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A Modeling Approach to Study the Water Inlet Flow Effect on Slow Sand Filtration Removal of Metallic Pollutants in Unsafe Water

Yassir Barkouch[1], Abdelaziz Ait Melloul[2], Khadija Flata[3*], Sana El Fadeli[4], Abdelilah El Abbassi[5], Alain Pineau[6]

[1] Laboratory of computer mathematics and modeling of complex systems , Higher School of Technology of Essaouira, Cadi Ayyad University, Km 9, Route of Agadir, Essaouira Aljadida BP.383, Essaouira, Morocco.
[2] Higher Institute of Nursing Professions and Health Technology, ISPITS - Marrakech - Morocco.
[3] Regional Laboratory for Epidemiological Diagnosis and Environmental Hygiene, Boulevard des Hôpitaux, Gueliz-Marrakesh, Morocco.
[4] Higher Institute of Nursing Professions and Health Technology, ISPITS - Essaouira - Morocco.
[5] Laboratory of Agrifood Biotechnology and Valorization of Plant Bioressources. Department of Biology, Faculty of Science Semlalia, Cadi Ayyad University, Marrakech- Morocco.
[6] UFR de Sciences Pharmaceutiques et Biologiques, Centre de Dosage des Eléments Minéraux (CDEM), 9 rue Bias, BP 53508, 44035 Nantes, France.

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Abstract

In various regions confronting water scarcity, the agricultural reuse of wastewater presents potential challenges, prompting the need for economical methods to reduce metallic pollutants, such as the implementation of slow sand filtration. This investigation sought to understand the efficacy of metallic pollutant removal using sand as an adsorbent, employing the adsorption process to develop a cost-effective strategy for treating water contaminated with heavy metals from the Tensift River. This river directly receives wastewater from the industrial unit of Zn and Pb extraction at the Draa Lasfar mine, located 13 km northwest of Marrakech City, Morocco. The results indicated that slow sand filtration efficiently purifies water, with its effectiveness significantly influenced by the water inlet flow in filtration columns. A decrease in water inlet flow prolonged the residence time of solutes in the filter bed, augmenting contact time and fostering chemical bonds between metallic trace elements and their binding sites on the sand. Logistic component analysis, ensuring coherence between the model, experimental outcomes, and interpretation, facilitated the prediction of the dynamic behavior of the adsorption mechanism in the slow sand filtration process, articulated by a single logistic model.

Keywords: *Metallic Trace Elements, Modeling, Slow Sand Filtration, Inlet Flow, Removal Efficiency, Unsafe Water Reuse.*

1. Introduction

Improving agricultural water management is critical for enhancing productivity in arid regions globally (Zhou et al., 2021; Magombeyi et al., 2018), where agriculture plays a pivotal role in sustainable development, food security, and poverty reduction. The past century, particularly the last two decades, has witnessed significant water body contamination due to diverse human activities, intensifying water management challenges amid the ongoing trends of urbanization and industrialization (Hussien et al, 2022; Hadef et al, 2021; Calmuc et al., 2020; Pham et al., 2017; Gokul et al., 2015). The escalating human population density and anthropogenic actions contribute to environmental degradation, introducing detrimental substances through resource mismanagement and improper waste disposal (Omonona and Azombe, 2024; Siddiqua et al, 2022). These substances jeopardize ecosystem stability and the renewal of natural resources such as air, water, and soil (Bani Khaled et al, 2024; Al Rabadi et al., 2023; Changyoon et al., 2023), leading to environmental mismanagement and consequent water crises like water scarcity (Chiedozie and Tosan, 2022).

Globally, water scarcity is emerging as a pivotal challenge to human health and environmental stability (Carlo et al., 2023; Al-Qawasmi and Al Sharif, 2022). The increasing demand for this vital resource has spurred innovative techniques to preserve its sustainability and ensure a secure status concerning both quantity and quality, employing novel recycling processes. Among these strategies, the reuse of non-potable water in activities with less stringent water quality standards stands out, reducing the demand for potable water and extending the service life of freshwater resources (Al-Mubaidin et al, 2022).

