive dissolution of Mn minerals at depth from the fluvial-deltaic sediments, possibly related to water well pumping.
4. Leakage of [Mn]-contaminated water recharged from irrigation canals and drains; and
5. Drawdown of [Mn]-contaminated water from the overlying Bilqas confining layer sourced by dissolution of Mn carbonates or hydrous Mn oxides.

2. The study area

The Nile Delta covers an onshore area of about 25,000 km^2. Twenty km north of Cairo, the Nile divides into the Rosetta (Rashid) and Damietta (Dumyat) branches as it enters the Delta (Fig. 1). The Nile River and associated Nile Delta Aquifer are the principle sources of water for the majority of the population of Egypt. Since at least 4000 B.C. (Theroux, 1997), the river has been used for irrigation in Egypt by a complex network of canals and drains. The present day steady discharge from Lake Nasser Reservoir impounded behind the Aswan High Dam is $\sim 10^8$ m^3 d^{-1} with 75% diverted into irrigation canals. A representative Nile water composition at Giza (near Cairo) is 1.5 mmol L^{-1} Na, 0.75 mmol L^{-1} Cl, 1.1 mmol L^{-1} Ca + Mg, 2.2 mmol L^{-1} HCO_3, and 0.2 mmol L^{-1} $SO_4^{=}$, a pH ~ 8.3 (Khalil and Hanna, 1984), which is consistent for water in equilibrium with calcite and atmospheric CO_2.

3. Hydrostratigraphy

Fig. 2 summarizes the hydrostratigraphy of the area. The Holocene-Pleistocene Bilqas confining unit overlies the Mit Ghamr and El Wastani Formations that together form the Nile Delta Aquifer. These units generally thicken towards the Mediterranean and the depth to the freshwater–saltwater interface becomes shallower so that near the City of Kafr El Sheikh (~75 km north of Tanta), freshwater resources are minimal. The Bilqas Formation is formed from the uppermost 10–30 m of overbank flood deposits sediments that form the organic-rich silty clay-sand confining unit that is an aquitard near Tanta but permeability decreases northward so that it is considered an aquiclude near the coast (Barrocu and Dahab, 2010; Ebraheem et al., 1997; Rizzini et al., 1978). The primary groundwater producing unit is the Pleistocene Mit Ghamr Formation with >300 m of fluvial sand and gravel and the deeper Pliocene El Wastani Formation consisting of about 200 m of marine sands and clays. Mit Ghamr sediments are quartz and alkali feldspars with a mixed assemblage of heavy minerals in the coarse fraction and with smectite and kaolinite dominating the clay fraction (Atwia 1998; Atwia et al., 2006). Dahab (1994) subdivides the Mit Ghamr into 3 sub-aquifer units, but these are generally not mapped in the study area. The unit underlying the aquifer is the

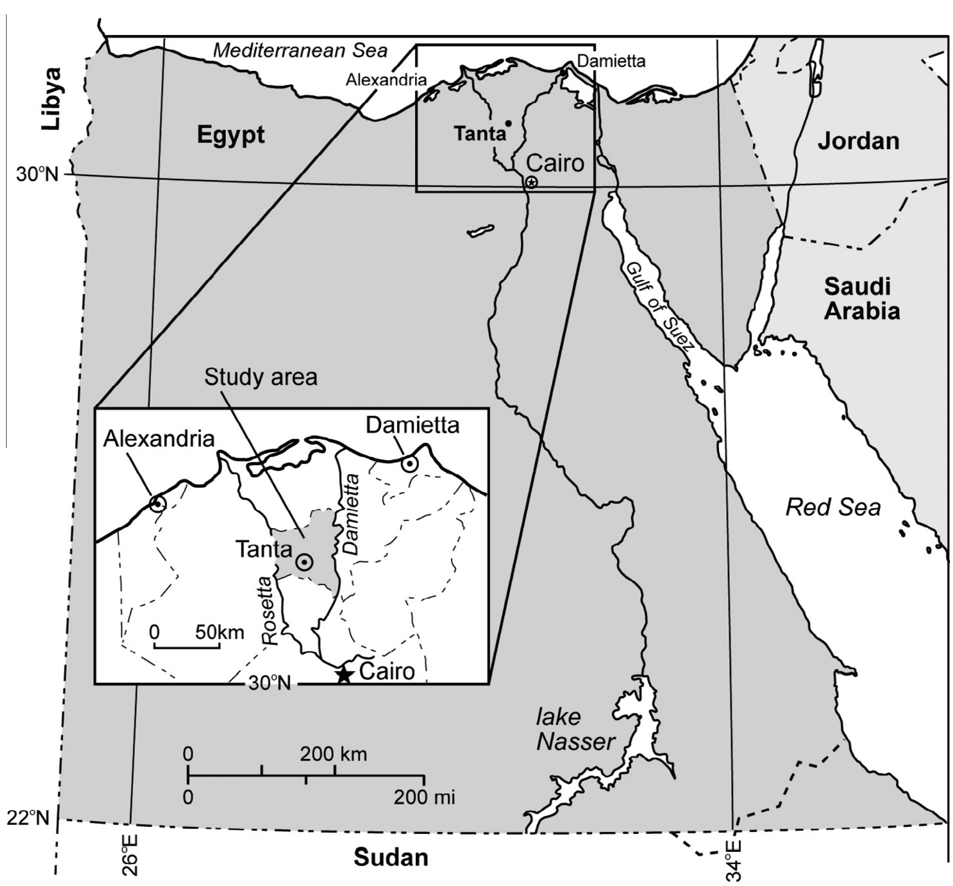

Fig. 1. Location map of study area and surroundings.