

SLOW SAND FILTRATION OF EFFLUENT FROM AN ANAEROBIC DENITRIFYING REACTOR FOR TERTIARY TREATMENT: A COMPARABLE STUDY, USING THREE MOROCCAN SANDS

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Abstract: The aim of this study was to evaluate the feasibility of slow sand filtration as a technique for tertiary treatment of effluent from an anaerobic denitrifying reactor (ADR) treating domestic wastewater. The performance of different Moroccan sand media in tertiary filtration of wastewater has been assessed by conducting pilot-scale filtration assays. The treatment efficiency of a slow sand filtration method depends on several parameters, namely the sand media used, the wastewater characteristics and the organic loading rate. The experimental pilot system consisted of three columns, each one containing a different type of Moroccan sand, namely desert sand (DS), river sand (RS) and beach sand (BS). We found that the optimum hydraulic loading rate at which the effluent is in compliance to water reuse standards equals to 0.16 m/h for all sand filters. Additionally, the RS filter showed the highest pollutant removal efficiency at 0.16 m/h, namely 88% of COD, 86% of TSS, 72% of TKN, 76% of NH₄-N, 65% of TP, 2.4 log-units of FC and 2.7 log-units of FS. The effectiveness of the RS filter is found to be attributed to the highest Al₂O₃, Fe₂O₃ and OM content as well as to the smaller particle size of the sand in comparison to DS and BS filters.

Keywords: Wastewater, sand characteristic, slow sand filtration, tertiary treatment, water reuse.

1. INTRODUCTION

In Morocco, as well as in other developing countries, the growing urbanization has resulted in a significant increase of generated amounts of urban wastewater (Langhari Moubarrad & Assobhei, 2007). The use of treated wastewater for plant and crop irrigation is gradually becoming a common practice worldwide (Angelakis et al., 1999; Lubello et al., 2004), as well as, they are applied on industry, and for ground water recharges (Salgot et al., 2006; Ernst et al., 2007; AL-Ananzehl et al., 2012). For these reasons it is necessary stop the consumption of freshwater by pollution and to return wastewater to the water cycle as a beneficial source of water (Gurzau, et al., 2010; AL-Ananzehl et al., 2012). One of the most processes used around the world for on-site and small community's wastewater treatment is the Sand filter systems (Rolland et al., 2009). It is a simple technology that has been successfully used for

over 200 years in drinking water purification. It has been used for the removal of suspended particles and pathogens by combining biological, physical and chemical processes (Langenbach et al., 2009). In view of the stringent quality standards imposed on wastewater reuse, more focus has, recently, been given to the use of sand filters systems for tertiary wastewater treatment (Nakhla & Farooq, 2003; Langenbach et al., 2009). The main advantages of such method is the simple and economical constructions involved as well as the low cost operation and maintenance processes of the systems using local skills and clean materials rather than chemicals and energy. Furthermore, less land is required compared to other natural tertiary wastewater treatment technologies, i.e. fast sand filtration, due to higher hydraulic loading rates (0.1 to 0.5 m/h) and shorter residence time (Muhammad & Hooke, 2003). In sand filtration systems, the depth of the sand layer may impact the treatment because sand

particles provide the surface for biofilm formation and biological activity (Gaur et al., 2010). Sand filtration systems for wastewater treatment can, therefore, be considered as fixed media bioreactors which rely on active biofilms on sand particles and are relatively resistant to temporal changes of pH, surfactants and metal concentrations in wastewater. Additionally, they provide the necessary conditions for the biodegradation and mineralization of organic matter and the assimilation of nutrients by diverse microbial populations (Gaur et al., 2010). Effectiveness of slow sand filters for tertiary treatment of wastewater has already been investigated at both laboratory and pilot scales. These studies have shown that slow sand filters are capable of removing up to 68% of total suspended total (TSS), up to 88% of turbidity and over 99% of total coliforms (Pell & Nyberg, 1989). Farooq & Al-Yousef (1993) conducted a pilot study using slow sand filtration with effective sand particle sizes of 0.31 and 0.56 mm for the treatment of secondary chlorinated effluents. They reported a chemical oxygen demand (COD) removal efficiency of 50-67% as well as a total bacterial count reduction of 90%.

Despite the dependency of sand filter systems on multiple variables, they have been conventionally designed according, only, to hydraulic and organic loading rates. At the present time, the sand is implemented without particular care, only the variation of hydraulic loading rate, sand grain size distribution (Langenbach et al., 2009) and effective size (or D_{10}) and uniformity has been studied. However, the composition of sand is highly variable. This article shows the first results and aims to point out the importance of the chemical composition of sand on processes implied in tertiary treatment of wastewater by sand filtration. The objectives of the present work were also to quantify the effect of the study of the sand grain size and the hydraulic loading.

2. MATERIALS AND METHODS

2.1. Experimental columns

The experimental pilot system consists of three opaque PVC columns, each of which having a surface area of 0.3m^2 , 9cm internal diameter and a

150 cm height. Each column was filled up to 75cm with the respective natural sand as shown in table 1 (column 1: DS; column 2: RS; column 3: BS), whereas 10cm-high support gravel layers were placed on the top and the bottom of the sand layers in order to enhance the uniformity of the flow. A schematic representation of the pilot-scale sand filtration system is shown in figure 1.

