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Study of filter height effect on removal efficiency of Cd, Cu, Pb and Zn from water by slow sand filtration

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ABSTRACT

In Morocco, many regions suffer from water scarcity. In order to address the arid zone water shortage in the Marrakech region, the reuse of wastewaters in agriculture can present new alternatives. However, there are significant concerns about the safety of wastewater reuse especially for irrigation purposes that can be insured by reducing the wastewater pollutants amount by accessible and inexpensive processes like slow sand filtration (SSF). In order to study the removal efficiency of SSF, a continuous fixed-bed adsorption study was achieved by using sand as an adsorbent of metallic trace elements (Cd, Cu, Pb and Zn) from contaminated water of Tensift River. This river received wastewater directly from industrial unit of Zn and Pb extraction of Draa Lasfar mine located at 13 km in north-west of Marrakech City in Morocco. Results showed that SSF can remove 100% of metallic pollutants and the removal efficiency of this process to decontaminate water depends greatly on the sand bed height (filter). Thus, the long filter eliminates more pollutants than the smaller ones.

This result can be attributed to the exposition of new fixation sites of metallic pollutants on the sand surface that facilitates their adsorption process. The dynamic behavior of adsorption mechanism used in SSF process is predicted by using Langmuir kinetics of adsorption-desorption with no axial dispersion.

Keywords: Slow sand filtration; Removal efficiency; Metallic trace elements; Modeling; Decontamination

1. Introduction

Environmental pollution has become a global concern and attracts more attention [1]. The rise in human population density and anthropogenic activity experienced by the world since the industrial revolution are responsible for the degradation of the environment by the introduction and spread of many pollutant substances through the misuse of environmental resources and improper disposal of wastes [2,3]. These harmful substances can endanger the stability of ecosystems and consequently the renewal of natural resources such as air, water and soil [3–6]. Such

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situation has been described as water mismanaged factors and consequently is responsible for water crisis.

Water penury is one of the most worrying and prominent challenges to human health and environmental integrity in most parts of the world [7]. With the rapid industrial development, technological progress and demographic expansion of water demands increase without the possibility to increase the supplies. The mounting demands in this finite and vital resource has inspired creative strategies in order to achieve sustainable development and reach a secure status regarding both quantity and quality of water bodies using new techniques for wastewater recycling [8].

Wastewater reuse is one of the strategies that can reduce the demand for potable water, and its usefulness to satisfy non-potable water needs should be thoroughly investigated. This usefulness can be explored in many activities which require less stringent standards of water quality parameters.

Several activities can be carried through the reuse of this reclaimed water such as gardening, agricultural and landscape irrigation, golf courses, fire suppression, air conditioning, soil compaction, construction works, toilet flushing, and public park irrigation. This will increase the service life of fresh water resources.

Water treatment can be provided through a variety of techniques and technologies [9]. These techniques may differ from region to region or according to the pollution's rate. However, the basics are the same. We can mention several types of water treatments such as sedimentation, filtration, disinfection, fluoridation, etc. Nonetheless, in this study the focus is on the filtration and specifically "slow sand filtration (SSF)".

This process has been recognized as an appropriate technology for all types of wastewater treatment in rural areas, and is recognized as a suitable filtration technology for removing water borne pathogens, organics and reducing turbidity [10].

SSF system is a filtration process in which contaminated water percolates through a sand medium and through various physical, chemical, and biological processes, in which the contaminants are removed. The first known SSF system was made in 1804 by John Gibb in Scotland to produce drinking water [11]. Since then, this technique has been widely used not only for drinking water production [12], but also for improving the quality of wastewater before being reused [13,14] or discharged into the environment [15].

SSF combines a high efficiency system in reducing turbidity and harmful microorganisms along with a financial advantage. SSF is relatively simple, requiring no close operator supervision or sophisticated instrumentations. It uses minimal power input and no chemical requirements, uses locally available materials and labor, and does not produce unwanted by-products [16]. This cost-effective technique now has special application in the treatment of wastewater at smaller scales such as isolated households in rural areas or in small businesses with high water consumption, like plant nurseries and mines [13,14]. This is likely to be a robust treatment method applicable in developing countries and helps to remove existing metallic pollutants in water.

