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Managed aquifer recharge: study of undisturbed soil column tests on the infiltration and treatment capacity using effluent of wastewater stabilization pond

Recarga gerenciada de aquíferos: estudo em amostras indeformadas de solo sobre a capacidade de infiltração e de tratamento de efluente de lagoa de estabilização

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ABSTRACT

Managed Aquifer Recharge (MAR) is a useful tool for the treatment and use of sewage effluent because it complements conventional treatment, recovers the aquifer and minimizes risk of saltwater intrusion. This study aims to investigate technical data to determine the treatment of wastewater stabilization pond effluent using undisturbed soil columns collected from a coastal watershed study area within the BRAMAR (BRAzil Managed Aquifer Recharge) project. The treatment efficiency was monitored by measuring physico-chemical parameters (BOD_5, COD, DOC, TSS, NH_3 and NO_3) in two columns filled with undisturbed sandy soil in which sewage effluent was infiltrated under unsaturated condition for 72 days with an average input flow of 10 mm h^{-1}. Results indicated reduction greater than 60% of organic matter, suspended solids and ammoniacal nitrogen. However, high concentrations of nitrate in the outflow were detected originating from nitrification of ammoniacal nitrogen. Moreover, difficulties in relation to soil clogging were observed. Furthermore, this study brought relevant contributions to understanding the influence of the infiltration rate and ability to treat effluent from wastewater stabilization ponds using undisturbed soil columns. Future research should be undertaken to improve the pretreatment methods and the operation of a MAR system in the study area.

Keywords: Managed aquifer recharge; Infiltration rate; Clogging.

RESUMO

A Recarga Gerenciada de Aquífero (RGA) é uma ferramenta útil para tratamento complementar aos convencionas, recarga de aquíferos, e contenção da intrusão salina. Este trabalho objetiva verificar a capacidade de infiltração e o tratamento do efluente de lagoa de estabilização, em colunas com amostras indeformadas de solo, retiradas em uma bacia hidrográfica litorânea de estudo do projeto BRAMAR (*BRAzil Managed Aquifer Recharge*). Para isso, a taxa de infiltração e eficiência de tratamento, através do monitoramento de parâmetros físico-químicos (DBO_5, DQO, COD, SST, NH_3 e NO_3), foram medidas em 2 colunas, preenchidas com solo predominantemente arenoso, ao longo de 72 dias, em condição não saturada do solo, e uma vazão média de entrada de 10 mm h^{-1}. Resultados mostraram remoção superior a 60% da matéria orgânica, sólidos suspensos e nitrogênio amoniacal. Todavia, foram detectadas altas concentrações de nitrato no filtrado que podem ser devido à nitrificação do nitrogênio amoniacal. Também foram observadas dificuldades quanto à colmatação do solo. Por fim, constataram-se importantes informações sobre a capacidade de infiltração e o tratamento de efluente de lagoa de estabilização usando colunas com amostras indeformadas de solo. Futuras pesquisas devem ser realizadas para aprimorar os métodos de pré-tratamento e de adequada operação da RGA na área de estudo.

Palavras-chave: Recarga gerenciada de aquífero; Taxa de infiltração; Colmatação.

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INTRODUCTION

Several studies have been performed in arid and semi-arid regions with the aim of creating alternatives to attenuate the social and environmental problems related to water scarcity. In order to reset water in its natural cycle, the use of treated effluent has been considered as a suitable alternative. Regarding the use of treated wastewater, Sautchúk et al. (2004) have stated that the investment in this option has been growing from 1990s, driven by increasingly stringent environmental requirements and costs associated to the effluent's treatment and appropriate framework of effluent quality to be discharged into water bodies.

A promising effluent use option is through the application to soil infiltration basins, which can both reduce the environmental risks associated with direct release of effluent into water bodies and provide aquifer recharge. This is one of the driving concepts of the Managed Aquifer Recharge - MAR (KANAREK; MICHAIL, 1996; VANDERZALM et al., 2015; SCANLON et al. 2016; WANG et al., 2018). The MAR technique can be a full tool for effluent use by providing complementary effluent treatment, increasing the availability of water in aquifers and providing a front safety factor to soil subsidence and saltwater intrusion (SILVA et al., 2006; SPRENGER et al., 2017; ZHENG et al., 2018). Fernández-Escalante et al. (2014) reported on the costs for several MAR techniques in Spain. They found monetary values less than those needed to build dam for surface reservoirs (about 75% less) and for drilling wells (about 75% less).

