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Modeling as a New Tool to Predict Slow sand Filtration Efficiency to Remove Pb from Contaminated Water: Water Velocity Effect

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ABSTRACT

To address water scarcity in the Marrakech region of Morocco, the agricultural reuse of wastewater emerges as a promising solution. Slow sand filtration has gained prominence in wastewater treatment, presenting an effective approach. This study explores the potential of slow sand filtration in removing Pb from contaminated water, specifically from the Tensift River, which receives wastewater directly from the industrial unit of Zn and Pb extraction at the Draa Lasfar mine situated 13 km northwest of Marrakech City. Physicochemical analysis revealed Pb concentrations of 133 ± 16 µg/L upstream and 317 ± 27 µg/L downstream of the mine discharge point. This study incorporates a continuous fixed-bed adsorption study, utilizing sand as an adsorbent for Pb. The impact of three water velocites (0.5, 1, and 2.5 cm/min) on the removal process is investigated, revealing that breakthrough curves are influenced by water velocity. Results showed that the lowest velocity (0.5 cm/min) achieved the best Pb removal, with delayed breakthrough and improved adsorption efficiency. The saturation of the adsorption sites was reached more rapidly at higher velocities (2.5 cm/min). This phenomenon is attributed to slower transport at low velocities, allowing sufficient time for Pb to bond with sand sites. A logistic model was applied to describe the adsorption kinetics, demonstrating good agreement between predicted and experimental breakthrough curves. This model incorporated water velocity (Vi), Pb concentration [Pb](t), and a system-specific constant K, offering a predictive tool for optimizing filtration performance in real conditions.

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INTRODUCTION

Water plays a pivotal role in ensuring nutrition security, agricultural production, and sustainable development, serving as the lifeblood of ecosystems vital for the well-being of present and future generations. However, water resources globally face significant challenges, with contamination from anthropogenic activities, notably mining extraction (Mohsen et al., 2024; El Nwsany et al., 2019). Water pollution has evolved into a global concern, contributing to water scarcity, a pressing challenge for human health and environmental integrity worldwide (Lin et al., 2022; Dalia et al., 2015; Sugashini et al., 2015). Among surface water pollutants, trace metals pose a serious threat due to their toxic nature, persistence and effects when the concentration exceeds the safety limit (Karki et al., 2024; Naz et al., 2023; Tianxin et al., 2016;

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Chowdhury et al., 2013).

Morocco is one of the countries in the world where the sustainability of healthy water sources is threatened, due to short-term climate change scenarios and anthropogenic activities that lead to deterioration of water quality (Alberto et al., 2022; Ahmed et al., 2021). Faced to this critical situation, Morocco has outlined two strategies to meet the growing demand for water due to increasing population pressure. Two strategies are generally adopted: (i) Improving the management of traditional water sources, and (ii) Producing additional unconventional water supplies. Several countries have managed to combine the two strategies, while Morocco is struggling to do so due to several constraints (Ortega-Pozo et al., 2022). In arid areas, the use of unconventional water resources such as water reuse is an alternative solution to ensure water quantity and quality requirements (Karimidastenaei et al., 2022; Yazdandoost et al., 2021; Hussain et al., 2019). To address the escalating demand for water resources, innovative techniques have emerged, including electrochemical methods, ion exchange, and membrane filtration (Li et al., 2016; Nassar and Hajjaj, 2013; Jiménez Madrid et al., 2012). However, this study focuses on the slow sand filtration technique, recognized globally as a cost-effective, operationally simple, and low-maintenance solution for water treatment, particularly in rural communities (Bai et al., 2024; Trikannad et al., 2023; Andreoli and Sabogal-Paz, 2020; Nassar and Hajjaj, 2013). The research aims to investigate the impact of water velocity on the slow sand filtration's efficacy in removing metallic trace elements from Tensift River water, directly receiving wastewater from the Draa Lasfar mine near Marrakech, Morocco.

In addition to water reclamation, this study seeks to develop a predictive model for the slow sand filtration process, integrating the factor of water velocity governing the migration of metallic pollutants. The ultimate goal is to secure the quality and quantity of Tensift River water through comprehensive understanding and effective treatment strategies.

MATERIAL AND METHODS

Zone of study

The rural area of Draa Lasfar is located roughly 10 kilometers west of the city of Marrakech, as illustrated in Figure 1. This region, closely positioned to the Tensift River, encompasses a rural community covering approximately 5790 hectares, with 65% of the area dedicated to farmland.

