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RESEARCH ARTICLE

Transport Phenomena and Numerical Modeling of Fluid Loss in Porous Media: A Case Study of Canal Systems for Environmental Process Optimization

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ABSTRACT

This study presents a chemical engineering-based analysis of transport phenomena in porous media, focusing on the coupled mechanisms of fluid flow and solute migration within an unlined canal system. The work is framed within environmental chemical engineering, where seepage is interpreted not only as a hydraulic loss but also as a transport-driven mechanism governing solute migration, adsorption, and process inefficiency. A combined experimental – numerical approach is employed to characterize porous media properties and simulate transport behavior using finite element modeling (FEM). The governing equations incorporate advection, diffusion, and reaction terms to describe coupled flow and reactive transport processes. Key parameters, including permeability, porosity, and adsorption characteristics of clay-rich soils, are evaluated to quantify both fluid flux and solute transport under varying hydraulic conditions. Results indicate that under low hydraulic gradients, both fluid and solute transport are negligible, whereas high-gradient conditions significantly enhance convective mass transfer and promote contaminant migration. Spatial analysis reveals localized transport "hotspots," analogous to channeling effects in chemical reactors, leading to non-uniform system efficiency. The findings demonstrate that porous media systems can be effectively modeled as distributed chemical transport reactors, where fluid loss and solute migration are governed by coupled physicochemical interactions. This study provides a novel framework for integrating transport phenomena and process optimization principles in environmental systems, offering strategies for minimizing losses and improving system efficiency through material and operational modifications.

Keywords: Reactive transport; Environmental chemical engineering; Porous media; Mass transfer; Adsorption; Finite element modeling; Process optimization

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1. Introduction

Transport phenomena in porous media constitute a fundamental aspect of chemical engineering, governing a wide range of processes involving fluid flow, heat transfer, and mass transport in heterogeneous systems. These processes are particularly critical in environmental chemical engineering applications, where the movement of fluids through natural or engineered porous structures is often coupled with solute migration, adsorption, and chemical transformation[1-3]. Systems such as packed-bed reactors, adsorption columns, filtration units, and subsurface remediation technologies all rely on an in-depth understanding of the interplay between hydrodynamic transport and physicochemical interactions within porous media. In this context, the analysis of fluid flow and associated mass transfer mechanisms provides essential insights into process efficiency, resource utilization, and environmental sustainability.

In conventional hydraulic engineering, seepage from open-channel systems such as irrigation canals is typically treated as a purely physical phenomenon governed by pressure gradients and soil permeability [4-6]. However, from a chemical engineering perspective, such systems can be more comprehensively interpreted as open transport reactors with distributed mass transfer across permeable boundaries. In these systems, fluid flow is not only responsible for volumetric losses but also serves as a carrier for dissolved species, enabling the migration of solutes into surrounding porous media. This coupling of fluid flow and solute transport introduces additional complexity, as the porous matrix may actively interact with transported species through adsorption, ion exchange, and other surface-mediated processes [7-9].

Porous media, particularly those rich in clay minerals, exhibit significant physicochemical heterogeneity that influences transport behavior at multiple scales. Clay particles possess high specific surface areas and carry surface charges that promote electrostatic interactions with dissolved ions and polar molecules [10-12]. These interactions can result in adsorption or retardation of solutes, effectively altering their transport velocity relative to the bulk fluid flow. Consequently, the migration of contaminants or dissolved constituents in such media cannot be accurately described by hydraulic considerations alone. Instead, it requires a coupled transport framework that integrates advection, diffusion, and reaction mechanisms. This approach is well established in chemical engineering, where similar principles are applied to describe transport-reaction systems in catalytic reactors and separation processes.