Some studies with satisfactory results on MAR have been reported in Brazil (FREITAS et al., 2012; SANTOS et al., 2014; MELO et al., 2014), in which techniques such as bank filtration and rainwater harvesting were used. By the other side, these types of investigations are not widespread, and in some cases, they are inconclusive for the following reasons: i) surface sealing soil layers studied, ii) lack of a proper monitoring of the soil, iii) lack of sites where to apply the effluents, or even by iv) the lack of knowledge of the of most aquifers' behavior. Therefore, the need for more research exists in Brazil to better support the treatment capacity through the soil, as well as its maintenance (OKPALA, 2011; SANTOS; LOPES, 2013; CHAVES et al., 2016; COELHO et al., 2018; MACEDO et al., 2018).

Conducting tests on soil columns is one of the ways of evaluating the soil's capacity to treat an effluent. According to Lewis and Sjöstrom (2010), soil columns are blocks of soil that can be laid in a laboratory or in the field and which enable the infiltration monitoring or control and the permeate collection, without losses caused by permeability of the columns' material. The tests on soil columns, which must contain soil samples from a potential area to be used for MAR, consist in their feeding with a percolating solution (GILBERT et al., 2014; REGNERY et al., 2016; SILVA; ALBUQUERQUE; SCALIZE, 2016). The use of undisturbed soil samples is a viable option that warranties a good representation of the natural environment (GILBERT et al., 2014). Studies carried out in Brazil with undisturbed soil samples related to MAR were not found.

Among the information that can be collected in an undisturbed soil column test are: infiltration rate, water treatment capacity and clogging occurrence. Soil clogging consists in a process that reduces the infiltration rate and the duration of a MAR system (FERNÁNDEZ-ESCALANTE; PRIETO-LEACHE, 2013). This type of phenomenon is common in MAR systems and according to Hutchison, Milczarek and Banerjee (2013), can occur in both superficial layers (accumulation of biofilm and solid particles) and deeper layers (soil sediments with organic and inorganic particles). It is a complex process that may have physical, chemical and biological origin, in which new combinations emerge from the interactions in soil-groundwater-atmosphere (FERNÁNDEZ-ESCALANTE et al., 2016). Several authors have been studying the types of clogging and its attenuation techniques (ANDELMAN et al., 1994; MIOTLIŃSKI et al., 2010; RINCK-PFEIFFER et al., 2013; SMITH, 2014; VYMAZAL, 2018; YADAV; MATHUR; YADAV, 2018).

This article is a product of the international cooperation project of research and technological development between Germany and Brazil (BRAMAR Project-BRAzil Managed Aquifer Recharge) that has started in 2014 and is focusing on the study areas located in the states of Paraíba, Pernambuco and Rio Grande do Norte, Northeast Brazil. The BRAMAR project aimed at proposing strategies for water shortages attenuation and to ensure the sustainable development in the semi-arid region of Northeast Brazil, as well as to increase mutual contribution between German and Brazilian research institutes for the development of integrated water resources management.

Expected BRAMAR project contribution are: planning and preparation of MAR operation schemes that mitigate the water shortage, recover the static level of the water table, improve the quality of effluent and control saltwater intrusion. In this context, this study aims to investigate the soil infiltration capacity and treatment process that the effluent of a facultative stabilization pond (local wastewater treatment plant) undergoes in undisturbed soil columns. These columns were taken from a coastal river basin in the BRAMAR study area, in order to verify the technical feasibility of using a MAR system in the coastal region of Northeast Brazil.