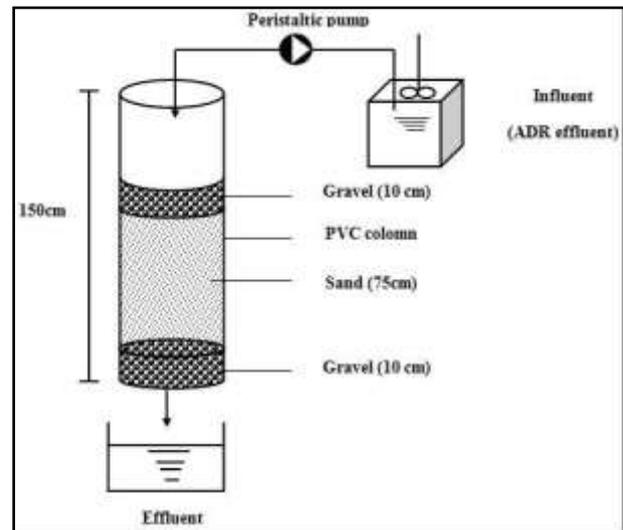


Figure1. Schematic diagram of laboratory scale slow sand filter column

2.2. Filter bed

Before filling the columns, the tested sand was washed with distilled water before use in order to remove clay and other mineral contaminants from the sand particles. The granulometric analysis was carried out by dry sifting on column sieve (NF P 18-560 standard method). The effective size (D_{10}) is equal to 0.25 mm 0.15 mm and 0.23 mm for DS, RS, and BS respectively, while the uniformity coefficient ($UC=D_{60}/D_{10}$) is 1.36, 1.33 and 1.52 respectively (Table 1). The pea gravel used had an effective size of 3.8 mm and a uniformity coefficient of 1.68. According to Healy et al., (2007), a D_{10} equal to 0.33mm and a UC of less than 3 are recommended for single-pass operations with a filter depth of 0.61–0.91m. In our case the uniformity coefficient data seem to satisfy the aforementioned requirements.

Table 1. Sands origin and characteristics

	Origin in Morocco	D_{10}	UC
Desert sand (DS)	Merzouga (Moroccan Sahara)	0.25	1.36
River sand (RS)	North of El Jadida from OumRabiiRiver (16.2 Km far from the city)	0.15	1.33
Beach sand (BS)	South of El Jadida from SidiBouزيد Beach (3 Km far from the city)	0.23	1.52

2.3. Effluent used

The filters were fed using the effluent resulting from an anaerobic denitrifying reactor (ADR) as secondary treatment that treated domestic wastewater. The ADR is currently operating at the wastewater treatment plant in El Jadida's city in Morocco (figure 2) which serves approximately a population equivalent of 1000 habitant-equivalent.



Figure 2. Location of the study area

2.4. Filtration procedure

The ADR effluent was collected in a 100 L plastic tank in which all settleable solids were maintained in suspension through slow and continuous stirring. The influent was pumped from the 100L tank to the top of the columns and passed through the filter bed at different flow rates in order to determine optimal flow rate in terms of effluent compliance to water reuse standards. Once the optimal flow rate was determined, the filter columns were operated at a constant flow rate in order to assess slow sand filtration efficiency under different sand media. As well as, the evaluation of the clogging of the filters until a low flow rate at the outlet of the sand filters. Samples were collected from the outlet end of the filter column every 12hrs, the filter column every 12hrs, i.e. two samples per day; each sample was conducted in triplicate.

2.5. Analytical methods

The mineralogical characteristics of the three

sands were determined by X-ray diffraction (XRD) using X'pert High Score PANalytical diffractometer (at Technical Support Units for Scientific Research, Morocco) with monochromated CuK α radiation operating at 45kV/40mA. All XRD data were collected under the same experimental conditions, in the angular range $3^{\circ} \leq 2\theta \leq 90^{\circ}$ with a scan rate of $1^{\circ}/\text{min}$ at room temperature. The compositions of the chemical components of the three sand filters were obtained from the chemical analysis determined by X-ray fluorescence (XRF).

The determination of loss on ignition (L.O.I.) was obtained by heating the raw sand materials at 1000°C . The samples collected were assayed for microbiological fecal coliforms (FC), fecal streptococci (FS) and physicochemical parameters (COD, TSS, total kjeldahl nitrogen (TKN), ammonium ($\text{NH}_4\text{-N}$) and total phosphorus (TP) as described in the standard methods for the examination of water and wastewater (APHA, 1995).

3. RESULTS AND DISCUSSIONS

3.1. Sand characterization

The granulometric analysis carried out by dry sifting, shows that the RS and DS consists of average grain sized sand, while the BS consists of medium to coarse grain sized sand according to Soltner (1990) textural classification. The ideal media for sand filtration consists of medium to coarse sand with an effective size between 0.3 and 1.5 mm whereas the uniformity coefficient should be less than 4.0 in order to have an adequate hydraulic conductivity and to minimize clogging risk (Tao & Mancl, 2008).

3.2. Chemical and mineralogical analysis of sand

The results of the XRF analysis (Table 2) show that SiO_2 is the major compound in DS and RS. DS is more siliceous consisting of 90.2% SiO_2 due to the high content of quartz and, possibly, free silica that originates from siliceous microfossils such as radiolarians and diatoms (Moore & Reynolds, 1989).

Table 2. X-ray fluorescence analysis of different sands.

Sand media	% of oxide										
	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	SO_3	P_2O_5	L.O.I.*	Total
DS	90.2	1.47	3.92	0.869	0.862	0.602	0.397	0.332	0.0597	1.05	99.76
RS	58.9	11.9	8.25	3.54	2.99	0.954	0.913	0.436	0.243	11.0	99.12
BS	43.8	46.3	0.73	4.15	0.271	0.0677	0.955	1.33	0.135	1.74	99.47

L.O.I.: loss on ignition

*

The chemical composition of BS, shows that it is made up of SiO₂ (43.8%) and CaO (46.3%). The percentage composition of MgO and CaO were relatively higher in RS and especially in BS compared to DS which can be explained by the high content of dolomite (33.28% for BS and 25.27% for RS) and calcite (9.8% for DS and 15.83% for RS). The interpretation of each diffractogram obtained from the XRD analysis, given in figure 3, revealed the mineralogical assemblage of the different sands used in the study. The XRD analysis shows that the mineralogical composition of DS corresponds only to quartz and dolomite minerals, which is characterized by the reflections given in figure 3. Accordingly, RS corresponds to quartz, calcite and dolomite minerals in descending order of predominance by weight (quartz 58.9 wt %, calcite 15.83 wt % and dolomite 25.27 wt %). Finally the diffractogram of BS shows that the mineralogical composition corresponds to quartz, calcite and aragonite.