The concept of reactive transport provides a powerful theoretical and computational framework for analyzing such coupled processes. In reactive transport systems, the spatial and temporal evolution of solute concentration is governed by the combined effects of convective transport (advection), molecular diffusion, and chemical interactions, which may include adsorption, precipitation, or transformation reactions [13-15]. The relative contributions of these mechanisms are determined by system properties such as flow velocity, porosity, permeability, and the chemical characteristics of both the fluid and the solid matrix. In environmental systems, reactive transport modeling has been widely applied to study groundwater contamination, nutrient transport, and pollutant attenuation. Extending this framework to open-channel seepage systems offers a novel perspective for evaluating both fluid loss and solute migration in a unified manner.

From a process engineering standpoint, unlined canal systems can be conceptualized as continuous flow units with inherent inefficiencies arising from uncontrolled mass transfer into surrounding media. This perspective enables the application of chemical engineering principles such as mass transfer resistance, driving force analysis, and process optimization. The hydraulic gradient acting across the canal boundary serves as the driving force for both fluid flow and solute transport, while the porous medium provides resistance through its permeability and adsorption capacity [16-18]. This analogy is particularly useful for identifying conditions under which the system operates efficiently or suffers from significant losses. For example, under low hydraulic gradients, the driving force for transport is minimal, resulting in negligible fluid and solute migration. In contrast, high hydraulic loading conditions can induce substantial convective transport, leading to increased losses and reduced system efficiency.

Material properties of the porous medium play a crucial role in determining transport behavior. Parameters such as permeability and porosity govern the ease with which fluid can move through the medium, while adsorption characteristics influence the retention and mobility of solutes. In clay-rich soils, low permeability tends to restrict fluid flow, but high adsorption capacity can significantly retard solute migration, creating a complex interaction between hydraulic and chemical effects. This dual influence highlights the importance of considering both physical and chemical properties in the design and optimization of environmental systems. Modifying these properties through engineering interventions, such as canal lining or chemical stabilization of soils, can effectively reduce mass transfer losses and improve overall system performance.

Advancements in computational modeling have greatly enhanced the ability to analyze transport phenomena in complex porous systems. Finite element methods (FEM), in particular, provide a flexible and robust framework for solving coupled partial differential equations governing fluid flow and solute transport under realistic boundary conditions. These methods allow for detailed spatial resolution of key variables, including hydraulic potential, velocity fields, concentration distributions, and reaction rates. In chemical engineering, similar numerical approaches are routinely used for reactor design, process optimization, and scale-up studies [19-21]. Applying these techniques to environmental transport systems enables a more comprehensive understanding of the underlying mechanisms and supports the development of effective mitigation strategies.

Despite the extensive body of research on seepage and groundwater flow, most existing studies remain rooted in hydraulic or geotechnical perspectives, with limited integration of chemical engineering transport principles. In particular, the role of reactive transport and adsorption in influencing seepage behavior has not been sufficiently explored in the context of open-channel systems. This gap represents an opportunity to extend established chemical engineering methodologies to environmental applications, thereby providing a more holistic framework for analyzing and optimizing such systems.

The present study addresses this gap by developing a coupled experimental–numerical approach to investigate fluid flow and solute transport in a porous medium system representative of an unlined canal. By integrating Darcy-based flow modeling with advection–diffusion–reaction equations, the study captures the combined effects of hydraulic driving forces and physicochemical interactions. The objective is to quantify transport-driven losses, identify spatial variations in transport intensity, and evaluate the influence of material properties and operational conditions on system performance.

Through this approach, the study aims to demonstrate that environmental fluid systems can be effectively analyzed using chemical engineering transport frameworks, enabling the application of concepts such as reactor analogies, mass transfer optimization, and material design. The insights gained from this work are expected to contribute to improved strategies for water resource management, contaminant control, and sustainable process design in porous media systems.

