

ANALYTICAL SOLUTION OF MICROPLASTIC POLLUTANT TRANSFER THROUGH AQUIFER IN THE PRESENCE OF SOURCE/SINK

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ABSTRACT

An exact analytical solution is developed for the governing one-dimensional advection–dispersion–reaction equation by first separating the steady-state contribution associated with the source/sink term from the transient concentration. The governing advection–dispersion–reaction equation is solved analytically by decomposing the solution into steady-state and transient components, followed by an exponential transformation to eliminate the advective first-derivative term and separation of variables to obtain an eigenfunction expansion for the transient concentration. Finally, we have found the analytical concentration distribution of microplastic pollutants as a function of space and time. This procedure yields an analytical series solution that explicitly describes the transient concentration field. The proposed solution also enables the source and sink cases to be examined within the same mathematical formulation. A positive source term represents continuous addition of microplastics to the aquifer, whereas a negative term represents removal. Consequently, the model can be used to investigate how external loading or removal modifies pollutant persistence, concentration levels, and spatial migration. The analytical expression additionally provides a benchmark for numerical simulations and facilitates sensitivity analysis without requiring repeated numerical discretization.

Keywords: Microplastic transport, Laplace Transform technique, Pore water velocity, Microplastic sticking efficiency, Median particle diameter, Collector efficiency, Volumetric water content, etc.

1 INTRODUCTION

Microplastic pollution has emerged as a significant environmental concern because of the widespread occurrence, persistence, and mobility of small plastic particles in terrestrial and aquatic environments. Microplastics are generally defined as plastic particles smaller than 5 mm and may originate either from the direct use of small plastic materials or from the fragmentation and degradation of larger plastic products. Their presence has been reported in surface water, sediments, soils, wastewater, and groundwater environments. Because of their small size and relatively persistent nature, microplastics can be transported over considerable distances and may act as carriers for other contaminants.

Consequently, understanding their transport and fate in subsurface environments is important for evaluating groundwater quality and potential risks to water resources. Groundwater and aquifer systems represent important sources of drinking water, agricultural water, and industrial water. Unlike surface-water systems, aquifers are characterized by complex porous structures in which the movement of pollutants is governed by groundwater flow, dispersion, diffusion, adsorption, filtration, and degradation or attachment processes. Once microplastic particles enter the subsurface through sources such as wastewater infiltration, landfill leachate, agricultural activities, urban runoff, or accidental release, they may migrate with groundwater and become distributed within the porous matrix. Depending on particle characteristics and aquifer properties, microplastics can either remain mobile or become temporarily or permanently retained within the porous matrix. Therefore, mathematical descriptions of microplastic transport are useful for predicting their spatial and temporal concentration distributions.

According to Boyle and Ormeci (2020), global plastic production expanded from 1.5 million tons in 1950 to nearly 348 million tons in 2017. According to the United Nations Environment Program (UNEP), approximately 430 million tons of plastic pollution will occur in 2023, of which two-thirds will enter the ocean and be converted into MPs. Moodley and colleagues (2024) carried out a recent comparative analysis highlighting the use of mathematical models in exploring MPs transport and fate in water bodies over the period from 2012 to 2022. The flow velocity increased, within the barrier, pollution levels intensified significantly, with levels four times higher than those observed at normal flow velocity when the flow rate doubled (Xing et al., 2023). With growing concerns about the risks of MPs in groundwater human health and ecosystems, as reflected in (Y. Q. He et al., 2024), a contrast analysis of the Scales (CAS) approach to integrate existing data and build a hierarchical framework for understanding MP accumulation in groundwater. Genc et al. (2019) evaluated coastal regions where MPs pollution is expected to increase and disperse within Fethiye Inner Bay, as identified by modeling aspects for sustainable protection of marine environments. The European Union (EU) is considering a management plan to evaluate MPs in various water resources from 2020 to 2021. The Swedish Environmental Protection Agency (SEPA) supported projects associated with the eco-friendly utilization of plastics and proper management of plastic debris by private companies, research institutes, universities, and public organizations with the goals of reducing plastic utilization, effective plastic recycling, and preventing plastic pollution from land-based. The various mathematical models for solute transport in the aquifers and groundwater flow through many physical situations have been solved by the Laplace Integral transform approach and some of them numerically (Singh et al. 2014, 2016, 2019, 2021, Das et al. 2017, Chaudhary et al. 2019, Singh 2011) to predict the concentration of contaminants over time and distance. Chu et al. (2019) conducted column experiments using glass beads to study the behavior of polystyrene latex colloids, which were used as analogues for MPs particles. Using carboxyl-modified polystyrene latex colloids as representative MPs particles, they carried out column experiments to explore colloid transfer in porous media and highlighted the need for reliable models to understand MP behavior and subsoil dynamics. As per ADE, a hydrodynamic model was developed to estimate MPs mixing in submerging canopies (Ben et al., 2023). In this study, fluorometric tracing techniques were used to detect and compare the mixing and dispersion processes of MPs and solutes. Studies on porous materials have found interesting results in terms of unsteady and steady flow through different geometries (Tiwari et al. 2012, Tiwari and Singh 2010, 2015, 2022). Recently, (Muniz and Rahman, 2025) found that plastic pollution poses a serious threat to marine life, contaminates seafood, and endangers human health. After degradation of plastics into very small particles in aquatic environments, which infiltrate coastal and marine ecosystems, leading to significant physical and biological harm to organisms.

