



Evaporation as the transport mechanism of metals in arid regions



Ana T. Lima^{a,b,*}, Zeinab Safar^a, J.P. Gustav Loch^a

^a Department of Earth Sciences, Division of Geochemistry, Utrecht University, PO Box 80.021, 3508 TA Utrecht, The Netherlands

^b Ecohydrology, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo N2L 3G1, Canada

HIGHLIGHTS

- Evaporation dictates water flow and heavy metal transport in soils of arid regions.
- Heavy metals will accumulate at the surface of contaminated soil, especially if it is sand.
- Soil can be a great source of contaminated aerosol problem and incite public health issues.

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ABSTRACT

Soils of arid regions are exposed to drought and drastic temperature oscillations throughout the year. Transport mechanisms in these soils are therefore very different from the ones in temperate regions, where rain dictates the fate of most elements in soils. Due to the low rainfall and high evaporation rates in arid regions, groundwater quality is not threatened and all soil contamination issues tend to be overlooked. But if soil contamination happens, where do contaminants go? This study tests the hypothesis of upward metal movement in soils when evaporation is the main transport mechanism. Laboratory evaporation tests were carried out with heavy metal spiked Saudi soil, using circulation of air as the driving force (Fig. 1). Main results show that loamy soil retains heavy metals quite well while evaporation drives heavy metals to the surface of a sandy soil. Evaporation transports heavy metals upward in sandy soils of arid regions, making them accumulate at the soil surface. Sand being the dominating type of soil in arid regions, soils can then be a potential source of contaminated aerosols and atmospheric pollution – a transboundary problem. Some other repercussions for this problem are foreseen, such as the public ingestion or inhalation of dust.

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1. Introduction

Soil transport mechanisms depend on the climatic region they are located (e.g. Shi et al., 2012a,b). Temperate regions tend to have a high amount of rainfall where elements are leached and leached away from soil's surface. Arid region soils are characterized by an annual cumulative effect of potential evapotranspiration exceeding precipitation (Dregne, 1976). In such areas, the transport of elements in soils depends on the upward evaporative flux of water, which concentrates salts at the surface (Elrick and Mermoud, 1994; Aydin, 2008; Novak, 2010).

Soils of arid regions are characterized by having a high pH, relatively low organic matter (OM) and low soil moisture content, being generally of calcareous, salic or sodic nature (IUSS Working

Group WRB, 2007). They can be rich in silicates, carbonates and sulphate minerals (Sposito, 2008). In arid regions, ions are released into soil solution by mineral weathering or by intrusion of saline surface water, or even groundwater, and tend to accumulate in secondary minerals formed as the soil dries. The sources of ions in soil can also be external, through contamination sources such as landfills.

Heavy metals may occur in soils originating from both natural and anthropogenic sources (Alloway, 1995; Han and Banin, 1997, 1999). Anthropogenic sources of metals in soils are very diverse and include leakage of contaminated industrial effluent, sewage sludge, mining activities, application of fertilizers and pesticides in agriculture and municipal waste landfill (Alloway, 1995; Jalali and Khanlari, 2008). Heavy metals tend to accumulate and be immobilized by soil and their constituents, either by forming low solubility precipitates, by being adsorbed by minerals or both (Jalali and Khanlari, 2008; Lafuente and Gonzalez, 2008). The main sorption surfaces are clay particles, Fe, Al and Mn (hydro) oxides and organic matter (OM) (Rikers, 1999; Jalali and Khanlari,

* Corresponding author at: Ecohydrology, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo N2L 3G1, Canada. Tel.: +1 519 888 4567; fax: +1 519 746 2401.

E-mail addresses: atlima@uwaterloo.ca, lima.at@gmail.com (A.T. Lima).

2008; Lafuente and Gonzalez, 2008), which are highly dependent on pH.

Contamination issues in soil are normally intertwined with groundwater protection in temperate regions. The fate of contaminants, being them organic or inorganic, depends on the fluxes and flows of water, environmental conditions and soil properties (Batjes and Bridges, 1993). When in arid regions, the transport of solutes in soil is coupled to the volatilising water, where the non-volatile solutes that are dissolved in the water remain at the site of evaporation (Walton, 1993; Elrick and Mermoud, 1994; Dold and Fontboté, 2001; Grifoll and Gsto, 2005; Smuda et al., 2007). In this study we hypothesise that heavy metal transport in soils of arid regions follows the path of other major cations (solute) present in soil solution, i.e., it is coupled to the volatilization of pore water. We then propose to investigate the effect of evaporation in the transport of heavy metals in soils. For that, we elaborate a series of column experiments with two variables: type of soil (loam and sand) and duration of the evaporation (3, 5 and 7 weeks). The test resides on determining the depth at which the heavy metals are placed in soil before and after exposed to evaporation. Landfill leachate was manufactured according to heavy metal content in (Rawat et al., 2009) and used to spike the soils sampled from Saudi Arabia.