Various water treatment processes, tailored to pollution rates and regional disparities, facilitate the reuse of unsafe water. This study focuses on slow sand filtration, which is considered a suitable technology for purifying unsafe water, particularly in rural areas. It adeptly removes waterborne pathogens and metallic and organic components and diminishes turbidity (Maiyo et al., 2023). Originating in 1804, slow sand filtration has evolved into a widely employed technique for drinking water production (Maiyo et al., 2023; Guchi, 2015; Haig et al., 2011) and enhancing wastewater quality for reuse (Abdiyev et al., 2023; Zhang et al., 2022; Agrawal et al., 2021; Hijnen et al., 2004) or environmentally safe discharge (Islam et al., 2021).

The present study delves into the efficiency of slow sand

* Corresponding author e-mail: Kh.flata@yahoo.fr

filtration in purifying unsafe water from the Tensift River, which receives wastewater directly from the Draa Lasfar mine near Marrakech, Morocco. Physicochemical analyses were meticulously conducted on water samples before and after filtration, evaluating the filter's proficiency in removing metallic trace elements (Cd, Cu, Pb, and Zn) under varying column inlet water flow conditions. Additionally, the study aspires to pioneer a new prediction method, involving a mathematical model of the slow sand filtration process, while considering the column inlet water flow parameter, to ensure a secure status in water reclamation.

2. Material and Methods

2.1 Studied Location

Draa Lasfar mine, situated approximately 13 kilometers west of Marrakech city, is a geological site characterized by the presence of pyrite minerals. Discovered in 1953, the mine's commercial exploitation commenced in 1979, marked by the processing of minerals through flotation after primary and secondary crushing and grinding. This extraction yielded substantial production, with 60 million tons of products generated in the initial two years (1979 and 1980). Notably, Draa Lasfar mine became dormant in March 1981 but saw a resurgence in 1999 due to its rich reserves of polymetallic components, including arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), and zinc (Zn). The mining activities, while contributing valuable resources, have raised environmental concerns, particularly regarding the direct discharge of wastewater into the nearby Tensift River without pretreatment measures. The Draa Lasfar deposit contains 10 Mt of ore grading 5.3 wt.% Zn, 2 wt.% Pb, 0.3 wt.% Cu, and their orebodies consist dominantly of pyrrhotite (70 to 95 vol.% of sulfides, but commonly up to 90 to 95 vol.% in Zn and Cu-depleted zones), with lesser sphalerite (1 to 10 vol.%), galena (0.5 to 5 vol.%) and chalcopyrite (1 to 5 vol.%), and with local concentrations of deformed pyrite (2 to 3 vol.% of total sulfides) being arsenopyrite the most common of the minor minerals (Avila et al, 2012).

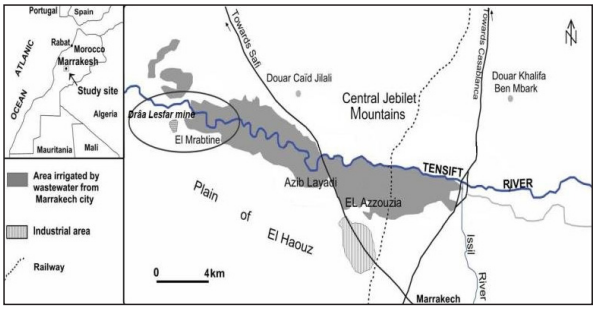

Figure 1. Geographical locations of Draa Lasfar mine and the Tensift River in the Marrakech Region.