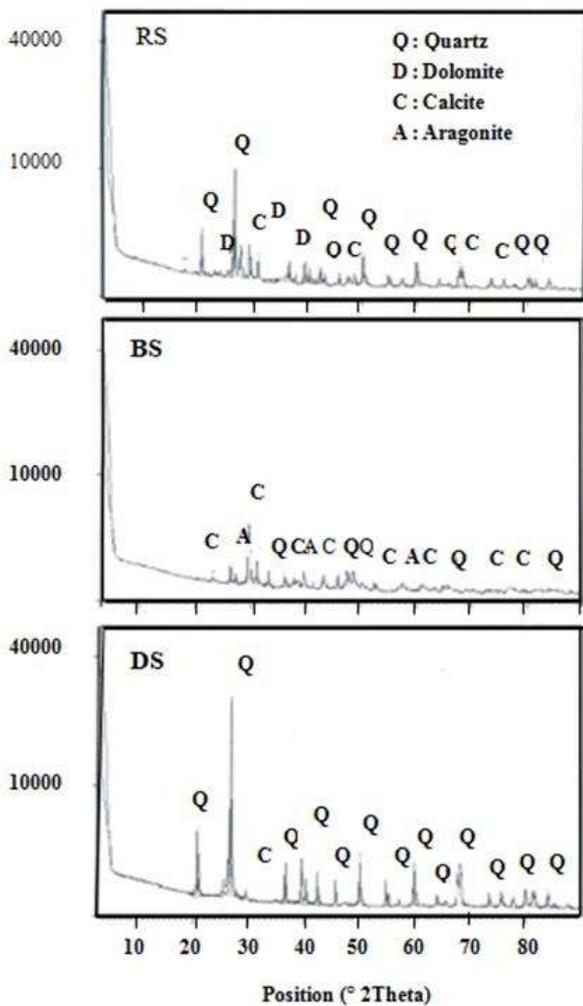


Figure 3. X-ray Diffractograms of DS, RS and BS.

3.3. Characterization of the effluent

The range and average values of the physicochemical and microbiological characteristics of the ADR effluent that is used as influent in the pilot scale system for slow sand filtration are reported in table 3.

3.4. Functioning and performance efficiency studies

This study was conducted in two phases. The first phase employs the optimization of the influent (i.e. ADR effluent) flow rate while the second phase involves the assessment of the sands efficiency by monitoring the physicochemical and biological characteristics of the treated effluent at optimized X-ray fluorescence analysis of different flow rate, as well as, the evaluation of the clogging of the filters until a low flow rate at the outlet of the sand filters. The criterion applied for terminating the filter run was the clogging of the filter.

Table 3. Characteristics of ADR effluent

Parameters	Values
pH	7.12 ± 0.21
TSS (mg/L)	80 ± 15
COD (mg/L)	250 ± 25
BOD (mg/L)	90 ± 12
TKN (mg/L)	60 ± 14
NH ₄ -N (mg/L)	54 ± 7
TP (mg/L)	5.2 ± 0.9
Fecal coliforms (CFU*/100 mL)	4.8 × 10 ⁴ ± 1.3 × 10 ³
Fecal streptococci (CFU*/100mL)	2.5 × 10 ⁴ ± 2.1 × 10 ³

*CFU: Colony-Forming Units.

3.4.1. Determination of the optimal hydraulic load

Filtration flow rate control is the key element in the operation of filters. Generally, a filtration rate of 0.1 to 0.32 m/h is recommended for surface water treatment (Central Pollution Control Board, 2005). However, filtration rates up to 0.6 m/h have been reported (Visscher, 1990). The optimization of the influent flow rate was performed by operating the filters at hydraulic loading rates between 0.10 and 0.28 m/h with an increase at each step of 0.02 m/h (thus 10 different flow rates were examined) and by comparing the physicochemical characteristics of the effluent (COD, TSS, TKN, NH₄-N, TP) against existing water reuse standards.

Figure 4(a) shows the effect of hydraulic loading rate on COD removal of the influent (ADR effluent) using different sand filters. It can be

concluded that the hydraulic loading rate influences COD removal with higher flow rates resulting in lower COD removal efficiency for all tested sand media. At a hydraulic rate of 0.1 m/h the slow sand filtration process performs more effectively in terms of COD percentage removal recorded at 85%, 90% and 81% for DS, RS and BS filters respectively.

At high hydraulic loading rates, i.e. 0.28 m/h, the COD removal is recorded at 51%, 60% and 49% for DS, RS and BS filters respectively whereas the corresponding COD effluents concentrations were equal to 122.5 ± 3.2 , 100.0 ± 5.1 and 127.5 ± 6.7 mg/L. Based on US EPA guidelines for water reuse, the hydraulic loading rate has to be set at values equal or lower than 0.16 m/h for all three sand filters tested, in order to comply with the COD effluent concentration limits (U.S. EPA 2004).

Figure 4(b) shows the TSS removal as a function of the hydraulic loading rate for the selected sand media. It is evident that TSS removal decreases with the increasing flow rate of the influent. The efficiency of slow sand filtration in terms of TSS removal percentage is recorded at 86, 92 and 83% for DS, RS and BS filters respectively at a hydraulic loading rate of 0.1 m/h, whereas TSS removal at 0.28 m/h is equal to 54, 57 and 46% for DS, RS and BS filters respectively. Therefore, it can be concluded that the flow rate of the influent has a significant influence on TSS removal. Additionally, at low hydraulic loading, i.e. 0.1 m/L, the TSS concentrations of the effluents are 12.1 ± 0.42 , 7.2 ± 0.65 and 15.4 ± 0.54 mg/L for DS, RS and BS filters respectively while at higher flow rates, i.e. 0.28 m/L, the TSS concentrations (42 ± 2.1 , 39 ± 1.5 , 46 ± 2.7 mg/L, for DS, RS and BS filters respectively) exceed the recommended U.S. EPA standards for authorized water reuse which are set between 20 and 30 mg/L (U.S. EPA, 1992). The maximum hydraulic loading for which the effluents of the tested sand filters are in compliance to the U.S. EPA and Moroccan water reuse standards for TSS concentration, is 0.16 m/h (U.S. EPA, 2004; Secretary of State at the Ministry of Energy, Mines, Water and Environment, 2007). At this flow rate, the effluent TSS concentrations are equal to 19 ± 2.4 , 13 ± 3.9 and 23 ± 5.7 mg/L for DS, RS and BS respectively this corresponds to a TSS reduction of 79%, 86% and 75%. It must be stated that the observed TSS removal is higher than the one reported by Nakhla & Farooq, which is equal to 63.9% at a hydraulic loading of 0.38 m/h and an effective sand particle size of 0.3 mm.