STUDY AREA

The BRAMAR project study area of João Pessoa, Paraíba (JPA), covers two main river basins: low Paraíba and Gramame. This area covers the municipalities of Cabedelo, João Pessoa, Bayeux, Santa Rita, Cruz do Espírito Santo, São Miguel de Taipu, Conde and Pedras de Fogo. For the limits of this study, only the coastal basin of the Gramame river was considered, from where the undisturbed soil samples (A and C) were collected (Figure 1).

Gramame river basin (GRB) is located between the south latitude coordinates of 7° 10 ' and 7° 40 ' and west longitude of 80° 34 ' and 35° 20 '. The drainage area of the river basin is 589.1 km^2. The main watercourse is the Gramame river 54.3 km long. The Köppen climate classification indicates a tropical rainy climate in the region, without cold periods and with predominant rain during autumn-winter. The average annual temperature is greater than 26° C, with annual rainfall ranging between 1400 and 1800 mm (SEMARH, 2000).

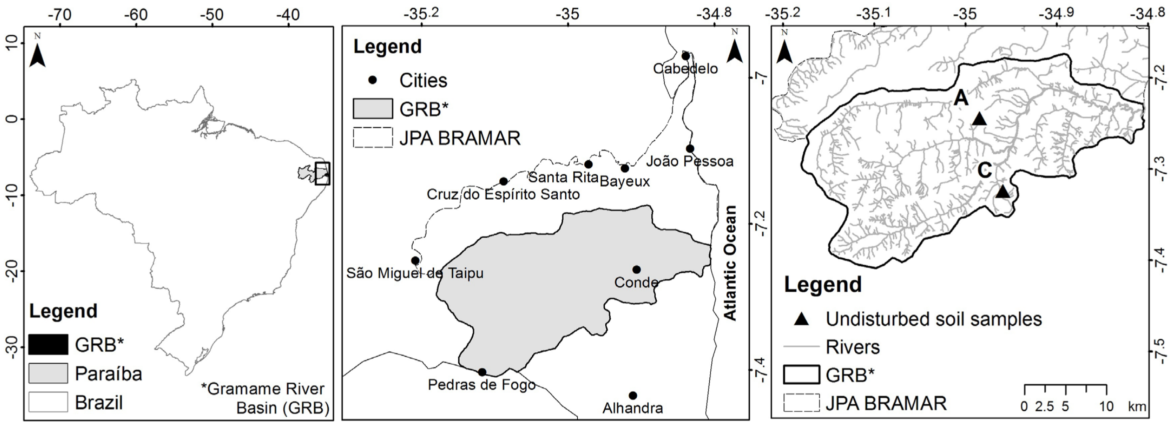

Figure 1. Gramame river basin (GRB) in the JPA BRAMR Project study area.

MATERIALS AND METHODS

Sampling and collection of undisturbed soil samples

The experiment was carried out with two undisturbed soil samples taken from two separate locations at GRB, one being in the area adjacent to cultivation of pineapple (column A) (Figure 2) and the other adjacent to corn cultivation (column C) (Figure 3).

The undisturbed samples were collected with stainless steel columns (65 cm high and 10 cm in diameter) inserted in the ground after superficial debris removal, without rotation, with the aid of a hammer. After sticking the column until approximately 5 cm was left above the ground level, the surrounding soil was removed, and the column was manually collected.

To analyze the particle size distribution and the porosity of the soil used in the experiment, samples were collected adjacent to the place from where the undisturbed soil column were taken, at the depths 0.05 m and 0.80 m, then were mixed (Table 1).

Figure 2. Undisturbed soil column sample collection adjacent to a pineapple crop area.

Figure 3. Undisturbed soil column sample collection adjacent to a corn cultivation area.

Soil column test at laboratory

For the feeding of the columns, the effluent from a facultative stabilization pond was placed in 28-liters plastic boxes. From the boxes, the effluent infiltrated by gravity to the columns, at room temperature, which, in general, was above 20 °C throughout the experiment (SILVA, 2016). The boxes with the effluent were placed about 1 m above the top of the columns, with an outlet of 17 mm in diameter, connected to a silicone hose that allowed flow rate control using chokers. From the hose outlet, the effluent reached the top of the columns by dripping, which could be measured using a volumetric bottle and a timer.