Samples of mine wastewater and Tensift River water were collected directly, both upstream and 50 meters downstream from the point of mixing with wastewater from the Zn and Pb extraction industrial unit at Draa Lasfar mine. The collection involved using sterile plastic bottles with a capacity of 2000 milliliters, and each bottle was rinsed three times with sample water before collection. For river sample collection, a bottle with a string attached to the neck was deployed, and upon retrieval, the bottle was sealed. The collected samples were promptly transported to the laboratory in ice within an insulated container to conduct the slow sand filtration study in laboratory columns.

2.2 Slow Sand Filtration Experiment

The experimental setup for slow sand filtration involved three polypropylene plastic columns, each sharing a standard diameter (D=10cm) (Farrag et al., 2017). These columns, open at both ends, facilitated the inlet of contaminated water at the top and effluent discharge at the bottom. The study focused on assessing the efficiency of slow sand filtration in removing metallic trace elements (Cd, Cu, Pb, and Zn) from Tensift River water. This assessment was conducted by percolating untreated water through two columns filled to a uniform sand height of 10 cm. Before each experiment, a continuous overnight flow of distilled water through the columns at a rate of 20 ml/min was employed to eliminate any residual metal elements (Farrag et al., 2017).

To investigate the influence of water inlet flow rate on the dynamics of waterborne metallic pollutants, two columns with identical diameters (D=10cm) were utilized, filled to the same sand height of 10 cm. Water samples were systematically poured through these columns at three distinct flow rates: 6 ml/min, 10.1 ml/min, and 20 ml/min. Effluent from the filtration column was collected through a test tube connected to the bottom opening. Subsequently, the collected water samples were preserved in ice within a designated container and subjected to analysis within 24 hours of collection.

3. Results and Discussion

Table 1 presents the textural characteristics of the sand employed in the study. Table 2 outlines the average concentrations of lead (Pb) in Draa Lasfar mine wastewater (DW) and Tensift River water before (WB) and after (WA) the receipt of mine wastewater. Figures 2, 3, 4, and 5 depict visual representations of the concentrations of metallic trace elements (Cd, Cu, Pb, and Zn) in the reclaimed solutions (effluent).

Table 1. Particle size analysis of the sand

Sieve size (mm)	Retained weight (g)	% of retained weight	% of cumulative weight
0.3	338	16.9	16.9
0.15	1358	67.9	84.8
0.09	218	10.9	95.7
0.075	42	2.1	97.8
0.001	44	2.2	100

Table 2. Chemical and physical properties of DW, WB, and WA.

Parameters	DW	WB	WA
pH	6.79 ± 0.19	7.01 ± 0.98	7.03 ± 0.11
O_2 (mg/l)	0.21 ± 0.11	6.81 ± 0.29	6.59 ± 0.39
T (°C)	28.09 ± 0.38	27.49 ± 0.41	27.69 ± 0.48
CE (mS/cm)	4.02 ± 1,01	4.71 ± 0.78	4.39 ± 0.57
SM (mg/l)	78.28 ± 1.62	56.68 ± 2.57	57.78 ± 4.46
SO_4^{2-} (mg/l)	192.21 ± 6.36	100.72 ± 5.72	123.66 ± 8.35
Cl^- (mg/l)	2356 ± 24.51	80.73 ± 12.81	1819 ± 13.12
NH_4^+ (mg/l)	4.12 ± 1.21	5.92 ± 1.73	4.54 ± 1.22
NO_2^- (mg/l)	1.72 ± 0.41	9.14 ± 1.12	9.63 ± 1.47
Ca^+ (mg/l)	1358.68 ± 24.96	218.89 ± 27.48	468.86 ± 17.92
K^+ (mg/l)	111.1 ± 10.12	77.42 ± 20.89	104.48 ± 12.03
Na^+ (mg/l)	383.38 ± 21.78	225.34 ± 25.67	274.39 ± 19.12
PO_4^{3-} (mg/l)	6.58 ± 1.75	44.76 ± 3.48	37.57 ± 4.77
Metallic trace elements			
Cd (µg/l)	6.1 ± 0.8	3.4 ± 0.8	4.2 ± 1.2
Cu (µg/l)	89.9 ± 4.9	45.9 ± 6.5	66.9 ± 6.0
Pb (µg/l)	455,7 ± 72,5	131.9 ± 18.0	314.9 ± 42.9
Zn (µg/l)	889.1 ± 36.1	529.9 ± 31.9	797.1 ± 26.9