Figure 4(c) illustrates the TKN removal as a function of the hydraulic loading rate (0.10 to 0.28 m/h) for the three tested sand filters. It is clearly observed that in all sand filters the flow rate increase reduces the TKN removal level. More specifically the

TKN removal efficiencies at 0.1 m/h is recorded at 74, 85, and 65%, for DS, RS, and BS filters respectively, while the corresponding TKN concentrations of the effluents are 15.6 ± 2.4 , 10.0 ± 3.5 and 21.0 ± 6.2 mg/L. Accordingly, the TKN removal efficiencies at a flow rate of 0.28 m/h, equal only 39.0, 53.3 and 36.0% for DS, RS, and BS filters respectively whereas the corresponding effluents TKN concentrations are 36.6, 28.0 and 38.4 mg/L. Therefore, the hydraulic loading rate plays an important role in nitrogen removal since the longer the contact time the higher the interaction between nitrogen and the sand filter. Additionally, the TKN concentrations of the effluents are in accordance to the U.S. EPA water reuse standards (2004), when the applied hydraulic loading rate is less than 0.24 m/h for the DS filter i.e. 26.4 ± 2.1 mg/L, and less than 0.16 m/h for the BS filter i.e. 25.8 ± 3.2 mg/L. For the RS filter the TKN concentrations of the effluents comply with the existing water reuse standards for all the tested influent flow rates, i.e. 0.10 to 0.28 m/h. The performance of each sand filter in regard to $\text{NH}_4\text{-N}$ removal level at different flow rates is given in Figure 4(d). The results indicate that $\text{NH}_4\text{-N}$ removal in the three pilot scale columns (DS, RS and BS filters), decreases with increasing flow rate. More specifically at hydraulic loading rate of 0.1 m/h the $\text{NH}_4\text{-N}$ concentration of the effluents is recorded at 14.5 ± 1.9 , 9.7 ± 2.1 and 21.0 ± 1.8 mg/L for the DS, RS and BS filters respectively, whereas the corresponding $\text{NH}_4\text{-N}$ removal is 73, 82 and 60%. Accordingly, the $\text{NH}_4\text{-N}$ concentrations of the effluents is 28, 23 and 36 mg/L for the DS, RS and BS filters respectively at a flow rate of 0.28 m/h accounting for 48, 57 and 33% $\text{NH}_4\text{-N}$ removal levels. The optimum hydraulic loading rate for which $\text{NH}_4\text{-N}$ concentration of the effluents are in compliance with the U.S. EPA standards of water reuse (2004) is set at 0.18 m/L for the BS filter whereas for the RS and DS filters the flow rate is not a limiting factor.

Figure 4(e) shows the total phosphorus (TP) percentage removal for the selected sand filters as a function of the hydraulic loading rate.

It is noted that at a hydraulic loading rate of 0.1 m/h the sand filters remove, effectively, 65, 67 and 63% of the influent's TP for DS, RS and BS filters respectively, whereas the resulting TP effluents concentrations equal to 1.8 ± 0.3 , 1.7 ± 0.2 and 1.9 ± 0.12 mg/L. Accordingly, the TP concentration of the effluents at a flow rate of 0.28 m/h is reported at 2.7 ± 0.1 , 2.2 ± 0.3 and 3.2 ± 0.2 mg/L for the DS, RS and BS filters respectively COD, (b) TSS, (c) TKN, (d) $\text{NH}_4\text{-N}$ and (e) TP over time which correspond to 48, 56 and 40% TP removal levels. The TP concentration of the treated effluents

using the different sand media is in compliance with the U.S. EPA standards of water reuse (2004) for all hydraulic loading rates tested.

3.4.2. Efficiency of slow sand filtration

The optimum hydraulic loading rate for the effective treatment of the ADR effluent is set at 0.16 m/h since at that flow rate the resulting effluents comply simultaneously with all existing water reuse standards for the tested parameters, namely COD, TSS, TKN, NH₄-N and TP. The efficiency assessment of the selected sand filters is performed by monitoring the TSS, TKN, NH₄-N, TP, FC and FS of the treated effluents on a 7 day operation of

the systems at the optimum hydraulic loading rate of 0.16 m/h. The results obtained (Fig. 5a) show that the maximum percentage COD reductions attained in each tested column is 83%, 88% and 78% for DS, RS and BS respectively. The aforementioned COD removal levels were maintained for 144, 156 and 132hrs when the DS, RS and BS filters were used respectively. At the end of the filtration processes (i.e. 168hrs), the COD percentage removal levels decreased to 81, 87 and 75% for the DS, RS and BS filters respectively, which correspond to COD concentrations of 47.5 ± 1.3 , 32.5 ± 2.5 and 62.5 ± 4.7 mg/L after 7 days of slow sand filtration.