At certain interval of time, sand filter may get saturated due to its interaction with metallic ions present in water and, consequently, decrease the efficiency of filter bed that has become inactive to purify water.

At that time, the used sand filters needs to be disposed of and fresh sand to be used in re-sanding the filters.

The disposal of sand to the usual solid waste dumping area or in a sanitary landfill is not a good idea because of the risk of metal leachate and probably pollution of ground water.

Hence it should be considered as a hazardous waste and two options in this respect are possible:

1.1. Glassification

One of the most effective ways to contain very dangerous materials is to incorporate the material into glass. This technique is called glassification. Hence the used sand in SSF can be used in manufacturing glass that it is considered as one of the most inert synthetic materials and strongly resistant to leaching. It is considered as a very effective means of fixing metallic elements contained in wastes.

1.2. Cement-based fixation

This method consists of mixing waste with common cement (Portland cement) such as that used in construction. The mixture hardens to form concrete material in which the hazardous materials are immobilized. This method was developed for the safe disposal of low level radioactive waste. It can be used to dispose of the SSF sand as well.

Thus, this study aims to investigate the efficiency of slow sand filter in purifying Tensift River water that receives directly wastewater of industrial unit of Zn and Pb extraction of Draa Lasfar mine using sand as the filter medium.

In order to achieve a secure status regarding this reclaiming water, this study also tries to develop a new prediction method that consists of developing a mathematical model of the SSF process taking into consideration filter height factor governing pollutant migration, in order to produce reasonable guidance for environmentally sustainable mining in the future.

2. Material and methods

2.1. Studied zone

The rural region of Draa Lasfar is located at approximately 13 Km in the north-west of Marrakech City (Fig. 1). It is located a few hundred meters from the Tensift River, close to a rural community of about 5,790 ha, with 65% is occupied by farmland. This region consists on deposit of pyrite mineral discovered in 1953 although their commercial exploitation did not begin until 1979. Mineral was processed by flotation after primary and secondary crushing and grinding, producing 60 Mt of products in the first two years (1979 and 1980). Industrial activity stopped in March 1981, although it restarted in 1999 due to its great resource of polymetallic components (As, Cd, Cu, Fe, Pb and Zn).

During its exploitation, wastewater was directly evacuated into Tensift River without any pretreatment.

Water samples were collected directly from the mine wastewater (MW), Tensift River before and 50 m after mixing with wastewater from industrial unit of Zn and Pb