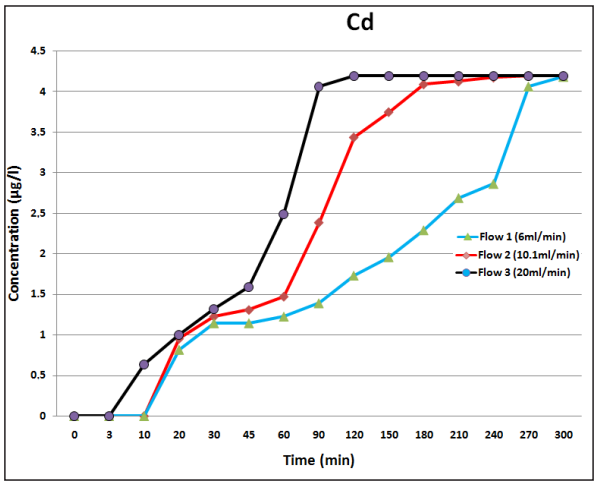

Figure 2. Cd concentration evolution in filtered water over time at three distinct inlet flow rates.

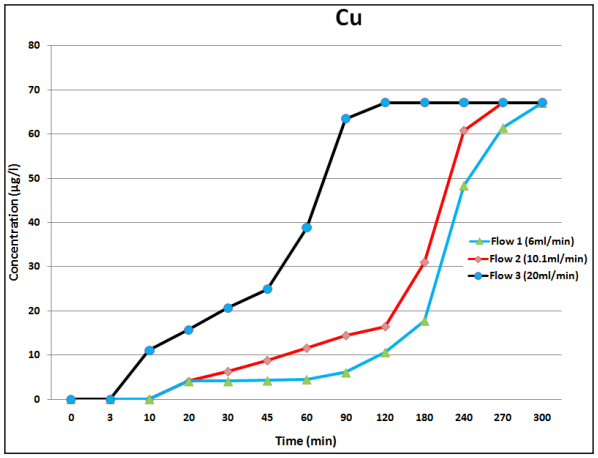

Figure 3. Cu concentration evolution in filtered water over time at three distinct inlet flow rates.

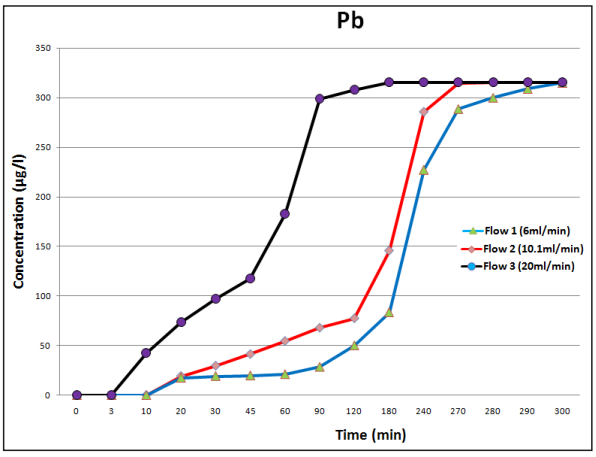

Figure 4. Pb concentration evolution in filtered water over time at three distinct inlet flow rates.