Draa Lasfar's geological composition primarily comprises deposits of pyrite minerals, initially discovered in 1953, with commercial exploitation commencing in 1979. The mineral underwent processing through flotation post-primary and secondary crushing and grinding, yielding 60 million tons of products in the initial two years (1979 and 1980). Although industrial activity ceased in March 1981, it was reinstated in 1999 due to the abundant polymetallic resources present, including As, Cd, Cu, Fe, Pb, and Zn.

Throughout its exploitation phase, wastewater was indiscriminately discharged into the Tensift River without undergoing any prior treatment.

Water samples were collected directly from the Tensift River, which receives wastewater discharge from the industrial unit extracting Zn and Pb at the Draa Lasfar mine. Sterile 1000-milliliter glass bottles were used for sample collection, each thoroughly rinsed three times with the river water prior to filling. For sampling, a string was attached to the bottle's neck, and an additional sterile string was fastened to ensure the bottle could be safely submerged. Once filled, the bottle was sealed and transported on ice in an insulated container to the laboratory, where it was used for slow sand filtration experiments in laboratory columns.

Slow Sand Filtration experiment

The dynamic adsorption mechanism was studied using three polypropylene plastic columns,

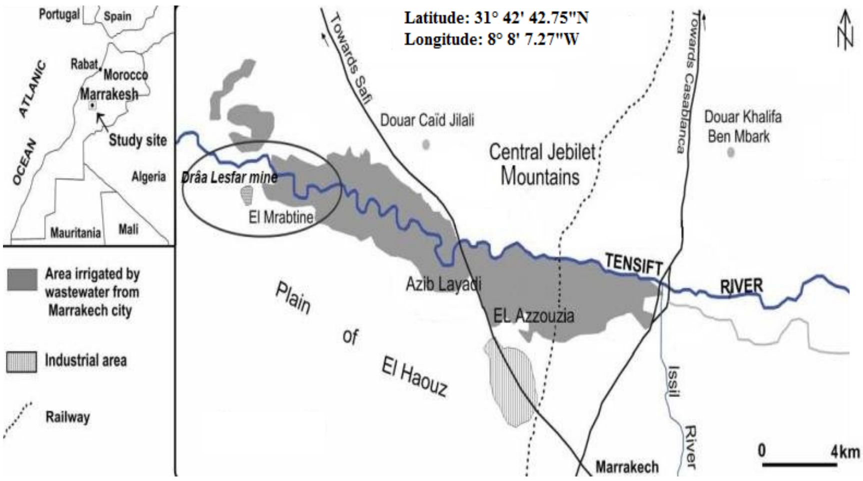

Fig. 1. Geographical location of the Draa Lasfar mine in the Marrakech region (Latitude: 31° 42' 42.75"N, Longitude: 8° 8' 7.27"W).

Table 1. Physicochemical properties of wastewater from the Draa Lasfar mine (W), Tensift River water upstream (B) and downstream (A) of the mine wastewater discharge.

Properties	W	B	A
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
MES 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
PO_4^{3-} mg/l	6,58 ± 1,75	44,76 ± 3,48	37,57 ± 4,77
Ca^+ mg/l	1358,68 ± 24,96	218,89 ± 27,48	468,86 ± 17,92
Na^+ mg/l	384,40 ± 19,78	224,34 ± 24,67	273,39 ± 20,12
K^+ mg/l	109,77 ± 9,78	80,39 ± 19,39	99,48 ± 13.03
Pb µg/l	453 ± 36	133 ± 16	317 ± 27

each 50 cm in height and open at both ends. Untreated water (influent) was introduced through the top opening, while air circulation was maintained via a tube connected to a peristaltic pump. The effluent was discharged through the bottom opening.

To assess the effect of water velocity on the efficiency of slow sand filtration, experiments were conducted by passing polluted water through laboratory columns uniformly filled with sand (H = 10 cm, D = 10 cm). Various water velocities were tested (0.5 cm/min, 1 cm/min, and 2.5 cm/min). Before each experiment, distilled water was circulated through the columns overnight at a flow rate of 20 ml/min (Barkouch et al., 2007), to remove any residual metal elements from the sand (Sugashini et al., 2015).

Filtrated water (effluent) was collected using a test tube connected to the lower opening of the column. The samples were then stored on ice in an insulated container and analyzed within 24 hours of collection.

RESULTS AND DISCUSSION

The mean concentrations of Pb in Draa Lasfar mine wastewater (W), Tensift River water before (B) and after (A) receiving the mine wastewater are shown in table 1.

