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ScienceDirect
Procedia Earth and Planetary Science 17 (2017) 332 – 335
Procedia
Earth and Planetary Science

15th Water-Rock Interaction International Symposium, WRI-15

Assessment of wastewater contaminants retention for a Soil-Aquifer Treatment system using soil-column experiments

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Abstract

Soil-Aquifer Treatment systems are increasingly seen as a relatively inexpensive and complementary water quality enhancement process, which may be particularly relevant in water scarcity scenarios. In this context, a set of soil-column experiments were conducted aiming to replicate the conditions of infiltration basins using soil as a depuration media for wastewater quality increment previous to managed aquifer recharge. The results showed a decrease in a set of contaminants analysed, when comparing to the inflow concentrations, showing that retention and degradation are occurring inside the experimented soil. Ultimately a set of conclusions were achieved that allowed to define the composition of a reactive layer to be installed in real scale infiltration basins that will act as a complementary wastewater treatment method.

Peer-review under responsibility of the organizing committee of WRI-15
Keywords: Soil-column experiments; Soil-aquifer Treatment; Contaminant retention; Wastewater

1. Introduction

Soil-Aquifer Treatment (SAT) is a well-established Managed Aquifer Recharge (MAR) complementary method which main purpose is to increase water availability in aquifers and simultaneously improve its quality during the injection process. SAT-MAR methods are an important way of addressing water scarcity challenges by reusing water of impaired quality, such as wastewater, converting it into a reliable resource. This can be quite useful in water resource management, particularly in semi-arid regions, helping to face decrease of rainfall and long drought periods resulting from climate change. In this context, SAT can also present itself as a relatively simple and inexpensive complementary method of treatment, lessening possible environmental problems.

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Peer-review under responsibility of the organizing committee of WRI-15
doi:10.1016/j.proeps.2016.12.084

The research presented was developed in the framework of EU 7th Framework Project MARSOL project which aims to demonstrate the reliability of MAR processes to face water scarcity problems in Southern Europe and Mediterranean regions. Soil-column experiments were conducted at National Laboratory for Civil Engineering (LNEC) using a soil collected in São Bartolomeu de Messines (SBM), one of the DEMO sites in Algarve region (Portugal) where SAT-MAR basins are to be constructed using treated wastewater as primary infiltration water source.

2. Objectives

These experiments aimed to characterize the soil behaviour at lab scale by simulating infiltration basin conditions, determining the hydraulic characteristics and contaminant retention capacities. Natural soil results obtained were compared to those obtained for a soil mixture produced in LNEC. This soil mixture purpose is to act as a reactive layer to be installed in the bottom of the infiltration basins, increasing its capacity to retain certain contaminants detected in the infiltration water, but also keeping acceptable hydraulic conductivity without hindering the water-soil interaction. The referred mixture results from a combination of easily available and inexpensive materials with the natural soil.

3. Soil-column experiments

3.1. Materials and methods

Several soil-column experiments were conducted for different time lengths, testing different methods of column assembling, thickness, soil packing, saturation conditions and injection method. This was done both for natural soil and produced soil mixture. Outflow samples were collected for the experiments that used wastewater as injection source and several parameters were analysed giving special attention to metals, nitrogen cycle components and major ions. Fig. 1 presents the soil-column apparatus. This consists in an acrylic transparent column with 5 cm diameter with enough height to allow the existence of a controlled height of water on the top of the soil, simulating the conditions of real scale infiltration basins. The material follows the DEMEAU[2] project specifications for this type of experiment.