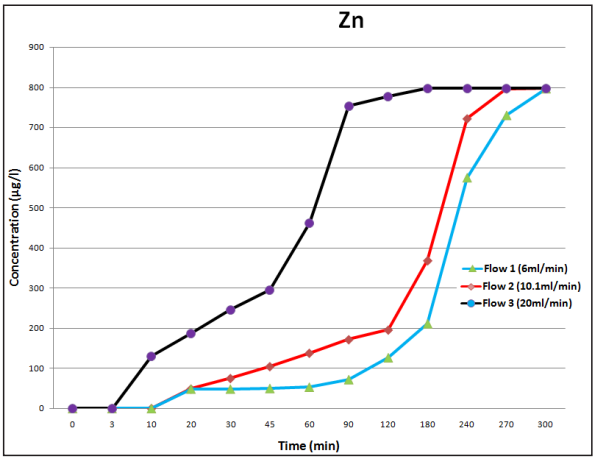

Figure 5. Zn concentration evolution in filtered water over time at three distinct inlet flow rates.

These results indicate a progressive shift in the concentrations of the investigated metallic trace elements in effluents, showing a gradual increase and stabilization toward a maximum equilibrium value (Ω), contingent on the specific

metallic trace element and its initial concentration in the inlet water (Barkouch et al., 2007). Notably, this equilibrium value remains nearly identical to the concentration of the initial water (influent).

Furthermore, the outcomes highlight that the efficiency of the filtration process, designed for water decontamination, is notably influenced by the water inlet flow rate in the filtration columns (Barkouch et al., 2018). Lower water inflow rates demonstrate a more effective removal of metallic pollutants than higher rates. This phenomenon is attributed to the prolonged residence time of metal pollutants in the sand filter due to the resistance imposed by the sand bed, facilitating the establishment of chemical bonds on exposed binding sites. The slow filtration rates result in an extended contact time between the filtered water and the sand filter, progressively enhancing the fixation of metallic pollutants until the saturation of sand binding sites, evident at the end of the filtration process (approximately 300 min).

Results also show that the removal efficiencies for specific metallic trace elements (Cd, Cu, Pb, Zn) were indeed variable, as detailed in Figures 2, 3, 4, and 5. Copper (Cu) demonstrated the highest removal efficiency, followed by cadmium (Cd), lead (Pb), and zinc (Zn). The observed removal efficiencies were dependent on the flow rate through the filtration columns. For instance, at the highest flow rate tested (20 ml/min) at 60 min, Cu removal efficiency was approximately 43.4 %, whereas Cd, Pb, and Zn removal efficiencies were around 40%, 14.3%, and 5%, respectively. As the flow rate decreased, the removal efficiencies for all metals increased, confirming the inverse relationship between flow rate and residence time in the filter bed (Casas and Bester, 2015).

The particulate nature of sand introduces distinctive behaviors, with varying residence times for solutes within different zones of the sand bed. Achieving concentration equilibrium takes considerably longer with lower water flow rates compared to higher rates with greater hydraulic conductivity. This non-equilibrium condition may arise during mass transfer processes, with weak water flow rates leading to preferential interactions between solutes and sand binding sites. As depicted in Figures 2, 3, 4, and 5, the exhaustion of sand particulate beds occurred more rapidly at higher bed water flow rates (Chowdhury et al., 2013), resulting in an earlier breakthrough point. The breakpoint time decreased with increasing water flow rate, indicating insufficient residence time for metallic pollutants to establish bonds with the sand, leading to an early breakthrough. Lower water flow rates produced extended breakthrough curves, signifying the treatment of a higher solution volume, attributed to the slower transport caused by a reduction in diffusion coefficient or mass transfer coefficient (Abdulhusain and Abd Ali, 2023).