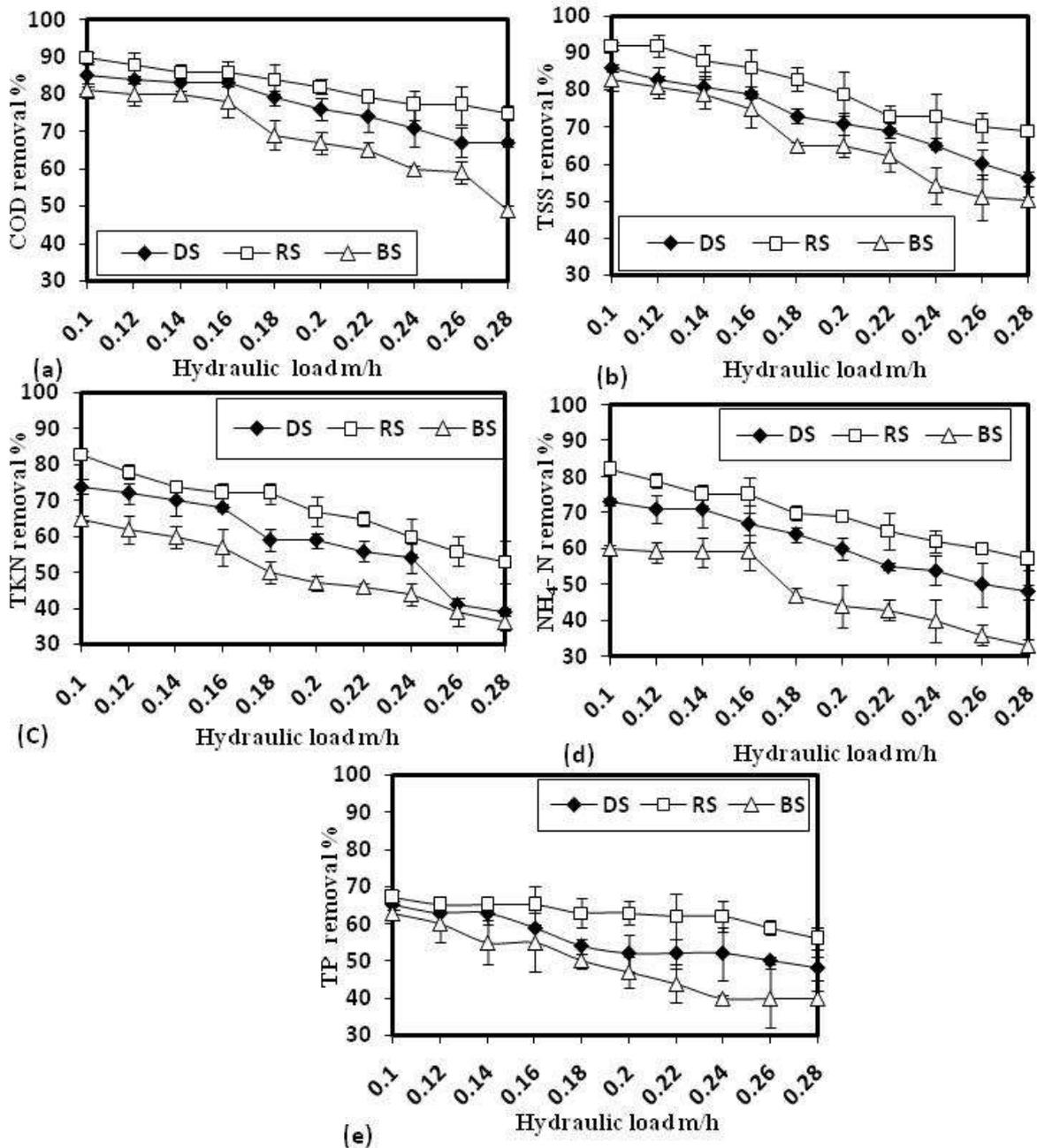


Figure 4. Effect of hydraulic loading rate on the removal of (a) COD, (b) TSS, (c) TKN, (d) NH₄-N and (e) TP in the three slow sand filters

The COD reduction can be attributed partly to the physical phenomena (sedimentation, filtration of the particulate forms) but is also attributed to biological processes in the layer of slime material that accumulates above the sand surface (schmutzdecke) and within the upper layers of the sand bed. The formation of a biological layer at the top of the sand media column, which favor the development of bacterial population (unpublished data). The obtained results indicate, clearly, that the type of sand used in the filtration process has an important role in the COD removal with smaller particle size media i.e. RS ($D_{10}=0.15$), achieving the highest performance. Additionally, in this study the efficiency in regard to COD removal using slow sand filter operation processes is remarkably superior to the levels reported by Amin et al. (2010) i.e. 52%, and similar to the ones (85%) reported by Prochaska & Zouboulis. (2003).

Figure 5(b) illustrates the TSS removal over time for the tested sand media. The averaged concentration of TSS in the ADR effluent was 80 ± 15 mg/L. The corresponding TSS percentage removal levels were equal to 79, 86 and 75% for DS, RS and BS respectively whereas the TSS reduction levels were maintained for a processing time of 132, 144 and 168 hrs. After that operational slow sand filtration period the TSS percentage removal level decreased for DS filter at 74% (16.0 ± 0.6 mg/L) and for RS filter at 79% (i.e. 16.8 ± 0.7 mg/L) whereas for BS filter the TSS removal remained constant at 75 % (i.e. 20.0 ± 0.7 mg/L), throughout the filtration process. The efficiency of the tested sand filters is higher in terms of TSS removal than the values reported by Nakhla & Farooq (2003) i.e. 63.9% at a filtration rate of 0.19 m/h, whereas the results obtained are in good agreement with Tyagi et al. (2009), having recorded TSS removal equal to 82%. One of the important physicochemical characteristics of sand is porosity. Prochaska & Zouboulis (2003) have suggested that the principal mechanism, which contributes to the removal of incoming TSS within the filter media, is due to straining (mechanical filtration) and adsorption. Particles larger than the pore space of the filtering medium are strained out mechanically. These results can be explained by the dominant forces that can control the attachment of particles since there are electrical interactions between charged particles and the charged media surface (Gálvez et al., 2003). Other mechanisms may also coexist, even though their effects are smaller and they are mostly masked by the straining action. These mechanisms include interception, impaction and adhesion. The removal of the smaller particles can be accomplished in two

steps: the transport of particles to the surface where they will be removed, and the elimination of particles by one or more of the operative removal mechanisms. These two steps have been identified as transport and attachment (Prochaska & Zouboulis, 2003). This explains the higher TSS removal efficiency of RS filter since this it has the smallest particle size. The observations suggest that the use of RS, rather than DS and BS sand in a tertiary treatment improves the efficiency.