2. Materials and methods

The present study employs an integrated experimental–numerical framework grounded in chemical engineering transport phenomena to investigate coupled fluid flow and reactive solute transport in a porous medium system analogous to an unlined canal. The porous medium selected for the study is a clay-rich soil collected from a semi-arid irrigation region, chosen for its relevance to environmental chemical engineering applications due to its low permeability and high adsorption potential. The collected soil samples were air-dried, pulverized, and sieved to ensure uniformity before characterization. The physicochemical properties of the soil, including particle size distribution, bulk density, porosity, and mineralogical composition, were determined using standard laboratory protocols. Particle size distribution was obtained through combined sieve and hydrometer analysis, while bulk density was measured using the core cutter method. Porosity was subsequently calculated based on bulk density and specific gravity values. The presence of clay minerals and their surface characteristics, which significantly influence adsorption behavior, were qualitatively assessed to support the development of the reactive transport model.

Hydraulic characterization of the porous medium was carried out using a constant head permeameter under fully saturated conditions to determine hydraulic conductivity. The experimental setup consisted of a cylindrical soil column connected to a constant water supply system that maintained steady-state flow under controlled hydraulic gradients. The volumetric flow rate was measured over time, and permeability was evaluated using Darcy’s law. To incorporate chemical interactions into the system, adsorption studies were conducted using a batch equilibrium approach. A known mass of soil was mixed with aqueous solutions of a representative solute at varying initial concentrations under controlled pH and temperature conditions. After equilibrium was reached, the residual solute concentration in the solution was measured using spectrophotometric analysis. The adsorption capacity of the soil was quantified in terms of the distribution coefficient (KdK_dKd), calculated using mass balance relationships. This parameter is critical for describing the retardation of solute transport due to interaction with the solid matrix. The overall methodology adopted in this study is illustrated in Figure 1.

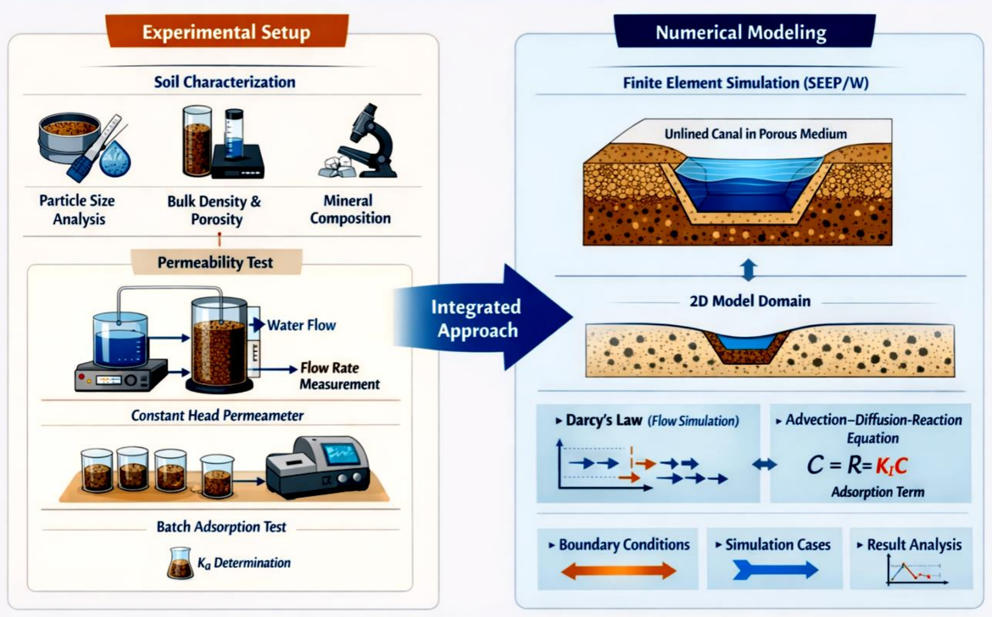

Figure 1. Schematic representation of the integrated experimental–numerical methodology adopted in this study.