Initially, the columns were continuously fed at the rate of 144 mL h^{-1} (mean value) over 43 days, when the first clogging event occurred. Subsequently, the columns were operated under cycles of dry conditions (no influent) and wet (normal flow rate) as follows: 8 days in dry period, 10 days in wet period, 5 days in dry period and 6 days in wet period, making up 72 days of experiment (Figure 4). The boxes that received the facultative pond effluent were refilled as necessary (10 times during the experiment period).

Table 1. Particle size distribution and mean porosity of the soil.

Particle size distribution and porosity	Column A	Column C
Gravel (d*>2mm)	1.00%	3.00%
Coarse sand (0.420mm<d≤2mm)	43.00%	45.00%
Fine sand (0.074mm<d≤0.42mm)	50.00%	43.00%
Silt + clay (d≤0.074mm)	6.00%	8.00%
Mean porosity	46.43%	51.56%

* diameter.

Before the effluent reached the soil column, it passed through a pretreatment installation with the use of geotextile Bidim® and gravel (1 cm diameter) arranged on the boxes' outlet. This procedure aimed to retain coarse solids. In addition, aluminium foil was fixed on the outside surface of the boxes to avoid light penetration and excessive microalgae development. The filtrate from the soil columns was diverted to a 1 L bottle by a silicone hose (6.5 mm) fitted to an outlet in the lower part of the cylinder. With the volume-filtered values in relation to time, the rate of infiltration was estimated. The general scheme of the test columns can be seen in Figure 5.

Physico-chemical analysis in the feeding wastewater and filtrate liquid

Physico-chemical analyses were performed in both feeding wastewater (effluent from a facultative waste stabilization pond) and filtrate liquid (soil columns effluent). Feeding samples were identified as number 1 (A1 and C1), while soil columns effluent as the number 2 (A2 and C2). Altogether, four analyses were carried out between 26th July and 13rd September 2016, on a biweekly frequency. An exception for this frequency was the interval between 2nd and 3rd analysis that was 21 days, due to the need to interrupt the inflow because of clogging.

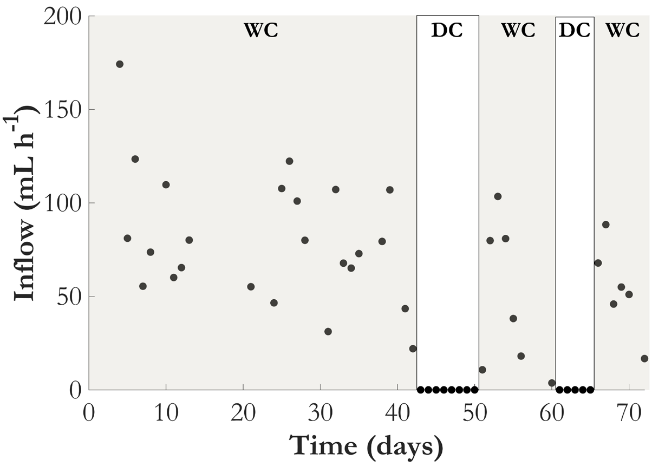

Figure 4. Feeding flow rate during wet (WC) and dry (DC) periods along the experiment in column A.

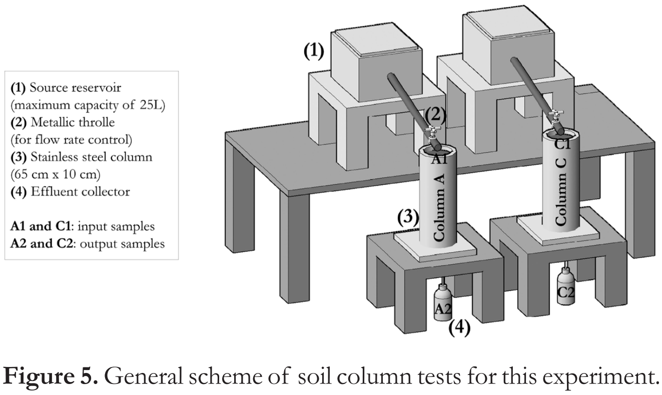

Figure 5. General scheme of soil column tests for this experiment.