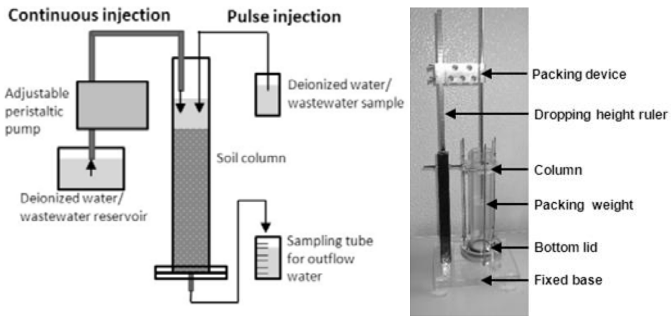

Fig. 1 – Soil-column experiments apparatus

The DEMO area natural soil that was used in experiments is a loamy sand (81.91% sand, 15.95% silt and 2.14% clay), having quartz, calcite, montmorillonite and anorthite as major mineral constituents and traces of dolomite, illite, kaolinite and hematite. It has 24.02% of carbonates percentage, low organic matter (OM) content (2.66%), average bulk density of 1.44 g/cm^3 and average porosity of 43.6%. Soil samples were collected at the approximate location of the infiltration site in the outskirts of SBM wastewater treatment plant, from a depth of 5 to 20 cm. The soil was dried at 40°C and large organic matter (roots, leaves, etc.) was manually removed.

For the soil mixture different components were considered. An increment of OM percentage, particularly in this natural soil which has low OM content, can greatly contribute to the increase of biological activity and therefore the chances of biodegradation processes to occur, as it represents a supply of dissolved organic carbon. A commercial organic soil was acquired to be used in the mixture. Another factor to be taken into account is the reactive layer hydraulic behaviour. In fact, although time of contact is essential for contaminant retention, it is also important that this reactive layer does not behave as a cap layer. This would result in long ponding periods in the area of infiltration. To increase the soil mixture permeability, an "artificial sand" was selected. This component results from the industrial extraction of inert materials, more specifically limestone, common in Algarve, which is crushed into specified particle sizes. The crushing process allowed for a larger reactive surface to be available which facilitates surface retention and cationic exchange processes. Also, the increment of calcium (Ca) and magnesium (Mg) concentration can enhance cationic exchange and retention processes by the displacement in rock matrix which ultimately can result in fixation of other elements such as heavy metals[1]. The soil mixture was previously tested in soil-column pre-experiments, and a final composition for the reactive layer was selected: 40 wt% of natural soil, 40 wt% of artificial sand and 20 wt% of organic matter. Other soil mixture compositions tested, with larger percentages of OM, resulted in macropores and compaction due to fine particle washing out.

The soil-column experiments were performed in a soil subject to a dry pack procedure. The objective of packing is to produce a homogeneous soil column having a bulk density similar to that observed naturally, while avoiding the formation of preferential flow pathways. This might be the most critical issue associated with soil-column experiments, since these preferential flow paths will result in spatial heterogeneity in flux and solutes transport, and will significantly bias results. This involves loading small discrete amounts or "lifts" of dry or damp soil into the column and then mechanically packing it either by hand or with some type of ram or pestle[3]. The process is repeated until the column is completely filled. The soil-column is then weighted.

Table 1 synthetises the procedures adopted, from different experiment time to the type of injection method. This is the result of a continuous learning process to achieve the more representative methodology of the real scale infrastructures. Initially water injection was continuous (C3 and C4), but throughout the experiments it was decided that the conditions should replicate those in the real scale basins[4]. This was achieved by saturation/non-saturation cycles, where water is inserted in controlled volumes on the top section of the column. This created a 20 cm pond above the soil which slowly infiltrated. Experiment time varied and in some cases (C4 and C5) the experiment was stopped as result of clogging which blocked water passage in the column.

Table 1 - Synthesis of the operating details of the soil-column experiments conducted

Soil-column experiment	A (C3)	B (C4)	C (C5)	D (C8)
Soil thickness (cm)	20	30	30	30
Type of soil	Natural	Natural	Natural	Mixture
Saturation conditions	Always saturated	Unsat./ saturated cycles	Unsat./ saturated cycles	Unsat./saturated cycles
Injection method	Continuous	Continuous/ pulse	Pulse	Pulse
Water matrix	Deionized/Wastewater	Wastewater	Deionized/Wastewater	Wastewater
Experiment time length (days)	5	33	16	46

3.2. Results

Although special attention was given to inflow/outflow contaminant concentration comparison, the soil hydraulic behaviour was also taken into account as it is fundamental knowledge to define the real scale basins functioning schedules. Considering hydraulic behaviour for natural soil, and taking as reference the first day of experiment, C5 showed highest flow rate (1.504 cm^3/min) and permeability (2.536 m/d) while C4 showed the worst results (0.363 cm^3/min and 0.589 m/d). For soil mixture behaviour, C8 had higher flow rate and permeability (3.340 cm^3/min, 3.278 m/d) when compared to the natural soil behaviour.