The numerical modeling component was implemented using the finite element-based SEEP/W module of the GeoStudio software suite, with conceptual extension to include reactive transport mechanisms. The physical domain was represented as a two-dimensional section of a trapezoidal canal embedded within a homogeneous porous medium. The domain was discretized using a refined finite element mesh comprising triangular and quadrilateral elements, with higher mesh density near the canal boundaries to capture steep gradients in hydraulic head and solute concentration. Fluid flow within the porous medium was governed by Darcy's law, while solute transport was described using the advection–diffusion–reaction equation. The velocity field obtained from the hydraulic simulation was used to drive solute transport, thereby ensuring coupling between flow and mass transfer processes. Adsorption was incorporated into the model using a linear isotherm based on the experimentally determined KdK_dKd, and the corresponding retardation factor was applied to account for delayed solute migration relative to the bulk fluid flow.

Appropriate boundary and initial conditions were defined to simulate realistic canal operation scenarios. A constant hydraulic head boundary condition was imposed along the canal surface to represent continuous water flow, while no-flow boundary conditions were assigned to the lateral and bottom boundaries of the domain. For solute transport, an initial concentration was specified within the canal region, and zero-gradient boundary conditions were applied at the far-field boundaries to simulate an open system. Two operational conditions were analyzed, corresponding to low and high hydraulic gradients, to evaluate the influence of driving force on seepage and solute migration. Model validation was performed through comparison with analytical solutions and experimental permeability data, ensuring the reliability of the simulation results. The integrated methodology enables a comprehensive assessment of coupled transport phenomena, providing critical insights into the interaction between hydraulic behavior and chemical processes in porous media systems.

3. Results

The integrated experimental − numerical analysis reveals that fluid flow and solute transport in the porous medium system are strongly governed by the interplay between hydraulic driving forces and physicochemical interactions within the soil matrix, thereby reinforcing the applicability of a chemical engineering transport framework to such environmental systems. The hydraulic characterization results indicate that the clay-rich soil exhibits low permeability, consistent with its fine particle size distribution and high porosity, which collectively contribute to significant resistance against fluid flow. Under low hydraulic gradient conditions, the simulated velocity field shows minimal seepage flux across the canal boundary, with flow predominantly confined to regions immediately adjacent to the wetted surface. This behavior is attributed to the limited pressure gradient, which reduces the driving force for advective transport. Consequently, both fluid loss and solute migration remain negligible, suggesting that the system operates in a diffusion-dominated regime with minimal convective contribution. In contrast, under high hydraulic gradient conditions, a substantial increase in seepage velocity is observed, resulting in deeper penetration of flow lines into the porous medium. The transition from diffusion-dominated to advection-dominated transport is clearly evident, with the hydraulic gradient acting as the primary control parameter for mass transfer intensity. As shown in Table 1, an increase in hydraulic gradient significantly enhances seepage velocity, while the retardation factor remains constant due to inherent material properties.

Table 1. Summary of hydraulic and transport parameters used in the simulation under low and high hydraulic gradient conditions.

Parameter	**Symbol**	**Low Gradient**	**High Gradient**	**Unit**	**Significance**
Hydraulic Gradient	(i)	0.02	0.10	–	Driving force for flow
Hydraulic Conductivity	(K)	1.5 × 10^{-5}	m/s	Governs permeability	
Average Seepage Velocity	(v)	2.1 × 10^{-6}	1.2 × 10^{-5}	m/s	Fluid transport rate
Effective Porosity	(n)	0.38	–	Storage and flow capacity	
Dispersion Coefficient	(D)	1.2 × 10^{-9}	3.8 × 10^{-9}	m^2/s	Solute spreading
Retardation Factor	(R_f)	3.5	–	Adsorption influence	

The solute transport analysis further highlights the critical role of adsorption in modifying transport behavior. The experimentally determined distribution coefficient (KdK_dKd) indicates a strong affinity between the solute and the clay matrix, leading to significant retardation of solute movement relative to the bulk fluid flow. This effect is quantitatively captured in the numerical model through the retardation factor, which effectively reduces the advective velocity of the solute phase. As a result, even under high flow conditions, the spatial extent of solute migration is considerably less than that of the fluid front. The concentration contours obtained from the simulation demonstrate a pronounced attenuation of solute concentration with increasing distance from the canal boundary, indicating that adsorption acts as a dominant sink mechanism within the porous medium. This behavior is analogous to mass transfer with surface reaction in packed-bed reactors, where the solid phase actively participates in the transport process by removing solute from the fluid phase. As indicated in Table 2, higher hydraulic gradients result in increased seepage losses and deeper fluid penetration, while solute migration remains comparatively limited due to adsorption-induced retardation.

