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# Modeling slow sand filtration for sustainable safe wastewater reuse in agriculture in Draa Sfar mine region (Marrakech, Morocco)

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**ABSTRACT**

Several regions in the world are facing the risk of water scarcity due to arid climatic conditions or resource contamination by metallic pollutants generated by anthropogenic activities. This situation is a significant threat to the agriculture industry. Slow sand filtration has been recognized as an effective and sustainable approach to decontaminating water contaminated by heavy metals. This study aims to present a general modeling approach of slow sand filtration process, with a focus on the removal of heavy metals from contaminated water for irrigation purposes in the Draa Sfar region in Marrakech - Morocco. This article outlines the theoretical basis of the modeling approach, including the kinetics of heavy metal removal and the role of adsorption mechanism of sand in the filtration process. The model considers various parameters: contaminated water (C), adsorbed water (A), diffused water (D) and filtered water (F). The simulation results indicate that slow sand filtration can achieve a high degree of heavy metal removal. The model can also predict the breakthrough point, which can be used to optimize the filter design and operation. The findings of this study suggest that slow sand filtration can be an effective and sustainable approach for decontaminating water contaminated by heavy metals in the Draa Sfar mine region, providing safe irrigation water for agriculture.

*Keywords:* Slow sand filtration; Wastewater reuse; Heavy metals; Modeling; Decontamination; Irrigation

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## 1. Introduction

Water is a fundamental resource for human survival and an essential requirement for animals and plants [1], but it is not always available in the quality and quantity required for various purposes, such as irrigation. The availability of clean water for agricultural purposes is crucial for sustainable development, particularly in regions where water scarcity is a significant challenge [1,2]. One such region is the Draa Sfar mine area, where heavy metal contamination of water poses a severe threat to the ecosystem and human health [3,4].

Heavy metals are naturally occurring elements that are essential in small quantities for many biological processes, but they can be toxic at high concentrations [5–7]. Mining activities in the Draa Sfar region have contributed to an increase in heavy metal concentrations in the water [8], making it unsuitable for agricultural use. Therefore, the decontamination of water is a pressing issue in this region.

One of the most effective and affordable methods of water treatment is slow sand filtration [9–11]. Slow sand filtration is a natural water treatment process that involves the use of a sand bed to remove impurities from the water [12,13]. The sand bed acts as a biological filter, which plays not only a crucial role in breaking down organic matter and removing pathogens microorganisms and heavy metals from the water [9,14] but also for improving the quality of wastewater before being discharged into the environment or reused [15,16].

Modeling the slow sand filtration process is essential for understanding the mechanism of removal of heavy metals and optimizing the performance of the filtration system [11,17]. A comprehensive model of the slow sand filtration process can aid in the design and operation of efficient filtration systems for the decontamination of water contaminated with heavy metals.

The aim of this scientific article is to present a general modeling approach to the slow sand filtration process, with a focus on the removal of heavy metals from contaminated water for irrigation in the Draa Sfar mine region. The article will outline the theoretical basis of the modeling approach, including the kinetics of heavy metal removal and the role of adsorption mechanism of sand in the filtration process.

The results of the modeling study will provide valuable insights into the performance of slow sand filtration systems for heavy metal removal from contaminated water, and contribute to the development of sustainable water treatment strategies in the Draa Sfar mine region. The article will also discuss the potential applications of the modeling approach in other regions facing similar challenges of heavy metal contamination in water resources.

## 2. Material and methods

The rural area of Draa Sfar is situated approximately 13 km west of the city of Marrakech - Morocco (Fig. 1). It is situated just a few hundred meters from the Tensift River, and is home to a rural community covering approximately 7,200 ha, of which 65% is dedicated to farmland. The region contains a pyrite mineral deposit that was discovered in 1953, but commercial mining did not begin until 1979 [3,18]. The mineral was processed using flotation after primary and secondary crushing and grinding, resulting in the production of 60 million metric tons of products during the first 2-y of operation (1979 and 1980). Although industrial activity ceased in March 1981, it resumed in 1999 due to the area's abundant polymetallic components, including As, Cd, Cu, Fe, Pb, and Zn. Throughout its operation, untreated wastewater from the mine was discharged directly into the Tensift River [18].