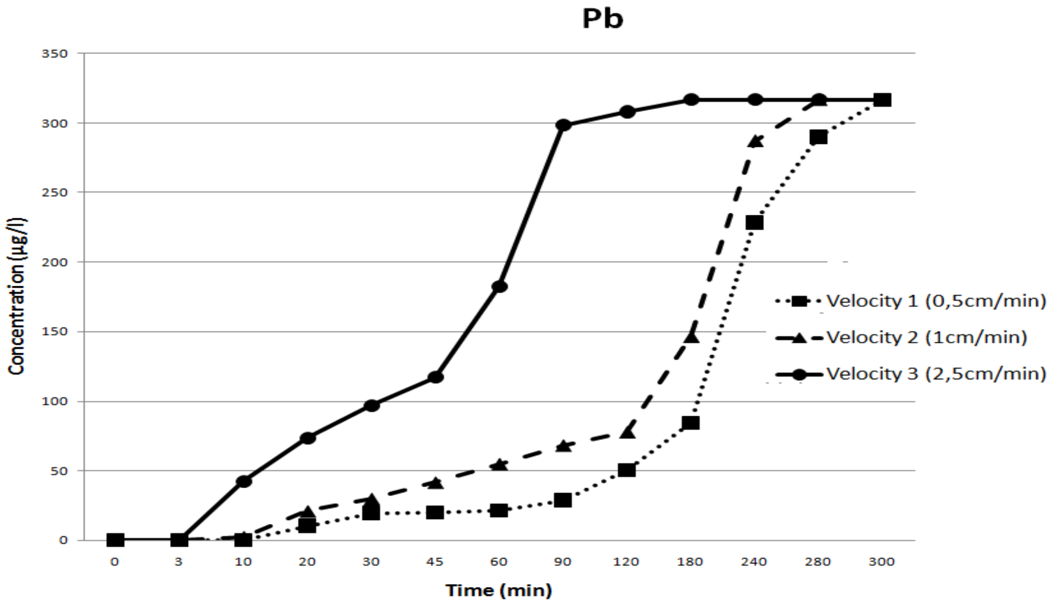

Fig. 2. Variation of Pb concentration in the effluent at different water velocities over the filtration time.

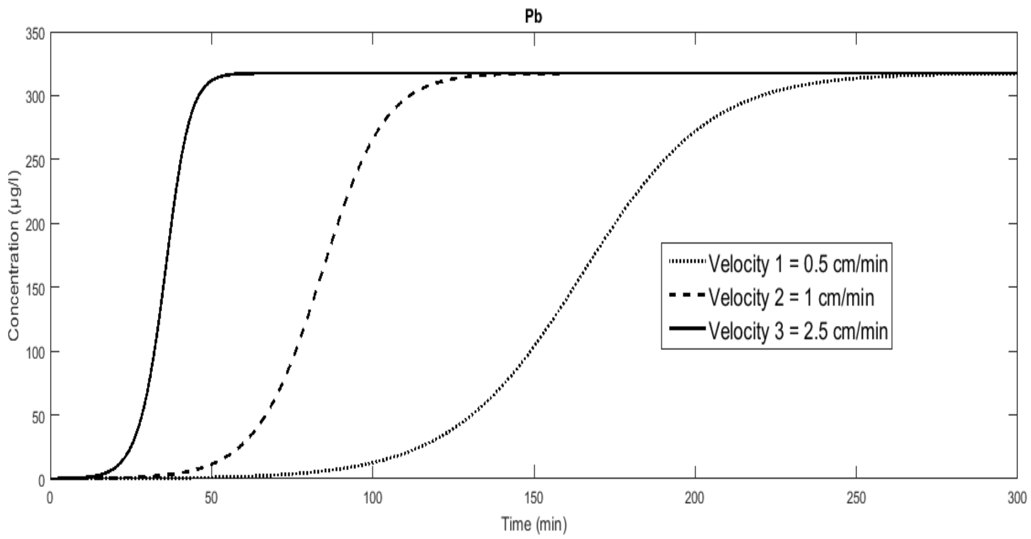

Fig. 3. Breakthrough curves of Pb adsorption at different water velocities

Pb concentrations in recovered solutions (effluent) at different water velocities (0.5 cm/min, 1 cm/min and 2.5 cm/min) are shown in figure 2.

Water velocities: 0.5cm/min (dot), 1cm/min (dash) and 2.5cm/min (solid).