Table 2. Transport Performance and Loss Analysis

Case	Fluid Penetration Depth (m)	Solute Penetration Depth (m)	Seepage Loss (%)	Solute Retention (%)	Dominant Mechanism
Low Gradient	4.2	1.6	8.5	72.3	Diffusion + Adsorption
High Gradient	9.8	4.1	21.7	54.6	Advection + Adsorption

A detailed examination of the concentration profiles reveals that the system exhibits non-linear transport characteristics due to the coupling between advection, diffusion, and adsorption. Near the canal interface, high concentration gradients drive rapid diffusion into the porous medium, while further away from the boundary, the combined effects of reduced velocity and adsorption lead to gradual flattening of the concentration profile. This spatial variation in transport behavior underscores the importance of considering both local and global transport mechanisms in system analysis. The presence of adsorption not only delays solute migration but also alters the effective dispersion characteristics of the medium, resulting in asymmetric concentration distributions. Such behavior cannot be captured using purely hydraulic models, thereby emphasizing the necessity of incorporating chemical interactions into the analysis.

The comparison between low and high hydraulic loading conditions provides valuable insights into system efficiency and loss mechanisms. Under low-gradient conditions, the negligible seepage flux implies minimal water loss, which is desirable from a resource conservation perspective. However, the limited transport may also restrict the natural attenuation of contaminants, potentially leading to localized accumulation. In contrast, high-gradient conditions enhance both fluid and solute transport, increasing the risk of water loss and contaminant migration into surrounding regions. From a chemical engineering standpoint, this trade-off can be interpreted in terms of process optimization, where the objective is to balance transport efficiency with loss minimization. The concept of a critical hydraulic gradient emerges as a key parameter, beyond which the system transitions into a regime of excessive mass transfer losses. The coupled behavior of fluid flow and solute transport obtained from numerical simulations is presented in Figure 2.

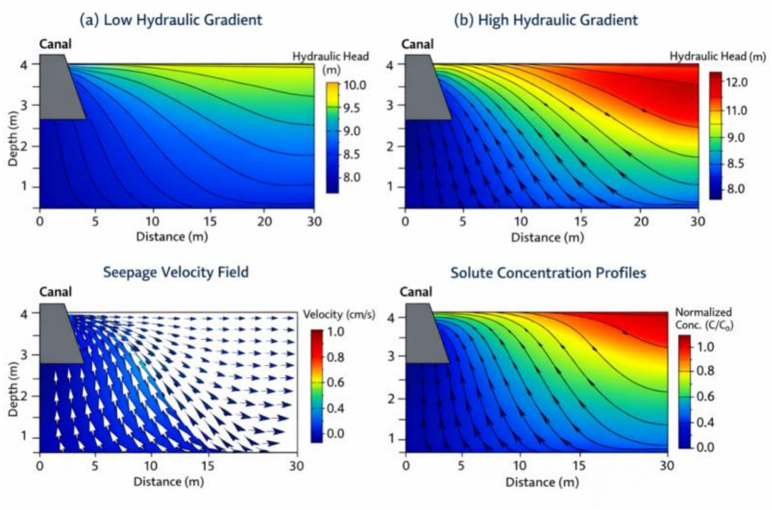

Figure 2. Numerical simulation results illustrating coupled fluid flow and reactive solute transport in the porous medium system. (a) Hydraulic head distribution under low hydraulic gradient conditions, showing limited potential variation and minimal seepage; (b) hydraulic head distribution under high hydraulic gradient conditions, indicating increased driving force and deeper penetration of flow; (c) seepage velocity vector field demonstrating flow direction and magnitude within the porous domain; and (d) normalized solute concentration contours highlighting the combined effects of advection, diffusion, and adsorption, with evident attenuation away from the canal boundary.