Physico-chemical parameters were analyzed using Alfakit®, which follows the methodologies adapted from Standard Methods for the Examination of Water and Wastewater (APHA, 2005). The studied parameters were biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), dissolved organic carbon (DOC), total suspended solids (TSS), ammoniacal nitrogen (NH_3) and nitrate (NO_3). BOD_5 was analyzed by titration while the DOC followed the direct method patented by Hach Company® for concentrations between 0 and 150 mg L^{-1} (HACH, 2014).

RESULTS AND DISCUSSION

Infiltration rate

Columns A and C presented similar infiltration rates, with a mean value of 10 mm h^{-1}, for the mean influent rate of 144 mL h^{-1} (Figure 6).

Infiltration rate at the 42nd day in the experiment reduced 49.6% and 28.7% for column A and C, respectively, in relation to the previous determination (33rd day in the experiment). In the 56th day of experiment, the rate also declined in both columns. This was the consequence of the clogging phenomenon that began to dominate in the soil column, making the interruption of feeding necessary. Therefore, it was decided to start, from the 42nd day of experiment, an alternation between wet and dry cycles. The duration of the dry periods adopted herein were enough to recover soil infiltration capacity. However, these periods were not uniform and must be better studied in future research.

In addition to the alternation of operation cycles, in field situations the clogged layer of soil could be removed, resulting in a recovery of the soil infiltration capacity. However, it was not possible to perform this procedure on the experiment herein described, given the risk of losses of the undisturbed samples, making it necessary to evaluate this additional measure in future research.

Treatment efficiency of the soil columns

Table 2 presents the arithmetic means and standard deviations for BOD_5, COD, DOC, TSS, NH_3 and NO_3 for the feeding wastewater and for the effluent of each column. The temporal variations of the same parameters are shown in Figures 7a to 7f.

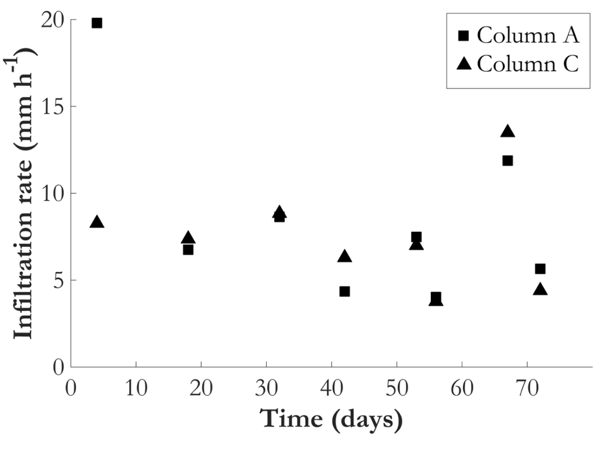

Figure 6. Infiltration rates along the experiment.

Table 2. Statistics for the physico-chemical parameters.

P*	Column A			Column C		
	Influent (A1)	Effluent (A2)	R**	Influent (C1)	Effluent (C2)	R**
BOD_5	15.25 ± 11.17	2.58 ± 2.75	83.1%	15.40 ± 8.74	4.45 ± 5.14	71.1%
COD	69.07 ± 20.88	51.57 ± 39.19	25.3%	78.13 ± 21.78	49.18 ± 20.78	37.0%
DOC	27.00 ± 19.47	11.33 ± 6.66	58.0%	14.33 ± 3.21	20.00 ± 12.17	-39.5%
TSS	26.50 ± 16.42	8.50 ± 4.20	67.9%	25.75 ± 21.67	9.75 ± 10.50	62.1%
NH_3	49.25 ± 7.00	15.35 ± 26.53	68.8%	44.28 ± 9.17	19.27 ± 19.69	56.5%
NO_3	1.00 ± 0.89	5.67 ± 8.98	-466.2%	7.37 ± 13.26	11.13 ± 9.69	-51.0%

*P: parameter; **R = (Influent-Effluent)/Influent.