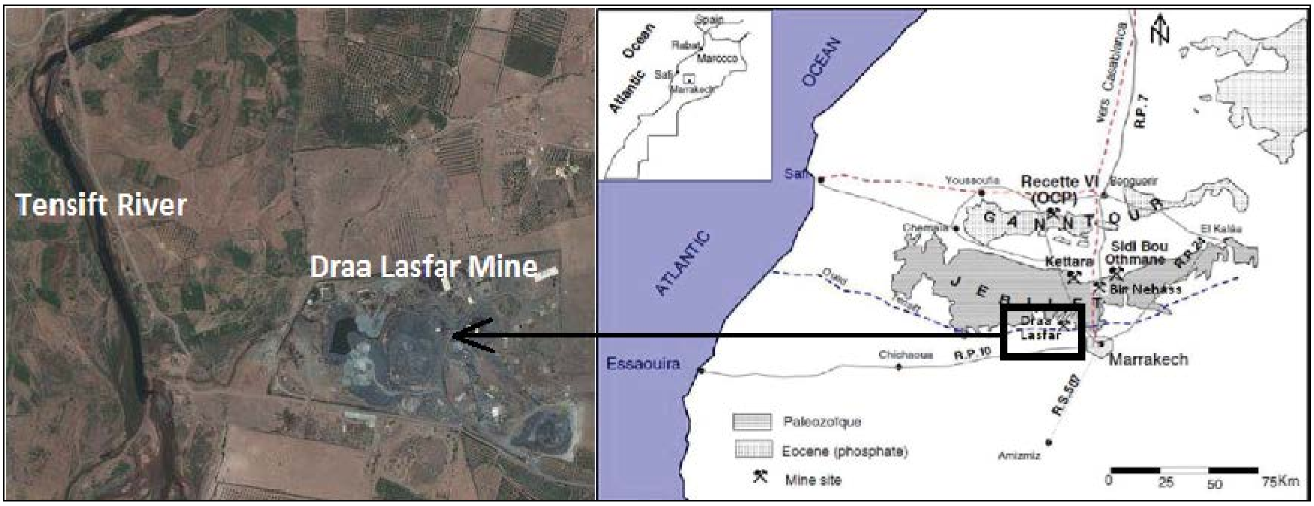

Fig. 1. Draa Lasfar mine geographic situation in Marrakech Region.

extraction of Draa Lasfar mine. Samples were taken in sterile glass bottles of 2,000 ml capacity, after rinsing the bottles three times with sample water. In order to collect the samples from the river, bottle with a string attached to neck was used, and then the bottle was raised and stoppered. The collected samples were transported to laboratory in ice within an insulated container and used to perform the SSF study in laboratory's columns.

2.2. SSF experiment

Each column is made of polypropylene plastic with the same diameter (D = 8 cm). The total height of the column is 50 cm. All columns were opened at both ends, one opening face at the top for inlet of untreated water was large enough to receive a tube from a peristaltic pump and allow air circulation and other at the bottom acting as an outlet for effluent.

The decontamination efficiency of SSF process was determined by percolation of untreated water through laboratory columns with same diameter filled to various heights with sand according to each experiment. Prior to each experiment, distilled water was continuously injected through the columns overnight at a rate of 20 ml min^{-1} [17].

To understand of the effect of sand bed depth on dynamics of water metallic pollutants (Cd, Cu, Pb and Zn), this study was carried out on 3 columns of the same diameter (D = 8cm) [17–19] filled to different heights with sand; 5 cm [19,20], 10 cm [21] and 15 cm [22]. Water samples were continuously injected through the columns at a rate of 20 ml min^{-1} [9].

A test tube was connected to the hole in the lower cap to collect filtrated water (effluent). The collected water samples were stored in ice in an isolated container and analyzed within 24 h of collection.

Physicochemical analysis using spectroscopy of atomic absorption were done on MW and Tensift River water sample before and after the filtration process to determine the efficiency of the slow sand filter to remove some anthropogenic chemical contaminants generated from Draa Lasfar mining site in Marrakech (Cd, Cu, Pb and Zn) using different filter depths.

3. Results and discussion

Textural characteristics of the sand used in this study are shown in Table 1.

The mean concentrations of Cd, Cu, Pb, and Zn in Draa Lasfar MW, Tensift River water before and after receiving the MW are shown in Table 2.

Heavy metals (Cd, Cu, Pb and Zn) concentrations in recovered solutions (effluent) are shown in Figs. 2–5, respectively.

These results show that studied metallic trace elements concentrations changed continuously in effluents according to the filtration process time and increased progressively in all recovered effluents [23]. The speed of this increase became increasingly weak and stabilized to reach a maximum equilibrium value (μ) [18]. This value remained almost equal to the concentration of the initial water concentration (influent).

These results show also that the removal efficiency of filtration to decontaminate water depends greatly on the sand bed (filter) height. Thus, the long filter eliminates more metallic pollutants than the smaller ones.

This finding can be justified by saturation of fixation sites of metallic ions on the sand bed filter, which is translated at the end of filtration process (about 300 min) by recovering a water solution which is roughly similar to the initial water solution (influent).