2. Materials and methods

2.1. Soil materials

Two different soils were used to test the transport of metals in soil by evaporation. Samples from two different soil locations were used in the present study: a sandy loam, taken from the oasis Al-Hassa, situated in the eastern province of Saudi Arabia about 170 km southeast of Dammam on the Persian Gulf; and a sand, taken from the desert south-east of Al-Hassa. The loam soil was taken from an irrigated date farm.

2.2. Soil analysis

Soil organic matter, carbonate and water were analysed by thermogravimetry (LECO-TGA 701). Soil pH and electrical conductivity (EC) were analysed by dispersing 1 g of soil in 2.5 mL of demineralized water, using pH and EC electrodes. Soil properties as cation exchange capacity (CEC) and particle size distribution (Malvern Zetasizer Nano) were also determined. CEC was quantified by the silver thiourea method. 1 g of soil sample was dissolved in AgTu solution (0.01 M Ag and 0.1 M Thiourea) and centrifuged. The extract was acidified with 50 μ L of HNO₃ 65% (van Reeuwijk, 2002). The concentration of the alkali metals (Ca, Mg, K, and Na), which occupy the CEC of the soils, were measured by ICP-OES (van Reeuwijk, 2002). These metals were released from the soil

by replacement with Ag⁺ ions in the diffuse double layers. The CEC was calculated according to Sposito (2008) (see Table 2).

The two soils were not contaminated, so metal spiking was carried out for the purpose of this study. Concentration levels of heavy metals to be obtained were derived from sewage sludge concentration ranges in a region of industrial contamination (Rawat et al., 2004). An artificial solution was prepared containing Cd, Cr, Cu, Pb, Ni and Zn for spiking the soil. Table 3 shows the concentrations of these metals, as well as the salts used to make the solution. This solution was then used to spike the loam and the sand. Soils were placed into small cylindrical reactors, with 4.2 cm diameters and 3 cm length (Fig. 1). The reactors have one opening at the bottom, from where the spiking solution was injected. Every reactor was spiked individually with the heavy metal solution by a flow of 1 mL/day until the soil is saturated. The sand was saturated after one day, while the loam was saturated after 7 days. After saturating the soil, the spiked solution was in contact with the soil for 3 weeks, so aging could occur. At this time, in the control reactors, the soil was sliced in 3 slices and *Aqua regia* was used to determine the total concentrations of the metals in the soil after spiking. The metal concentrations were then determined by ICP-OES. OM, carbonates and water content was determined by a thermo-gravimetric analyser Metler AT200 (TGA).

Soils before and after experiments were analysed with micro X-ray fluorescence (μ -XRF Edax Orbis[®], X-ray optics with capillary focusing to 30 μ m spot size) and X-ray diffraction (XRD). Soil air-blown particles captured in the water reservoirs during experiments, called dust from here on, were rinsed with 67% HNO₃ overnight at the end of the experiments. The extract was then measured by ICP-OES. The solid amounts of dust were too small for *Aqua regia* digestion.

2.3. Evaporation experiments

After this 3 week aging period, the soil reactors were subjected to the evaporation experiments. Three different evaporation time lengths were chosen: 3, 5 and 7 weeks, for both loam and sand. All experiments were done in duplicate and one blank (labelled “no evaporation” in Figs. 2 and 6). The blanks (“no evaporation”), the columns that were merely saturated and were not subjected to evaporation, were treated after the 3 week aging period. At this time, the columns were horizontally sliced, air dried and analysed.

Evaporation was induced by blowing compressed air over the samples (Fig. 1). The reactors were built with 3 openings at the top: one where the air was blown in, and two for collecting the air and particles that are blown out (Fig. 1). The dust that was blown out from the reactors was captured in reservoirs that contained water. The samples were weighted before and after saturation to determine the added water amount, and the water lost by evaporation. The weight of the dry soil was about 55 g for the sand samples and about 40 g for the loam samples. The sample weight and added water weight are listed in Table 4. The samples were weighted before flushing the solution, after saturation and after drying to measure the water mass balance.

After the evaporation experiments, soil was sliced: the sand soil was divided into 3 slices after 3 week evaporation; into five slices after 5 weeks of evaporation and into 6 slices after seven weeks of evaporation. The loam was divided into 8 slices in all stages and analysed as previously described.

3. Results and discussion

The collected soils are from the east coast region of Saudi Arabia, from marine deposits in which illite and smectite predominate, and have high level of salinity (Al-Barrak, 1990). Literature reports

Table 1
General characteristics of the loamy and sandy soil. pH, EC and CEC values are average of two replicates.

	Loam	Sand
pH	8.0 \pm 0.0	8.1 \pm 0.0
EC (mS/cm)	0.17 \pm 0.0	0.16 \pm 0.0
CEC (mol/kg)	1.23 \pm 0.0	0.04 \pm 0.0
Particle size distribution	7% Clay, 42% silt, 51% sand	2.2% Silt, 97.8% sand
Water content (%)	3.02	0.27
Organic matter (%)	1.98	0.34
FeCO ₃ content (%)	1.29	0.07
CaCO ₃ content (%)	12.0	1.96
Rest of carbonates (%)	0.12	0.01

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