The percentage TKN removal of the influent over time, using different sand filters (DS, RS and BS), is presented in figure 5(c). The concentration of TKN in the ADR effluent was 60 ± 14 mg/L, whereas the residual TKN concentration was recorded at 19 ± 2.8 , 17 ± 1.3 and 26 ± 3.2 mg/L for DS, RS and BS, respectively corresponding to TKN removal levels of 68%, 72% and 57% after 7 days of filter run. In the case where BS filter was used, the TKN removal rate remained constant throughout the experimental process, while for DS and RS filters the TKN removal decreased after 132 and 144 hrs respectively with TKN removal levels equal to 65 and 68%. At the end of the filtering procedure the TKN concentrations were recorded at 21 ± 2.3 , 19 ± 1.4 and 26 ± 2.5 mg/L for DS, RS and BS respectively. The TKN reduction is mainly attributed to ammonium reduction due to the nitrification process that takes place during filtration. To a smaller extend the retention of the particulate TKN on the biofilter also contributes to TKN reduction of the effluent.

The observed TKN removal for the three sand filters in our study is significantly higher than those reported by Liu et al., (2008) i.e. only 40% at a filtration rate less than 0.39 m/h. Similarly to COD and TSS removal levels, the RS filter performs better than the rest of the filters studied in lowering TKN concentration of the influent since the RS acquires higher specific surface area and consequently higher biomass densities are achieved (Nakhla & Farooq, 2003).

Figure 5(d) illustrates the percentage $\text{NH}_4\text{-N}$ removal over time for the three sand filters operated. The results obtained show that the $\text{NH}_4\text{-N}$ content of the ADR effluent decreases appreciably after its passage through the three different sand media with RS filter achieving the highest performance in terms of $\text{NH}_4\text{-N}$ removal level. For the longest duration of the filtration processes the $\text{NH}_4\text{-N}$ removal efficiency remains constant at 67, 76 and 59% for DS, RS and BS filters respectively. At the end of the filters run, i.e. 7th day, $\text{NH}_4\text{-N}$ removal levels decrease at 63% (20 ± 1.3 mg/L) for DS and 70% (16 ± 1.3 mg/L) for RS, whereas BS filter performance remained constant at 59%.

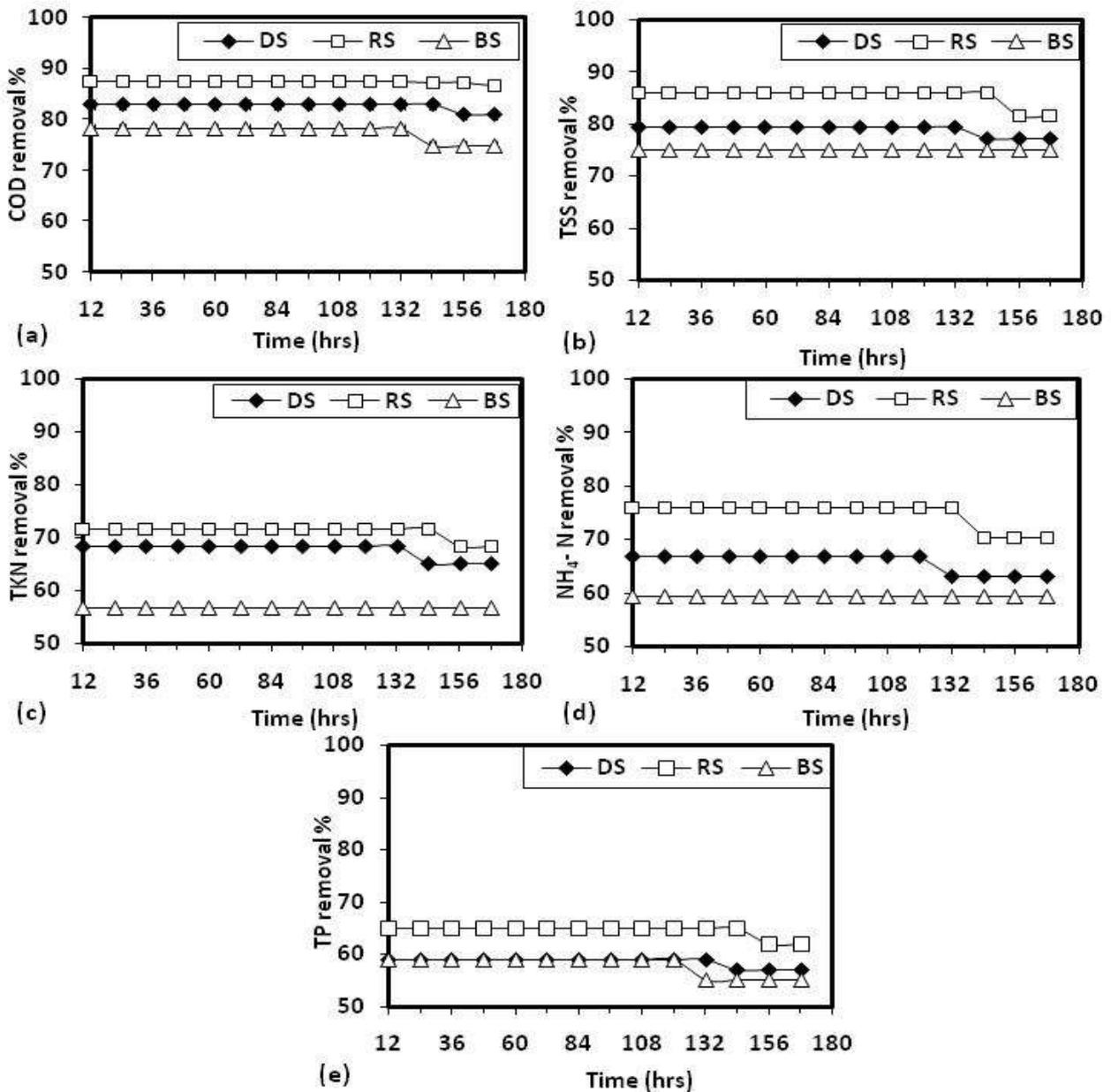


Figure 5. Effect of sand media over time on the removal of (a) COD, (b) TSS, (c) TKN, (d) NH₄-N and (e) TP in the three slow sand filters.