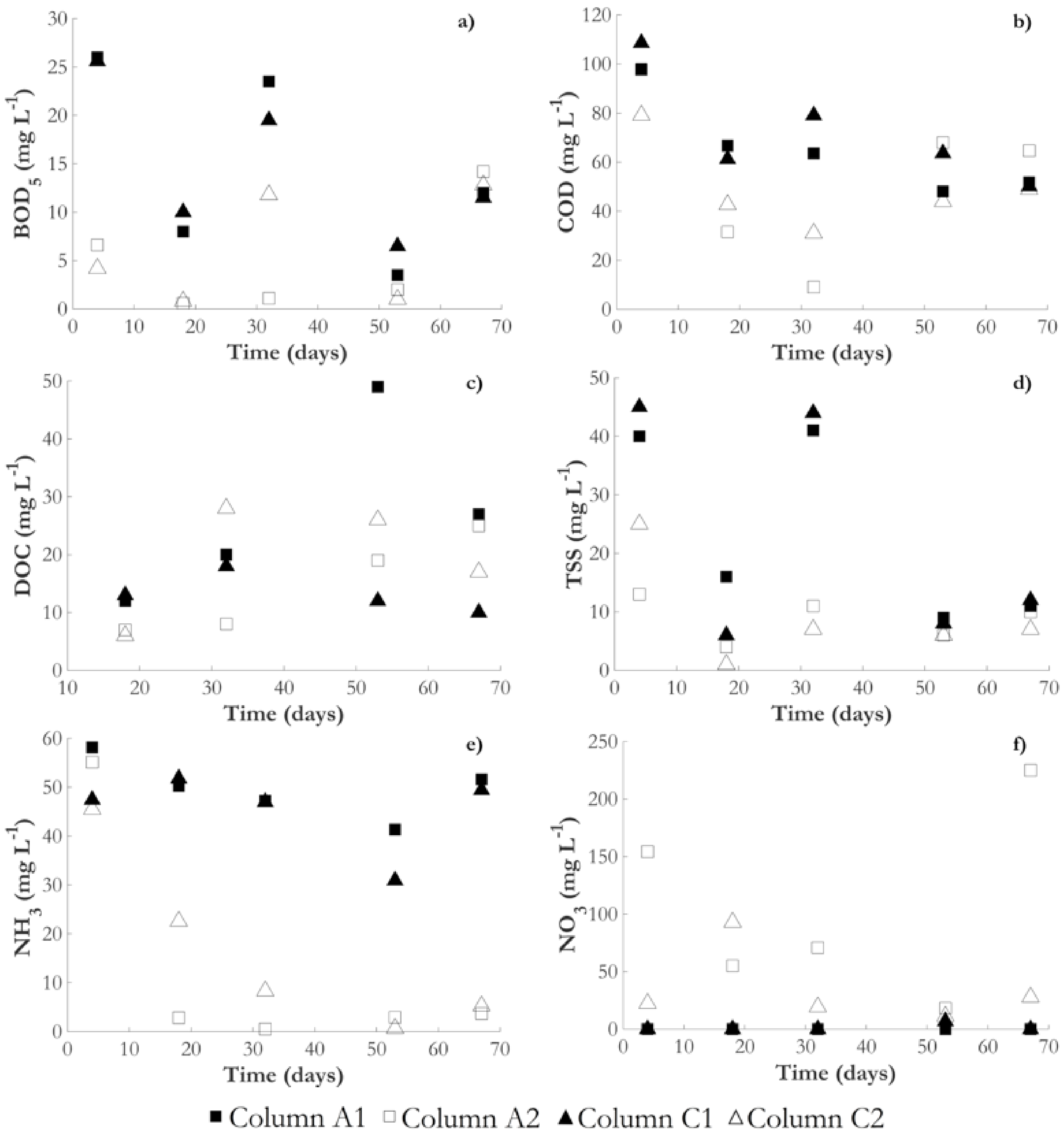

Figure 7. Temporal variations of physico-chemical parameters in columns A and C.