4. Modeling of Analytical Results

Modeling is an important tool in designing, scaling up, and optimizing environmental engineering processes such as slow sand filtration (Al-Haj-Ali and Al-Matar, 2024). The process functioning dynamics of slow sand filtration columns with sand as the adsorbent can be conceptualized by analyzing experimental data obtained at the laboratory level. Several mathematical models have been designed to evaluate the efficiency and feasibility of implementing this process on a large scale (Abdiyev et al., 2023). Predicting the column adsorption process in slow sand filtration is crucial for anticipating both the breakthrough curve (concentration-like profile) and the adsorption capacity of sand for metallic trace elements under specific operating conditions (Benjelloun et al., 2021). The anticipated behavior of these columns can be projected using established models like Adams–Bohart, Thomas, and Yoon–Nelson, playing a pivotal role in designing an effective fixed-bed adsorption system with optimal conditions (Barkouch et al., 2019). Notably, these models have yet to integrate the influence of water flow rates into their mathematical expressions for water decontamination. The modeling of the slow sand filtration mechanism is based on its resemblance to compliant processes having a unique logistic model, represented by the following formula:

$$d[M](t)/dt = Q*P*[M](t)*(1 - [M](t)/\Omega)$$ (Barkouch et al., 2019)

In the equation, Q represents the water flow rate, and the constant P incorporates various parameters influencing the transfer of metallic trace elements from contaminated water into the particulate bed (Barkouch et al., 2007). Additionally, Ω signifies the maximum equilibrium value of the effluent achieved at the particulate bed's maximum adsorption capacity.

The MATLAB code employed for Cd is structured as follows:

```
T=300; dt=1; k=0.8; om=4, Q1=0.06; Q2=0.10; Q3=0.20;
t=0:dt:T;
F0=0.1;
[M,N]= size(t);
F=zeros(M,N);
F1(1)=F0;
F2(1)=F0;
for i=1:T-1
F1(i+1)= Q1*P*(1-(F1(i)/om))*F1(i)*dt + F1(i);
F2(i+1)= Q2*P*(1-(F2(i)/om))*F2(i)*dt + F2(i);
F3(i+1)= Q3*P*(1-(F3(i)/om))*F3(i)*dt + F3(i)
end
plot(t, F1,'o-black',t, F2,'R--*',t, F3,'o-b')
```

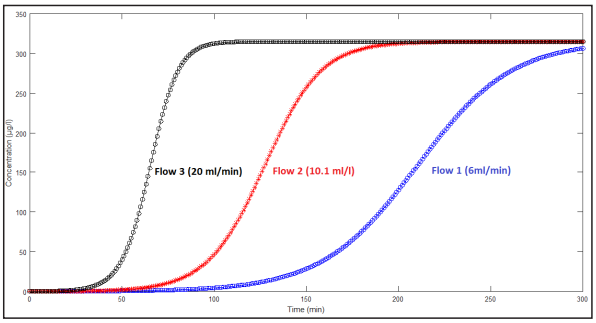

Figure 6. Breakthrough curves of metallic trace elements adsorption under different inlet water flow conditions.

5. Conclusion

This study demonstrates the effectiveness of slow sand filtration in removing metallic trace elements from the Tensift River water, which has been contaminated by wastewater discharge from the Draa Lasfar mine in the Marrakech Region, Morocco. The filtration process showed significantly better performance at lower water inlet flow rates. By decreasing the inlet flow, the residence time of solutes in the filter bed is extended, thereby enhancing contact time and facilitating the formation of chemical bonds between the metallic trace elements and the sand's binding sites. The application of a single logistic model provided a reliable framework for predicting the adsorption behavior within the slow sand filtration process.

While the results underscore the potential of slow sand filtration as an effective method for mitigating heavy metal contamination in water, several factors merit further consideration to enhance the practical application of this technique:

- Optimization of Flow Rates where the flow rate must be balanced with the water demand and filtration capacity.
- Long-term sustainability where the filter adsorption capacity should be monitored. Periodic regeneration or replacement of the sand filter might be necessary to sustain high levels of heavy metal removal over extended periods.
- Integration with other treatment methods to further improve water quality. Slow sand filtration could be integrated with other treatment technologies, such as ion exchange or advanced oxidation processes, to target a broader spectrum of contaminants.

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