The influence of material properties on transport behavior is also evident from the simulation results. The low permeability of the clay medium restricts fluid flow, thereby limiting seepage losses to some extent; however, its high adsorption capacity significantly enhances solute retention. This dual effect highlights the importance of material selection and modification in controlling system performance. For instance, increasing the permeability through soil modification would enhance flow but may simultaneously increase losses, whereas improving adsorption characteristics could mitigate solute migration without significantly affecting hydraulic behavior. Such considerations are central to the design of engineered systems in chemical and environmental engineering, where material properties are tailored to achieve desired process outcomes.

The finite element modeling approach proves to be highly effective in capturing the spatial variability of both hydraulic and concentration fields. The use of a refined mesh near the canal boundary allows accurate resolution of steep gradients, which are critical for determining local mass transfer rates. The coupling between flow and transport equations ensures that changes in hydraulic conditions are directly reflected in solute migration patterns, thereby providing a realistic representation of system behavior. The validation of numerical results against experimental permeability data and analytical solutions further confirms the reliability of the model. Minor deviations observed in certain regions can be attributed to assumptions such as homogeneity of the porous medium and the use of a linear adsorption isotherm, which may not fully capture complex soil – solute interactions under all conditions.

From a broader perspective, the results demonstrate that unlined canal systems can be effectively analyzed using chemical engineering concepts such as reactor analogies, mass transfer coefficients, and resistance networks. The canal – soil interface can be viewed as a semi-permeable boundary facilitating continuous mass exchange, while the porous medium acts as a reactive domain where transport and adsorption occur simultaneously. This interpretation enables the application of established chemical engineering methodologies to environmental systems, bridging the gap identified in the preliminary review. Furthermore, the study highlights the potential for integrating reactive transport modeling into the design and optimization of water conveyance systems, thereby improving efficiency and sustainability.

Overall, the findings provide a comprehensive understanding of the coupled transport mechanisms governing fluid and solute behavior in porous media. The strong dependence of transport on hydraulic gradients and material properties underscores the need for a multidisciplinary approach that integrates principles of fluid mechanics, mass transfer, and surface chemistry. By demonstrating the relevance of chemical engineering frameworks to environmental transport systems, the study not only addresses the limitations identified in conventional hydraulic analyses but also opens new avenues for research and application in process engineering, environmental remediation, and resource management.

4. Discussion

The results of this study clearly demonstrate that the behavior of seepage systems in porous media cannot be adequately explained using a purely hydraulic framework; instead, a chemical engineering perspective that incorporates coupled transport and reaction mechanisms provides a more comprehensive interpretation. The observed dependence of fluid flux on hydraulic gradient aligns with classical transport theory, where the driving force governs the rate of mass transfer. However, the inclusion of adsorption introduces an additional resistance term that significantly alters solute mobility, thereby transforming the system from a simple flow domain into a reactive transport medium. This shift is particularly important in clay-rich environments, where surface interactions dominate and strongly influence the fate of dissolved species.

One of the key insights from the study is the distinction between fluid transport and solute transport under varying operating conditions. While fluid flow responds directly to pressure gradients, solute movement is simultaneously influenced by advection, diffusion, and adsorption. As a result, the solute front consistently lags behind the fluid front, highlighting the role of the solid matrix as an active participant in the transport process. This phenomenon is analogous to retardation effects observed in catalytic and adsorption-based systems, where the residence time of species is extended due to interactions with the solid phase. Such behavior reinforces the importance of incorporating reaction terms into transport models when analyzing environmental systems.

The influence of material properties further emphasizes the interdisciplinary nature of the problem. The low permeability of the clay medium acts as a limiting factor for fluid flow, effectively reducing seepage losses under moderate conditions. At the same time, its high adsorption capacity enhances solute retention, thereby providing a natural attenuation mechanism for contaminant migration. This dual functionality suggests that material characteristics can be strategically utilized to optimize system performance. From a design perspective, modifying soil properties through chemical stabilization or engineered liners could be viewed as an approach to tailor mass transfer resistance and improve efficiency, similar to catalyst design in chemical reactors.