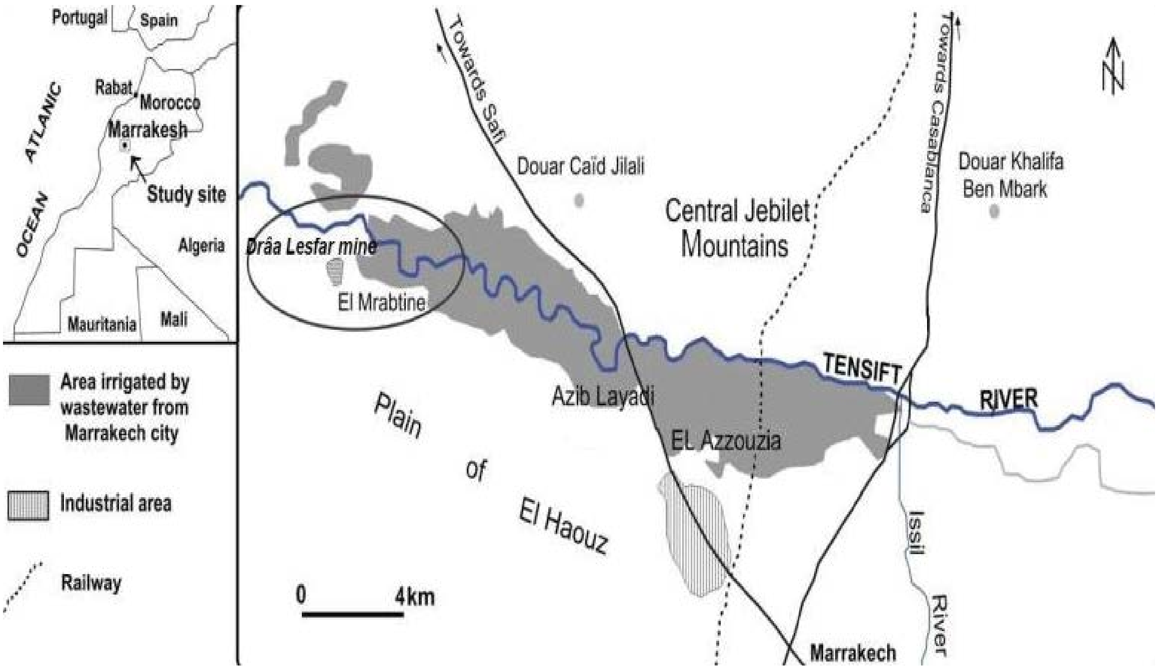


Fig. 1. Tensift River and Draa Sfar mine geographic situations in Marrakech region.

Water samples were collected from the Tensift River, which had mixed with wastewater from the industrial unit of Zn and Pb extraction of the Draa Sfar mine. Sterile plastic bottles with a capacity of 2,000 mL were used to collect the samples, after the bottles were rinsed three times with sample water. To collect the samples from the river, a bottle with a string attached to its neck was used, and then the bottle was raised and stopped. The collected samples were transported to the laboratory in an insulated container with ice and used to conduct the slow sand filtration study in the laboratory's columns.

The study on the dynamic behavior of the adsorption mechanism was carried out through a slow sand filtration experiment using three polypropylene plastic columns, each with a height of 50 cm and open at both ends. The top opening of the columns allowed for the inflow of contaminated water via a tube from a peristaltic pump, and also enabled air circulation, while the bottom opening served as an outlet for the effluent (filtered water). The decontamination efficiency of the slow sand filtration process was studied by percolating untreated water through the laboratory columns with the same sand filling height $H$ = 10 cm [13,19–22], and the same diameter $D$ = 10 cm [13,16,22,23]. Prior to each experiment, distilled water was poured continuously through the columns overnight at a flow rate of 20 mL/min to eliminate any residual metal elements present in the sand. The filtered water (effluent) was collected in a test tube connected to the hole in the lower cap and stored in an insulated container with ice for analysis within 24 h of collection.

## 3. Results and discussion

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

Table 2 displays the physico-chemical characteristics and the average levels of Cd, Cu, Pb, and Zn present in the Draa Sfar mine wastewater, in the Tensift River water prior to (WB) and subsequent to (WA) the influx of the mine wastewater.

Fig. 2 presents breakthrough curves ($C_t/C_0 \sim t$) of Cd, Cu, Pb, and Zn in the treated solutions (effluent) subsequent to filtration.