Despite increasing attention to microplastic contamination in groundwater, several limitations remain in the mathematical description of microplastic transport through aquifers. A substantial part of the existing transport literature has focused on experimental investigations, field observations, or numerical simulations, while relatively few studies provide explicit analytical solutions for transient microplastic transport in a finite aquifer. In particular, the simultaneous consideration of advection, hydrodynamic dispersion, first-order attenuation/attachment, and an explicit source or sink within a unified analytical framework remains insufficiently developed. Analytical solutions of pollutant transport equations are particularly valuable because they provide direct mathematical relationships between concentration, time, distance, and the governing physical parameters. Although numerical techniques such as finite-difference, finite-element, and finite-volume methods are widely used for complex groundwater transport problems, analytical solutions offer important advantages for fundamental analysis. They can be used to identify the relative influence of individual parameters, examine limiting cases, validate numerical simulations, and provide benchmark solutions for more complicated models. However, analytical treatment becomes more challenging when advection, dispersion, attenuation, and source/sink effects occur simultaneously.

2 FORMULATION OF THE PROBLEM

In this study, we considered a mathematical unsteady flow model of the microplastics through a finite water channel. In the channel, the fluid moves through the porous media, as shown in fig. 1. As MPs particles travel through porous water channels within saturated soil, they are transported downstream via both advection and diffusion. While some of these MPs adhere to soil particle surfaces, others that were previously attached may subsequently detach.

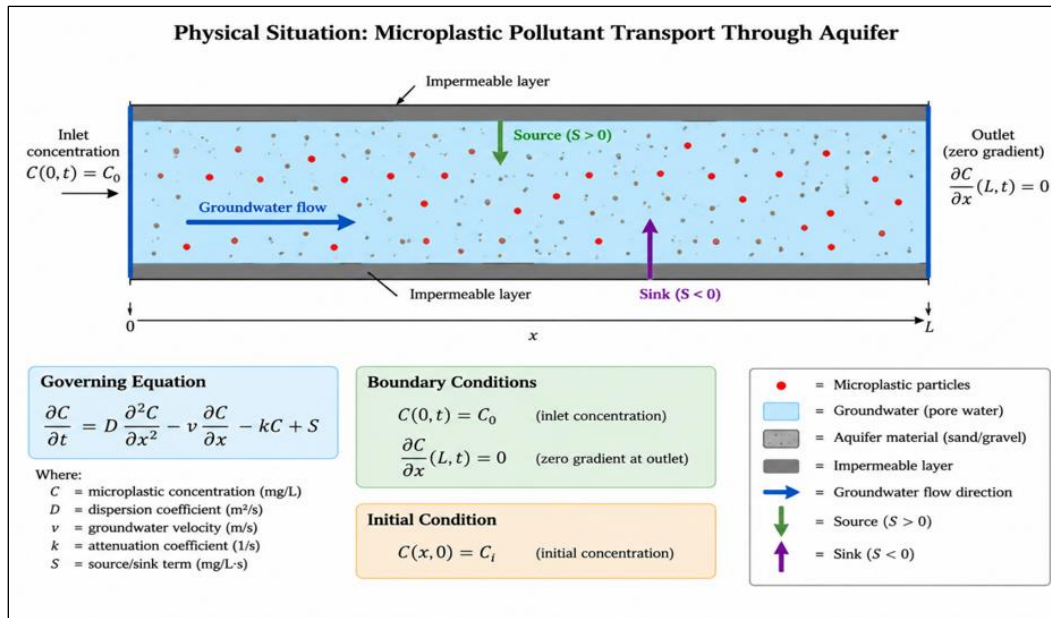


Figure 1: Physical Configuration

With the help of previous studies [Ryu et al. 2021, Lee et al. 2009, Kim et al. 2020], the balance equations for MPs particles are as follows:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} - k_a c + S \quad (2.1)$$