Due to its particulate structure, sand often exhibits atypical behaviors. The characteristic time of solute

Table 1
Sieve analysis of the sand

Sieve size (mm)	Retained weight (g)	% of retained weight	% of cumulative weight
0.3	342	17.1	17.1
0.15	1,366.11	68.3	85.4
0.09	224.72	11.2	96.6
0.075	29.05	1.5	98.1
0.001	38.1	1.9	100

Table 2
Physic-chemical characteristics of Draa Lasfar mine wastewater (MW), Tensift River water before (TRWB), and after (TRWA) receiving the mine wastewater

Parameters	MW	TRWB	TRWA
pH	6.8 ± 0.3	7.0 ± 0.5	7.0 ± 0.6
O_2 mg L^{-1}	0.2 ± 0.1	6.8 ± 0.3	7.6 ± 0.4
T °C	28.1 ± 0.4	27.5 ± 1.3	27.7 ± 0.5
CE mS cm^{-1}	4.0 ± 1.0	4.7 ± 0.8	4.4 ± 0.6
MES mg L^{-1}	78.3 ± 1.6	56.7 ± 2.6	57.8 ± 4.5
SO_4^{2-} mg L^{-1}	192.2 ± 6.4	100.7 ± 5.7	123.7 ± 8.4
Cl^- mg L^{-1}	2,356 ± 24.5	80.7 ± 12.8	1,819 ± 13.1
NH^{4+} mg L^{-1}	4.1 ± 1.2	5.9 ± 1.7	4.5 ± 1.2
NO_2^- mg L^{-1}	1.7 ± 0.4	9.1 ± 1.1	9.6 ± 1.5
PO_4^{3-} mg L^{-1}	6.6 ± 1.8	44.8 ± 3.5	37.6 ± 4.8
Ca^+ mg L^{-1}	1,358.7 ± 25.0	219.0 ± 27.5	468.9 ± 17.9
Mg^{2+} mg L^{-1}	385.0 ± 26.7	136.0 ± 13.7	224.0 ± 16.5
Na^+ mg L^{-1}	383.4 ± 21.8	225.3 ± 25.7	274.4 ± 19.1
K^+ mg L^{-1}	110.8 ± 10.8	77.4 ± 21.4	104.5 ± 12.0
Metallic trace elements			
Cd μg L^{-1}	6.2 ± 0.9	3.2 ± 0.7	4.3 ± 1.1
Cu μg L^{-1}	90.4 ± 5.4	46.7 ± 6.7	67.1 ± 5.9
Pb μg L^{-1}	454.9 ± 86.3	132.1 ± 17.8	315.5 ± 45.5
Zn μg L^{-1}	887.8 ± 35.8	530.7 ± 32.7	796.8 ± 27.8

transport is very different in each zone in a particulate bed such as sand, and the time required to achieve pressure and concentration equilibrium is much longer in the weakly conductive area than in the higher hydraulic conductivity.

This implies that the condition of non-equilibrium may appear during mass transfer processes. The contrast of the hydraulic properties leads to preferential flows/transports in the macro-pores with interactions or exchanges with the micropores.

These contribute to the propagation of solutes under conditions of non-local equilibrium. The acceleration of the flow in the macropores vis-à-vis the delay in the matrix is the phenomenon called the drag effect [24].

The evolution of the concentration of the metallic trace elements at the output of a fixe particulate bed (effluent), noted here by output $C(t)$, supplied continuously by a concentration solution (C_i) corresponds to the breakthrough curve.

As can be observed from the plots (Figs. 2–5), the particulate beds of sand were exhausted faster at lower bed height values [9]. That is earlier breakthrough point was reached at lower height of particulate bed (filter).

The breakpoint time was found to decrease with decreasing height's filter as the binding sites became more quickly saturated in the particulate bed [9]. An increase in height of filter gave an extended breakthrough curve, indicating that a higher volume of solution could be treated. This is due to the fact that lower height caused a slower transport due to a decrease in diffusion coefficient or mass transfer coefficient [25,26].