The mean concentration of heavy metals (Cd, Cu, Pb, and Zn) in treated solutions subsequent to slow sand filtration is a critical indicator of the efficiency of the filtration process in removing these pollutants from water. The study results showed that slow sand filtration was an effective method for removing heavy metals from the water. In the first steps of the filtration (first 30 min), the mean concentrations of heavy metals (Cd, Cu, Pb, and Zn) in the treated solutions were significantly lower than those in the raw water samples. The removal efficiency of heavy metals varied between 83% for Cu and Zn, 82% for Cd and 79% for Pb, depending on the metal species. The highest removal efficiency was observed for Cu and Zn, followed by Cd and Pb.

The variation in removal efficiency can be attributed to the different physico-chemical properties of the heavy metals, such as ionic charge, molecular weight, and solubility. It can be influenced by factors such as contact time, temperature, and initial concentration of heavy metals [24,25]. The results also showed that the mean concentrations of heavy metals in the treated solutions increased within the time of the sand filter filtration. Removal efficiency decreased as filtration time increased, indicating that the longer contact time between the water and the sand filter bed contributes to a saturation of heavy metal binding sites on the sand thus decreasing pollutant removal efficiency [19].

In recent years, the application of mathematical modeling and simulation techniques has emerged as a powerful tool for studying and optimizing SSF performance. Mathematical models provide insights into the underlying mechanisms of SSF, allowing for a deeper understanding of the process dynamics and the effects of various operational parameters. Additionally, modeling can help in predicting and optimizing the performance of SSF under different conditions, and can also aid in the design and scale-up of SSF systems for different applications.

The parameterization of the slow sand filtration process and the specialization of experimental data are of

Table 1
Results of the particle size analysis of the used sand

| Sieve size (mm) | Retained weight (g) | % of retained weight | % of cumulative weight |
|---|---|---|---|
| 0.3 | 340 | 17.0 | 17.0 |
| 0.15 | 1,365 | 68.25 | 85.25 |
| 0.09 | 226 | 11.3 | 96.55 |
| 0.075 | 28.9 | 1.44 | 97.99 |
| 0.001 | 40.1 | 2.01 | 100 |

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

| Parameters | MW | WB | WA |
|---|---|---|---|
| pH | 6.8 ± 0.3 | 7.0 ± 0.5 | 7.0 ± 0.6 |
| $O_2$ (mg/L) | 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) | 4.0 ± 1.0 | 4.7 ± 0.8 | 4.4 ± 0.6 |
| MES (mg/L) | 78.3 ± 1.6 | 56.7 ± 2.6 | 57.8 ± 4.5 |
| $SO_4^{2-}$ (mg/L) | 192.2 ± 6.4 | 100.7 ± 5.7 | 123.7 ± 8.4 |
| $Cl^-$ (mg/L) | 2,356 ± 24.5 | 80.7 ± 12.8 | 1,819 ± 13.1 |
| $NH_4^+$ (mg/L) | 4.1 ± 1.2 | 5.9 ± 1.7 | 4.5 ± 1.2 |
| $NO_2^-$ (mg/L) | 1.7 ± 0.4 | 9.1 ± 1.1 | 9.6 ± 1.5 |
| $PO_4^{3-}$ (mg/L) | 6.6 ± 1.8 | 44.8 ± 3.5 | 37.6 ± 4.8 |
| $Ca^+$ (mg/L) | 1,358.7 ± 25.0 | 219.0 ± 27.5 | 468.9 ± 17.9 |
| $Mg^{2+}$ (mg/L) | 385.0 ± 26.7 | 136.0 ± 13.7 | 224.0 ± 16.5 |
| $Na^+$ (mg/L) | 383.4 ± 21.8 | 225.3 ± 25.7 | 274.4 ± 19.1 |
| $K^+$ (mg/L) | 110.8 ± 10.8 | 77.4 ± 21.4 | 104.5 ± 12.0 |
| Heavy metals | | | |
| Cd (µg/L) | 6.2 ± 0.9 | 3.2 ± 0.7 | 4.2 ± 1.1 |
| Cu (µg/L) | 90.4 ± 5.4 | 46.7 ± 6.7 | 65.5 ± 5.9 |
| Pb (µg/L) | 454.9 ± 86.3 | 132.1 ± 17.8 | 307.9 ± 45.5 |
| Zn (µg/L) | 887.8 ± 35.8 | 530.7 ± 32.7 | 778.0 ± 27.8 |