The elimination of TKN can be explained by a denitrification in microcosms anaerobic when the filter is supplied with water. In this type of system this process is the major mechanism for the elimination of nitrogen (Achak et al., 2009). The retention of TKN can be intervening by the sand and/or volatilization of ammonium ions. Particularly when pH of the influent varies between 7.8 and 8.4 (Hammer & Knight, 1994). However, in the case for our study the volatilization seems not probable since the pH of the influent is in the range of 7.12 ± 0.21 .

The physical and chemical adsorption of NH₄⁺ on organic matter could account for the removal of a significant amount of N from wastewater. According to Davis et al., (2001) the increased NH₄-N removal

level that is achieved though RS filtration could also be attributed to the ammonium cation adsorption to the sand grains through electrostatic or ion exchange interactions. However the aforementioned mechanisms are not expected to contribute substantially to NH₄-N reduction due to the low cation exchange capacity of the sand. Therefore, the elimination of ammonium in this study suggests that intense mineralization is followed by a significant ammonium reduction which can be attributed to nitrification processes (Bastviken et al., 2009; Achak et al., 2009) Nitrification consists indeed of the NH₄⁺ transformation into NO₂⁻ and finally into NO₃⁻ which causes to decrease the N-NH₄⁺ concentration. The process of denitrification takes place in the anoxic

zones and consists of transformation of NO_3^- into NO_2^- then N_2O and finally the nitrogen molecular N_2 . The nitrogen molecular, thus obtained from nitrates by the breathing of denitrifying bacteria, evaporates then in the atmosphere.

According to figure 5(e) the percentage of total phosphorus (TP) removal, due to sand filtration, is maintained constant over time for the longest duration of the processes using different sand media. More specifically, the TP removal level is maintained at 59% (2.13 ± 0.12 mg/L), 65% (1.82 ± 0.1 mg/L) and 59% (2.13 ± 0.2 mg/L) for 132, 120 and 144 hrs using DS, RS and BS filters respectively. At the end of the filtration operation the TP removal is slightly reduced to 57%, 62% and 55% for DS, RS and BS filters respectively whereas the corresponding TP concentration of the effluent equals to 2.24 ± 0.1 , 1.98 ± 0.21 and 2.34 ± 0.14 mg/L. There are different processes by which phosphorus may be removed from the influent namely absorption, ionic exchange and adsorption (Carvalho et al., 2007; Billore et al., 1999). The highest TP removal efficiency is obtained using an RS filter (Fig. 4(e)), which might be explained by the high content of hydroxides, Al - Fe oxides and the presence of layer silicate minerals which are important sites for the sorption of phosphate anions (Tomar & Suthar, 2011).

The average FC and FS concentration of the influent equals to $4.8 \times 10^4 \pm 1.1 \times 10^4$ and $2.5 \times 10^4 \pm 1.3 \times 10^4$ CFU /100mL, respectively. According to figure 6, the FC and FS content of the influent (i.e. ADR effluent) decreases notably due to slow sand filtration using the different sand media. The FC and FS removal level is constant during sand filtration for all sand materials used for about 132hrs. During this operational period the FC removal levels are 1.7 ± 0.12 , 2.4 ± 0.15 and 1.5 ± 0.24 log-units using DS, RS and BS filters respectively which are similar to the values reported by Torrens et al., (2009). Accordingly, the FS removal levels equal to 1.86 ± 0.19 , 2.7 ± 0.2 and 1.5 ± 0.22 log-units for DS, RS and BS filters

respectively. The reduction of bacteria levels depend mainly on sand physical characteristics since the finer and more homogeneous a sand filter is, the higher the bacteria reduction (Langenbach et al., 2009). Therefore, the RS filter presents the highest efficiency in terms of bacteria removal due to the finer particle sand size in comparison to DS and BS.

3.4.3. Relationship between pollutants variables and chemical composition of sand

The relationships between the physicochemical, microbiological variables (COD, TSS, TKN, $\text{NH}_4\text{-N}$, TP, FC, FS) and the chemical composition of sand (Al_2O_3 , Fe_2O_3 , Organic Matter, SO_3 , and Cl) were investigated by applying linear regression analysis using the data obtained during the slow sand filtration processes at a hydraulic loading rate of 0.16m/h. Table 4 depicts the removal level of the physicochemical and microbiological pollutants which is significantly correlated to the presence of Al_2O_3 , Fe_2O_3 and Organic Matter (OM) of the sand media used. More specifically, the correlation coefficient, *r*, ranges from 0.850 to 0.999 for Al_2O_3 , 0.682 to 0.960 for Fe_2O_3 and 0.921 to 0.999 for OM, suggesting that an increase of Al_2O_3 , Fe_2O_3 and OM content in sand media has an appreciable impact on the performance of slow sand filtration.

Therefore, the adsorption properties and thus the removal efficiency of the pollutants using a RS oxides-coated quartz sand provide a high capacity adsorption and immobilization of TP from wastewater. In our study, it is evident that apart from Al_2O_3 and Fe_2O_3 , the OM content plays also an important role not only in the removal of TP but also in the rest of the physicochemical and microbial pollutants examined.