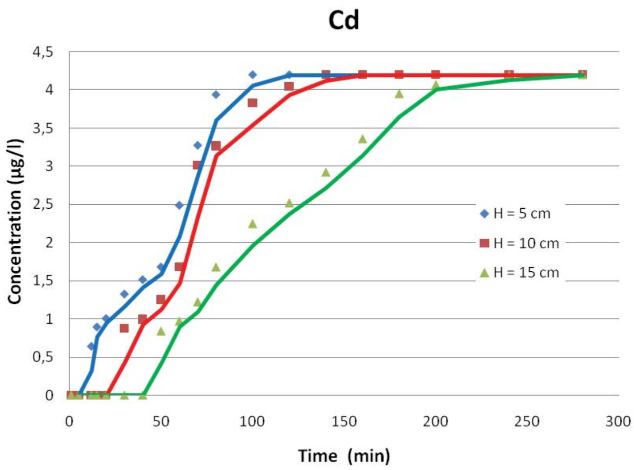

Fig. 2. Evolution of Cd concentration of filtrate water (effluent) at different sand filter height according to the filtration time.

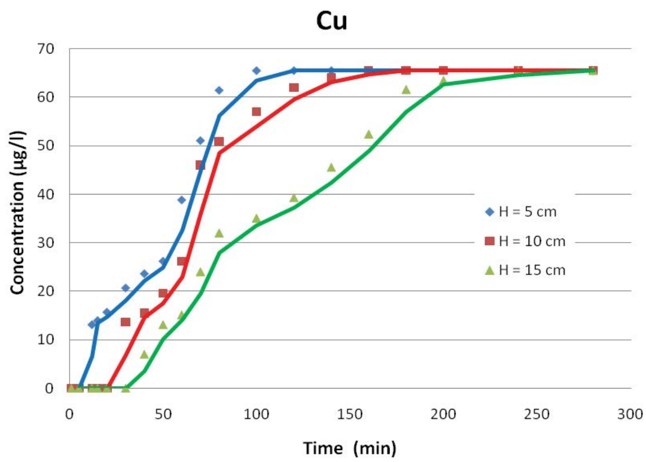

Fig. 3. Evolution of Cu concentration of filtrate water (effluent) at different sand filter height according to the filtration time.

3.1. Modeling of analytical results

Full-scale column operation used in sand slow filtration can be designed on the basis of data collected at laboratory level. Many mathematical models have been described to assess the removal efficiency and the applicability of this process for large-scale operations [27].

In order to describe a column adsorption process used in SSF, it is crucial to predict the breakthrough curve (concentration-like profile) and adsorption capacity of the used sand for the studied metallic trace elements under the given set of operating conditions (Fig. 6) [21].

This figure shows that breakthrough time increases with increasing of particular bed height. The shape and gradient of the breakthrough curves were slightly different with the variation of the sand filter depth. A higher efficiency of water decontamination represented by metallic pollutants uptake was noted at higher bed height due to the increase in the amount of sand which provided more active binding sites for the adsorption process to proceed [9,17]. This figure shows also that the mass transfer zone in the sand filter moves from the inlet of the column and proceeds towards the exit. Hence for the same influent concentration, an increase in sand bed height creates a longer distance for the mass transfer zone to reach the exit subsequently resulting an extended breakthrough time [17].

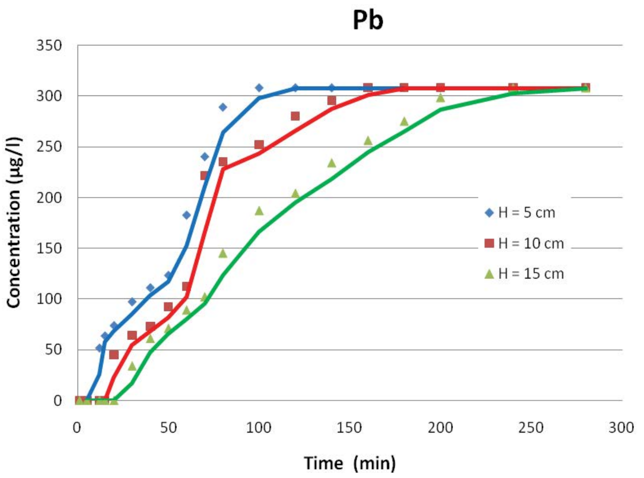

Fig. 4. Evolution of Pb concentration of filtrate water (effluent) at different sand filter height according to the filtration time.