Concerning inflow water quality, from 32 parameters analysed, C3 had 17 values above the limit of recovery (LOR), C4 and C5 had 17 and C8 had 26. Comparing the outflow in terms of quality, and more precisely average concentration of metals, from 11 parameters considered, C3 had 7 parameters where outflow concentration is higher than inflow, while C4 had 6 and C5 had 9. C8 had only 3 parameters in which outflow average concentration surpasses the inflow, although inflow sample presents a slight enrichment in certain metals when compared to other columns inflow water. Phosphorus shows the highest reduction in all columns. For nitrogen cycle components, ammonia showed high concentration at inflow and a reduction at outflow for all columns, while nitrites present low concentration at inflow and high concentration at outflow. C3, C5 and C8 show higher average concentration of nitrates at outflow when compared to inflow. Concentration at outflow in C8 reaches 140.46 mg/L, a very high value when compared to C3 (0.86 mg/L) and C5 (6.51 mg/L). This may be the result of OM increment.

Concerning major ions, for the 7 parameters considered, 4 were above inflow concentration C4, C5 and C8. C8 experiment shows a worse overall behaviour for these parameters than that with higher average concentrations.

Saturation and non-saturation cycles showed that after a long non-saturation period some contaminants concentration at outflow show an increasing trend. This was detected in C8 and may have resulted in a significant alteration in the column conditions, where pH values show a temporary decrease which ultimately resulted in the temporary release of some previously retained metals.

To also understand how concentrations of possible retained contaminants vary along column, soil samples were collected and analysed after C3 and C5 experiments stopped. C3 shows almost equal concentration of boron, copper and zinc in top and bottom sections, but boron concentrations were lower. Ammonia showed higher concentrations when compared with nitrates and nitrites, being heavily retained in the soil top section, while nitrates where not detected in both sections and nitrites showed very small concentration. Phosphorous and phosphates showed higher concentrations in the soil top section. For C5, boron and copper showed slightly lower concentrations to those detected in C3, and ammonia shows a high concentration on the top section. Nitrates and nitrites were also detected in higher concentration on column top section. Phosphorous and phosphates showed lower concentrations in both sections when compared to C3 and sulphates where not detected in both sections.

4. Conclusions

The removal of contaminants in the wastewater of SBM was analysed aiming to understand the best conditions for improving the water quality for the following main group of contaminants: metals, nitrogen and major ions. Both natural soil and different soil mixtures were studied using cycles of saturation and non-saturation, the latter allowing the oxygenation of the soil column. The main conclusions that can be drawn are: (1) the presence of a soil mixture with OM layer favours the retention/degradation, mainly through sorption and biotransformation processes, primarily for metals (retained both in clay fraction and OM); (2) the sequence of oxic/anoxic conditions is the best approach to ensure maximum attenuation efficiency, since some elements degrade better in oxic conditions (such as the biological oxidation of ammonia into nitrite, nitrate and nitrogen gas), while others are degraded under anaerobic conditions; and (3) the existence of high pH favours the retention of heavy metals attached to soils.

The soil mixture used in laboratory scale experiments will be later tested in infiltration basins that will be built in the outskirts of SBM wastewater treatment plant. Differences in soil behaviour are expected at real scale experiments due to exposure to external factors that are controlled at laboratory scale.

The knowledge achieved, particularly in quality of outflow aspects, may be of relevance in establishing reference values for injection/infiltration water quality, suitable soils, places, and materials to use in SAT-MAR processes, to produce successful results with minimum negative environmental impacts and an acceptable economic outcome.

Acknowlegments

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no 619120 (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought – MARSOL). We also thank Agência Portuguesa do Ambiente (APA-ARH Algarve) and Águas do Algarve (AdA) for all their support during this project.

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