Another important aspect highlighted by the study is the transition between transport regimes. At low hydraulic gradients, the system is predominantly diffusion-controlled, with minimal convective transport and negligible losses. As the gradient increases, advection becomes dominant, leading to a sharp increase in both fluid and solute flux. This transition can be interpreted as a regime shift, where the balance between driving force and resistance determines overall system behavior. Identifying such thresholds is critical for process optimization, as it enables the establishment of operating conditions that minimize losses while maintaining functional performance.

The application of finite element modeling provides valuable spatial insights that are difficult to obtain experimentally. The ability to visualize velocity fields and concentration distributions allows for detailed analysis of localized transport phenomena, particularly near the canal boundary where gradients are steep. This level of resolution is essential for understanding the mechanisms governing mass transfer and for validating theoretical assumptions. Although the model assumes homogeneity and linear adsorption, which may not fully capture complex field conditions, it serves as a robust framework for integrating hydraulic and chemical processes.

Overall, the discussion underscores the significance of adopting a chemical engineering approach to analyze environmental transport systems. By treating the porous medium as a reactive domain and the canal as a continuous flow system, the study bridges the gap between hydraulic engineering and applied chemistry. This perspective not only enhances the fundamental understanding of seepage and transport phenomena but also provides a pathway for developing more efficient and sustainable water management strategies.

5. Conclusion

This study successfully reinterprets seepage behavior in unlined canal systems through a chemical engineering framework by integrating fluid flow, mass transfer, and adsorption mechanisms within a coupled experimental – numerical approach. The results demonstrate that fluid transport in porous media is primarily governed by hydraulic gradients, while solute migration is significantly influenced by physicochemical interactions, particularly adsorption within the clay-rich matrix. The incorporation of a reactive transport model reveals that solute movement is substantially retarded compared to fluid flow, highlighting the active role of the porous medium as a reactive domain rather than a passive conduit. The findings further establish that transport behavior is highly sensitive to operating conditions, with a clear transition from diffusion-dominated to advection-dominated regimes as the hydraulic gradient increases. This transition directly impacts both fluid loss and solute dispersion, emphasizing the importance of optimizing operating parameters to balance efficiency and sustainability. Material properties, especially permeability and adsorption capacity, are shown to play a dual role in controlling transport processes, offering potential pathways for system improvement through material modification or engineering interventions.

The finite element modeling approach effectively captures the spatial variability of flow and concentration fields, providing detailed insights into localized transport phenomena and validating the applicability of chemical engineering principles to environmental systems. Overall, the study bridges the gap between hydraulic and chemical perspectives, demonstrating that unlined canal systems can be treated as reactive transport systems analogous to process units in chemical engineering. This integrated approach not only enhances the understanding of coupled transport mechanisms but also contributes to the development of more efficient, sustainable strategies for water resource management and contaminant control in porous media environments.

Author contributions

Conceptualization, Manal Abdulsattar Muhammed and Mahdi Nuhair Rahi; methodology, Manal Abdulsattar Muhammed; software, Mahdi Nuhair Rahi; validation, Manal Abdulsattar Muhammed, Mahdi Nuhair Rahi and Noor Mohammed Abd; formal analysis, Noor Mohammed Abd; investigation, Nuralhuda Aladdin Jasim; resources, Manal Abdulsattar Muhammed; data curation, Noor Mohammed Abd; writing—original draft preparation, Manal Abdulsattar Muhammed; writing—review and editing, Mahdi Nuhair Rahi; visualization, Nuralhuda Aladdin Jasim; supervision, Manal Abdulsattar Muhammed; project administration, Mahdi Nuhair Rahi; funding acquisition, Manal Abdulsattar Muhammed. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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