DISCUSSION

Figure 2 illustrates the dynamic variation of Pb concentration at the outlet of the filtration column continuously fed with polluted water from the Tensift River, representing the breakthrough curve (Farrag et al., 2017). The graph describes the continuous fluctuation of Pb concentration in the effluents over the time of the filtration process (Elhaya et al., 2024). This concentration shows a progressive increase to reach a maximum equilibrium value (µ). This equilibrium value remains stable at the end of the filtration and is almost identical to the initial concentration of polluted water (316.7µg/l) used to feed the filtration column at the beginning of this experiment. This observation can be justified by the progressive saturation of the fixation sites of metal pollutants on the sand filter (Abdiyev et al., 2023). Therefore, at the end of the filtration process (300 min), the recovered solution demonstrates similarity with the initial feed water (influent).

Figure 2 also reveals that the breakthrough time increases slightly with a decrease in water velocity. Lower water velocities result in longer breakthrough curves and slower breakthrough occurrences. Conversely, higher water velocities result in steeper breakthrough curve slopes and shorter breakthrough times (Malkoc et al., 2006). This phenomenon is attributed to the impact of lower water velocity in inducing slower transport due to a reduction in the diffusion coefficient or mass transfer coefficient, which allows sufficient time for Pb to settle and bind to the binding sites exposed by the sand (Ahmad and Hameed, 2010). These results highlight that variations in water velocity gradient affect the saturation rate of sand binding sites and breakthrough time, indicating a water velocity-dependent adsorption process in slow sand filtration. The adsorption capacity was expected to increase with decreasing water velocity because higher water velocities create a strong driving force counteracting the adsorption process. Consequently, this weakens the efficiency of the sand filter in establishing chemical bonds with lead and removing it from water (Satyam and Patra, 2024).

Modeling of analytical results

To understand the column adsorption process used in slow sand filtration, it is crucial to predict the breakthrough curve (which reflects the Pb concentration) and assess the adsorption capacity of the sand under specific operating conditions (Chafi et al., 2015). Various mathematical models have been developed to evaluate removal efficiency and the practicality of scaling up this process (Fitriani et al., 2023). Various models, such as the Adams–Bohart, Thomas, and Yoon–Nelson models, play a pivotal role in predicting the dynamic behavior of the adsorption mechanism in slow sand filtration. These models are particularly valuable in designing an efficient fixed-bed adsorption system under optimal conditions (Dalia et al., 2015).

It is noteworthy that these models, despite their significance, do not incorporate the effect of water velocity on water decontamination in their mathematical expressions. The modeling of the slow sand filtration process generally assumes a single logistic model, represented as follows:

d[Pb]/dt = 1/Vi*K*[Pb] (t)*(1 – [Pb](t)/Eq) (Barkouch et al., 2019)

In this equation, V represents water velocity, and the constant K incorporates various parameters influencing the transfer of Pb from polluted water into the slow sand filtration bed (Barkouch et al., 2018). The variable Eq represents the maximum equilibrium concentration in the effluent, indicating the highest adsorption capacity of the filtration bed.

The MATLAB code corresponding to this formulation is as follows:

```
T=300;
dt=1; K=0.1; Eq=317.6, V1=0.5; V2=1; V3=2.5;
t=0:dt:T;
C0=0.1;
[M,N]= size(t);
C=zeros(M,N);
C1(1)=C0;
C2(1)=C0;
C3(1)=C0;
```

```
for i=1:N-1
C1(i+1)= V1*K*(1-(C1(i)/Eq))*C1(i)*dt + C1(i);
C2(i+1)= V2*K*(1-(C2(i)/Eq))*C2(i)*dt + C2(i);
C3(i+1)= V3*K*(1-(C3(i)/Eq))*C3(i)*dt + C3(i);
end
plot(t, C1,'black :',t, C2,'black--',t,C3,'black')
```

CONCLUSION

This study confirmed the potential of slow sand filtration to remove lead (Pb) from contaminated water in the Tensift River, where downstream concentrations reached 317 ± 27 µg/L due to untreated discharges from the Draa Lasfar mine. Experimental results showed that decreasing water velocity significantly improves removal efficiency: at 0.5 cm/min, the delay in breakthrough was the longest, and Pb concentration in the effluent remained below 100 µg/L for over 200 minutes, whereas at 2.5 cm/min, saturation occurred rapidly, with effluent concentrations approaching the influent value. These findings highlight that Pb removal efficiency is inversely correlated with water velocity, due to longer contact time and increased adsorption potential at low flow rates. The proposed logistic model successfully predicted the breakthrough behavior at each tested velocity, validating its suitability as a predictive tool for optimizing slow sand filtration performance. These insights support the application of slow sand filtration, particularly at controlled flow rates, as a practical and cost-effective solution for lead-contaminated water treatment in mining-impacted regions.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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