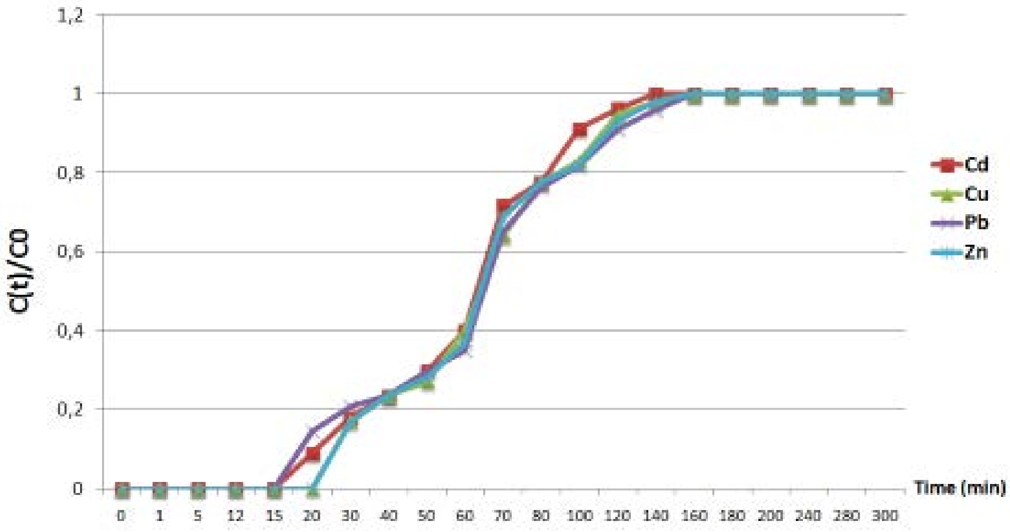


Fig. 2. Breakthrough curves ($C_t/C_0 \sim t$) of Cd, Cu, Pb, and Zn.

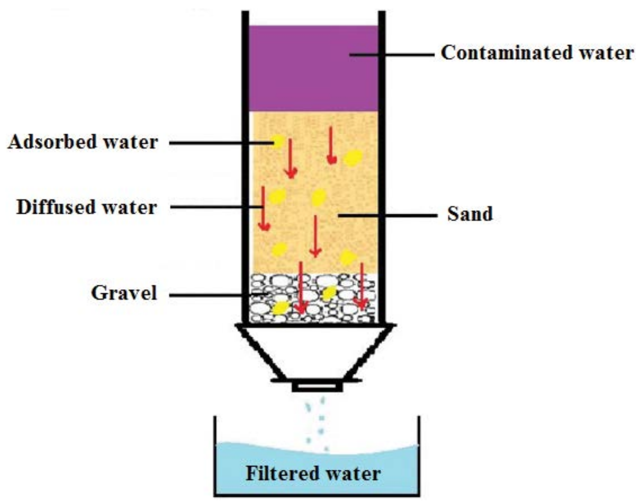


Fig. 3. Components of slow sand filtration process model.

paramount importance in the numerical modeling of this technique in order to properly understand its efficiency in mobilizing contaminants in water.

The model of slow sand filtration developed in this study is based on the principles of mass balance and fluid dynamics. The model consists of a set of differential equations that describe the transport of contaminants through the sand bed. The model assumes that the sand bed is homogeneous and that contaminants are uniformly distributed throughout the sand bed. The model also assumes that contaminants are in equilibrium with the water and that the transport of contaminants through the sand bed is primarily facilitated between four constituent fractions of the entire filtration process, which represent the four components of our model: contaminated water (C), adsorbed water (A), diffused water (D) and filtered water (F) (Fig. 3).

Contaminated water (C) infiltrates into the sand filter and will be divided into two fractions: the adsorbed fraction (A) and the diffused fraction (D). The latter will continue to diffuse until obtaining filtered water (F).

The conceptual model developed will take into account the four water fractions involved in the filtration process, namely: contaminated fraction, adsorbed fraction, diffused fraction, and filtered fraction.

The following diagram provides a comprehensive illustration of the water filtration process based on these four fractions (Fig. 4).

With $K_A$ is the adsorption constant and $K_D$ is the diffusion constant. Both constants are specific to each trace metal element and also depend on the nature of the sand composition.