The regression analysis has also shown that the pollutants removal efficiency is negatively correlated to SO_3 and Cl content in sand filters acquiring a correlation coefficient, “*r*”, between -0.999 and -0.921.

Table 4. Correlation coefficient obtained in the linear regression analysis between pollutants variables and chemical composition of sand

Elements	Correlation coefficient, <i>r</i>						
	COD	TSS	TKN	$\text{NH}_4\text{-N}$	TP	FC	FS
Al_2O_3	0.989	0.999	0.85	0.999	0.868	0.85	0.999
Fe_2O_3	0.893	0.960	0.656	0.938	0.682	0.936	0.850
OM	0.999	0.986	0.906	0.995	0.921	0.996	0.993
SO_3	-0.999	-0.986	-0.906	-0.995	-0.921	-0.996	-0.993
Cl	-0.999	-0.986	-0.906	-0.995	-0.921	-0.996	-0.993

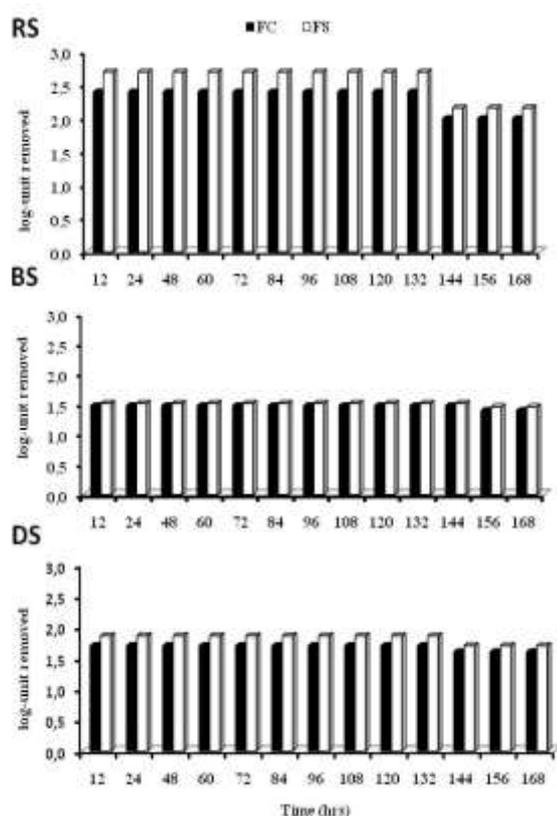


Figure 6. Influence of the type of sand on FC and SF removal versus time.

The findings of this study support the hypothesis that all physicochemical and microbial parameters examined exhibit a similar decreasing trend due to slow sand filtration and that the reduction is driven by a common force involving straining and attachment mechanisms, (Tyagi et al., 2009).

3.5. Clogging of sand filters

The evolution of the influent (i.e. ADR effluent) flow rate over time for the tested sand filters. It can be observed that the influent flow rate is arranged in the following order: BS>DS>RS. More specifically, the hydraulic loading rate varied between 16 - 172 m/h, 20-148 m/h and 7 - 238 m/h for BS, DS and RS filters. Therefore the RS filter presents the longest resident time, whereas, the BS filter the shortest. An overview of the flow rate studies shows that the residence time of the influent has a direct relationship with the sand size of the filter. After 7 days of operation, the flow rates in the three sand filters are significantly reduced indicating clogging of the sand pores due to TSS accumulation on top of the filters and due to the increased organic loading rate that is applied (Siegrist, 1987). The clogging mechanism is initiated through the absorption of particulate solids by electrostatic and Van der Waals' forces which causes a gradual

formation of an organic deposition layer restricting larger particulate solids to flow through (Hua et al., 2010). Clogging of the upper layers of the sand filter increases the average influent retention time and reduces the effective area available for infiltration. Rodgers et al., (2004) noted that the deposition of organic and inorganic solids on the upper layer of the filters have also been considered to cause surface sealing. Siegrist & Boyle (1987) found an accumulation of organic matter in the upper sand layer, and hypothesized that it may have undergone humification and gradually filled the pore space thus reducing its permeability. According to Hua et al., (2010) it is stressed that clogging conditions are probably formed due to biomass accumulation, rather than physical or mineralization processes of suspended solids filtration and simple traps. In this study, it is very likely that both mechanisms are contributing to sand filters clogging since the conditions are favorable for biomass development on the filter surface (i.e. presence of nutrients and microorganisms in inflow) and at the same time significant inorganic foulants contained in TSS are trapped. Therefore, substantial maintenance and long resting periods are necessary in order to recover filters capacity.

4. CONCLUSIONS

This study focuses on the effect of hydraulic loading and sand media characteristics on slow sand filtration efficiency of secondary effluent from ADR. The following conclusions can be drawn:

1. The pollutants removal efficiency of slow sand filtration is negatively correlated to the hydraulic loading rate with increased rate leading to reduced removal efficiency.
2. The optimum hydraulic loading rate in terms of COD, TSS, TKN, NH₄-N and TP removal efficiency and water reuse standards compliance is set to 0.16 m/h.
3. The effects of physicochemical variables (COD, TSS, TKN, NH₄-N and TP) as well as microbiological variables (FC and FS) on removal efficiencies are positively correlated to Al, Fe and OM content of sand filters.
4. Amongst the sand filters studied (BS, DS and RS filters), RS presented the highest performance due to the increased content of Al₂O₃, Fe₂O₃ and OM and the small particle sand size of the filter.
5. The observations revealed that the time of clogging slow sand filters is 7 days, In order to increase this time, the alimentation should be followed by a rest period.

Based on the findings of this study, it can be concluded that slow sand filtration can be used for

tertiary wastewater treatment for the effective removal of COD, suspended solids, nitrogen, phosphorus and microbiological pollutants.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the “Académie Hassan II des Sciences et Techniques” for their financial support (Project ADR).

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Received at: 22. 04. 2013

Revised at: 18. 07. 2013

Accepted for publication at: 24. 07. 2013

Published online at: 31. 07. 2013