The columns produced low values of BOD_5, COD, TSS and NH_3 in the effluents, resulting in high removal efficiencies for these parameters and demonstrating the suitability of the soil column as a wastewater treatment option. The values found are like those reported for the effluent of sand filter applied to wastewater treatment (TONON et al., 2015). With respect to DOC concentration, there was removal in column A and an increase in column C. The organic matter (BOD_5 and COD) suffered biological oxidation, resulting in CO_2, which can be volatilized to the atmosphere or be dissolved in liquid mass. Volatilization of CO_2 explains the decrease in DOC in column A, while its retention can explain the observed increase in column C.

For the NO_3, there was an increase of its concentration in both columns, what can be explained by the biological process of nitrification, in which NH_3 is converted to NO_3 by bacteria. The main NH_3 source in the facultative pond effluent is the nitrogen associated to the biomass (bacteria, phytoplankton and zooplankton) and residual material (ESTEVES, 1998). This nitrification process was also reported by Diab and Shilo (1998) during dry cycles in infiltration basins.

This kind of analysis of the reduction in the concentration of physico-chemical parameters in the effluent of wastewater stabilization ponds through soil columns emphasizes the importance of assessing the capability of treatment in the soil with other types of effluent, such as the urban drainage and irrigation effluent, for various scenarios in Brazil, as a tool for water resources management. If a MAR system using effluent from a wastewater treatment plant is not possible, other sources, such as rainwater, which has better quality, could be investigated. In the case of using rainwater for this purpose, besides increasing levels of groundwater, there will be a reduction on flooding problems (CADAMURO; CAMPOS, 2005; MONTENEGRO et al., 2005; ALMEIDA, 2011; NUNES, 2017). This type of solution can indeed contribute to the improvement of groundwater quality.

Occurrence of clogging in the soil columns

After 42 days of experiment, the columns showed a decrease in the infiltration rate that is associated to the clogging in the soil pores. The first hypothesis to cause the clogging is the high concentrations of microalgae, which were found in the feeding effluent (A1 and C1). Figure 8 shows greenish color in membranes that filtered the feeding effluent, due to the presence of microalgae.

High values of TSS (part of which is composed by microalgae) in the A1 and C1 samples were found in this analysis in the 32nd day of experiment (41 mg L^{-1} and 44 mg L^{-1}, respectively). This confirms what had been verified by Silva (2016), that the geotextile bags filled with gravel are not enough for the removal of these particles. According to Bekele et al. (2015), the maximum concentration suggested for TSS to avoid clogging is 5 mg L^{-1}, well below the current quality presented by the facultative stabilization pond effluent used in this study. It calls attention to the physico-chemical characteristics of the effluent to be used for MAR systems, because depending on its quality, complementary treatment must be installed before its application on the soil (RINGLEB; SALLWEY; STEFAN, 2016).

Figure 8. Microalgae retained in membranes that filtered samples from A1 e C1 (first and third filters from the left to the right).

CONCLUSIONS

Based on this study, it was found, for an average infiltration rate of 10 mm h^{-1}, removal efficiencies higher than 60% for organic matter, suspended solids and ammonia, in the application of facultative waste stabilization pond effluent in undisturbed soil columns. On the other hand, nitrate (NO_3) concentrations increased, possibly due to the nitrification process.

Problems concerning clogging have been detected in this study due to high concentrations of total suspended solids. As a solution to this phenomenon, alternating between dry and wet cycles restored the soil infiltration capability. A more detailed study should be carried out to determine the proper required range of wet and dry periods. The removal of the upper clogged layer should also be studied for the recovery of the soil infiltration capability in MAR systems.

Finally, it was concluded that the soil of the study area has characteristics of particle size (i.e. predominantly sandy), infiltration capacity and treatment capacity favorable to a Managed Aquifer Recharge facility. However, this approach should be further investigated aiming improvements on the methods of complementary treatment required for facultative waste stabilization pond effluent and on proper operation of the recharge (alternating between dry and wet cycles), that could contribute to the MAR viability.

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Cristiano das Neves Almeida: responsible and supporting partner of the BRAMAR project (BRAzil Managed Aquifer Recharge), supervisor of the study, structuring and revision of the paper.

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