By using the previous conceptual model, a system of reactions can be defined and can enable the creation of the mathematical model. The reactions formulated through this conceptual model:

$$C \times K_A \rightarrow A + D \tag{1}$$

$$D \times K_D \rightarrow F \tag{2}$$

Using the previously developed reaction system, a system of mathematical equations can be created to predict the evolution of the concentration of each metal species or fraction during the filtration process. The following system of mathematical equations can be formulated:

$$\begin{cases} \dfrac{dC(t)}{dt} = -K_A \times C(t) \\ \dfrac{dA(t)}{dt} = -K_A \times C(t) \\ \dfrac{dD(t)}{dt} = -K_A \times C(t) - K_D \times D(t) \\ \dfrac{dF(t)}{dt} = K_D \times D(t) \end{cases} \tag{3}$$

The last expression in the system of mathematical equations represents the evolution of the concentration of heavy metals recovered after filtration. This expression was established by (Barkouch et al. [13]):

$$\frac{d\mathrm{FW}(t)}{dt} = K \times \mathrm{FW}(t) \times \left(1 - \frac{\mathrm{FW}(t)}{\mu}\right) \tag{4}$$

According to Barkouch et al. [13], $K$ is an expression that takes into account various parameters that influence the transfer of heavy metals from contaminated water into the particulate bed. μ, on the other hand, represents the maximum equilibrium concentration value of the effluent reached at the particulate bed's maximum adsorption capacity. Therefore, the final expression of the mathematical model for the slow sand filtration process becomes (Fig. 5):

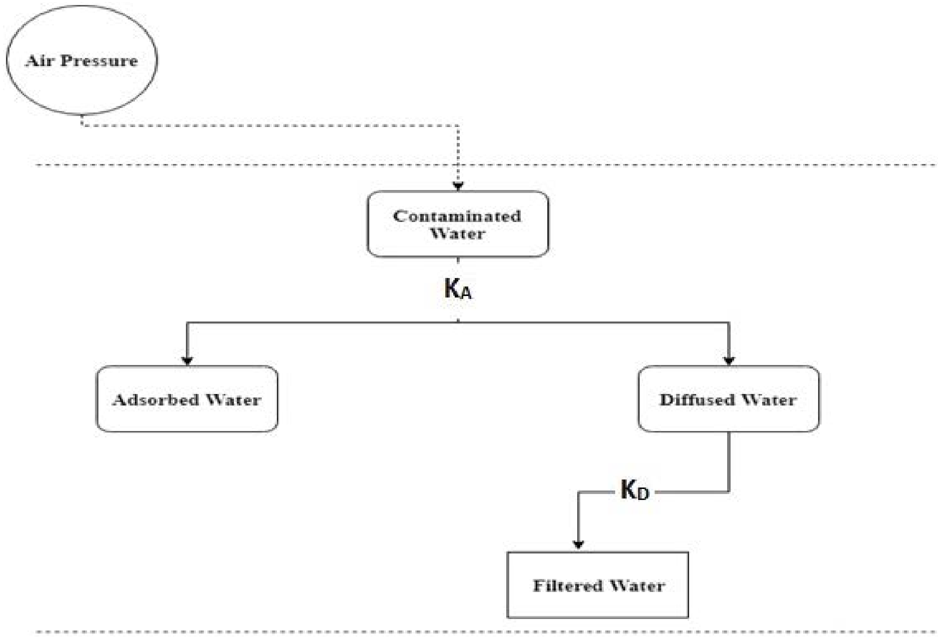


Fig. 4. Conceptual model of the slow sand filtration process.