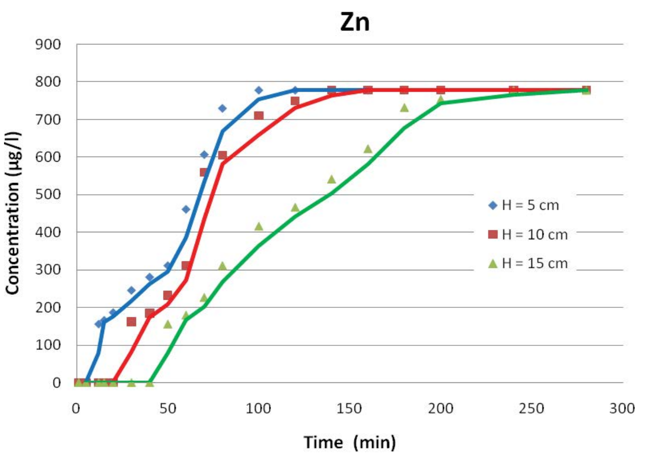

Fig. 5. Evolution of Zn concentration of filtrate water (effluent) at different sand filter height according to the filtration time.

The dynamic behavior of these columns can be predicted using Adams–Bohart, Thomas, and Yoon–Nelson models. These models are important when designing an efficient fixed-bed adsorption system with the optimum required conditions [1].

These models did not take in account in their mathematical expressions the effect of the particulate bed height used to decontaminate water. The modeling of SSF process is based on the assumption that the process follows Langmuir kinetics of adsorption-desorption with no axial dispersion. It describes that the rate driving force obeys the second-order irreversible reaction kinetics [1] that has the following form:

$$\ln\left(\frac{C_0}{C_1 - 1}\right) = K_L \times \frac{q_{\max}}{Q - K_L} \times C_0\left(t\right)$$

where $q_{\max}$ (mg g^{-1}) is the maximum amount of the ions per unit weight of the particulate bed whereas K_L (L mg^{-1}) is Langmuir constant related to the affinity of the binding sites.

4. Conclusion

This study showed that SSF is promising for removing metallic trace elements from Tensift River that received wastewater generated by Draa Lasfar mine near Marrakech - Morocco. Three laboratory-scale SSFs were developed and operated to investigate the removal of four heavy metals Cd, Cu, Pb and Zn. The initial doses of Cd, Cu, Pb and Zn were considered as 4.2, 65.5, 307.9, and 780.5 µg L^{-1} respectively. The removal of Cd, Cu, Pb and Zn were found as 100% for all these metals at the first step of the filtration and then decreased progressively as the binding sites became more quickly saturated in the sand filter. This study showed also that removal of these elements accomplished better with higher filter depths and declined at shallower ones. In order to design mathematically the column adsorption process used in SSF, a rate driving force obeying the second-order irreversible reaction kinetics was described.

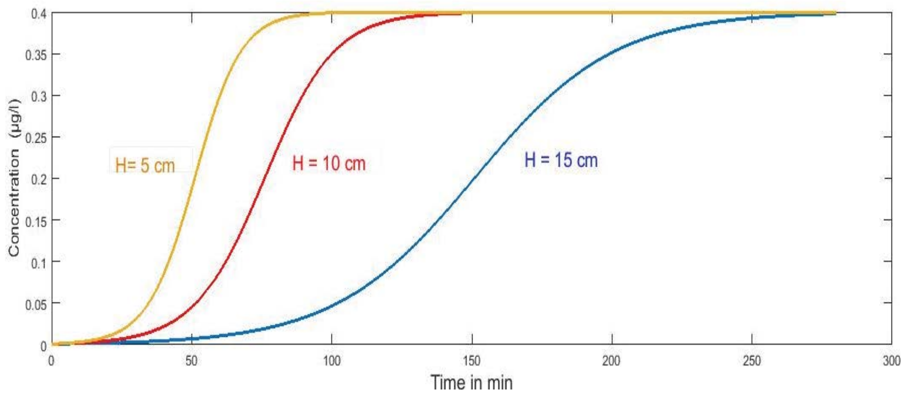

Fig. 6. Breakthrough curves for adsorption of metallic trace elements for different filter heights.

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