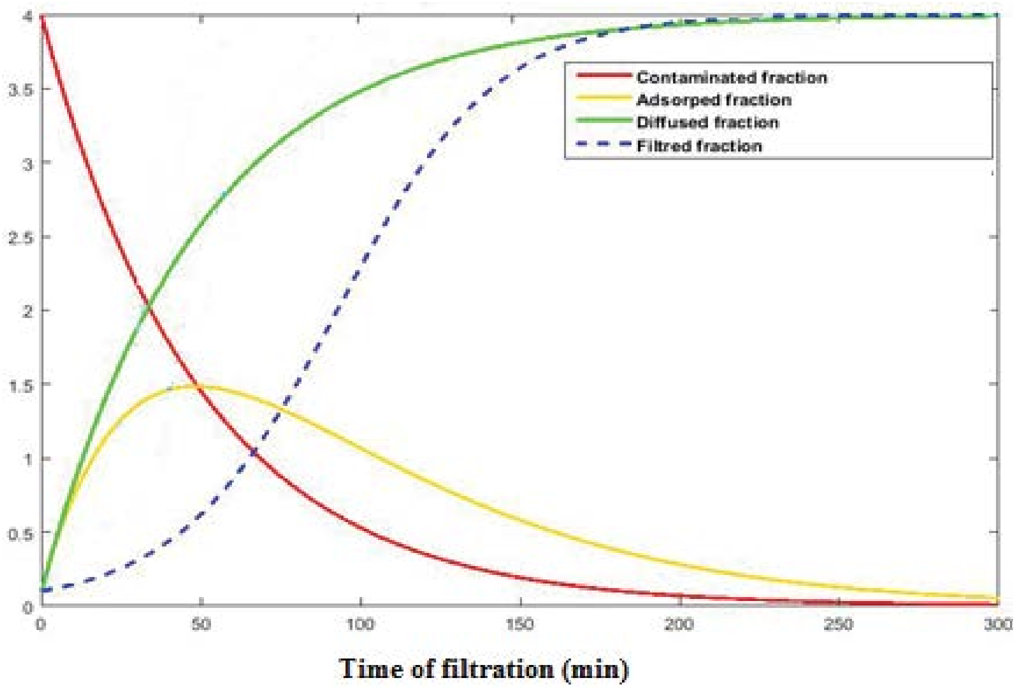


Fig. 5. Simulation of the mathematical model of the slow sand filtration process.

$$\begin{cases} \dfrac{dC(t)}{dt} = -K_A \times C(t) \\ \dfrac{dA(t)}{dt} = -K_A \times C(t) \\ \dfrac{dD(t)}{dt} = -K_A \times C(t) - K_D \times D(t) \\ \dfrac{d\mathrm{FW}(t)}{dt} = K \times \mathrm{FW}(t) \times \left(1 - \dfrac{\mathrm{FW}(t)}{\mu}\right) \end{cases} \tag{5}$$

The code used on MATLAB has the following form:
-For Cd:

***Given parameters for absorption model***

$T$ = 300;
$dt$ = 1; $K_A$ = 0.02; $K_D$ = 0.0195; $mu$ = 4;
$t$ = 0:$dt$:$T$; %Definition of time grid

***Initial concentrations***

$C_0$ = 4;
$A_0$ = 0.1;
$D_0$ = 0.1;
$F_0$ = 0.1;
[$M$,$N$] = size($t$);

***Memory allocation for concentration vectors***

$C$ = zeros($M$,$N$);
$A$ = zeros($M$,$N$);
$D$ = zeros($M$,$N$);
$F$ = zeros($M$,$N$);

***Initialization***

$C$(1) = $C_0$;
$A$(1) = $A_0$;
$D$(1) = $D_0$;
$F$(1) = $F_0$;

***Explicit Euler method***

for $i$ = 1:$N$ – 1;
$C(i + 1) = –K_A \times C(i) \times dt + C(i)$;
$A(i + 1) = K_A \times C(i) \times dt + C(i)$;
$D(i + 1) = K_A \times C(i) \times dt + C(i) – K_D \times D(i) \times dt + D(i)$;
$F(i + 1) = k \times (1 – (F(i)/mu)) \times F(i) \times dt + F(i)$;
end

***Solution visualization***

plot ($t$, $C$, $t$, $A$, $t$, $D$, $t$, $F$, ‘$B$--‘);

## 4. Conclusion

The slow sand filtration process has proven to be a valuable tool for the decontamination of water used for irrigation purposes in the Draa Sfar rural region. The results of this study indicate that slow sand filtration can effectively remove metallic contaminants from water, making it a sustainable and cost-effective option for the treatment of water for irrigation. The mathematical model developed in this study has provided a comprehensive understanding of the various parameters that affect the filtration process, and has enabled to optimize the design and operation of slow sand filters. The findings from this research can contribute to the development of more efficient and sustainable SSF systems for providing safe drinking water, particularly for communities facing water contamination challenges, and can pave the way for further research and advancements in the field of water treatment.

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