$$\text{where, } k_a = \frac{3(1-\theta)}{2d_{50}} \eta \alpha v$$

Here, k_a [T^{-1}] is the first-order attachment coefficient or attenuation coefficient for MPs production in the liquid phase, c [ML^{-3}] is the concentration of dispersing MPs in the aqueous phase, D [L^2T^{-1}] is the diffusivity in the longitudinal direction, v [LT^{-1}] is the pore water velocity in the downward direction, x [L] is the length in the longitudinal direction of flow and t [T] is time, η is the collector efficiency (-), α is the MPs sticking efficiency (-), d_{50} is the Median particle diameter (L) and θ is the volumetric water content (-).

The main focus of this paper is to solve equation (2.1) in analytical form with appropriate initial values at the boundary conditions. Initially, the aquifer is dependent on the initial background concentration (c_i) and inversely proportional to average pore water velocity (v). The initial boundary conditions in mathematical form for the above assumptions can be written as:

$$c(x, t) = c_i, \quad x > 0, \quad t = 0 \quad (2.2)$$

At one end of the aquifer channel, the channel is affected by a chosen a constant input concentration c_0 as

$$c(x, t) = c_0, \quad x = 0, \quad t > 0 \quad (2.3)$$

On the other end of the channel, there is no mass flow, i. e

$$\frac{\partial c}{\partial x} \rightarrow 0, \quad x = L, \quad t > 0. \quad (2.4)$$

2.1 Analytical solution

We will find here analytic solution of above problem into the two parts. One part of the solution is steady state solution and other transient state solution.

2.2 Steady State Solution

In the case of steady state we have assume concentration c_s . For this purpose we put $\frac{\partial c}{\partial t} = 0$ in equation (2.1), we get

$$D \frac{\partial^2 c_s}{\partial x^2} - v \frac{\partial c_s}{\partial x} - k_a c_s + S = 0 \quad (2.5)$$

With boundary conditions

$$c_s(0, t) = 0, \quad \frac{\partial c_s(L, t)}{\partial x} = 0$$

The solution of equation (2.5) with above boundary conditions as

$$c_s = A e^{r_1 x} + B e^{r_2 x} + \frac{S}{k_a} \quad (2.6)$$

$$\text{Where } A = \frac{c_0 \cdot \frac{S}{k_a}}{1 - \frac{r_1}{r_2} e^{\frac{(r_1 - r_2)L}{2}}}, \quad B = -A \frac{r_1}{r_2} e^{\frac{(r_1 - r_2)L}{2}}, \quad r_1 = \frac{v + \sqrt{v^2 + 4Dk_a}}{2D}, \quad r_2 = \frac{v - \sqrt{v^2 + 4Dk_a}}{2D}$$

If we take $a = \frac{v}{2D}$, $\mu = \frac{\sqrt{v^2 + 4Dk_a}}{2D}$, then solution in equation (2.6) can be rewritten as

$$c_s(x) = \frac{S}{k_a} + \left(c_0 - \frac{S}{k_a} \right) e^{ax} \left\{ \cosh \mu x - \left(\frac{\mu \sinh \mu L + a \cosh \mu L}{\mu \cosh \mu L + a \sinh \mu L} \right) \sinh \mu x \right\}$$

2.3 Transient State Solution

In the case of transient steady state, we have assume concentration c_T , we get equation (2.7) from equation (2.1)

$$\frac{\partial c_T}{\partial t} = D \frac{\partial^2 c_T}{\partial x^2} - v \frac{\partial c_T}{\partial x} - k_a c_T \quad (2.7)$$

The boundary conditions become as

$$c_T(0, t) = 0, \quad \frac{\partial c_T(L, t)}{\partial x} = 0 \quad \text{and} \quad c_T(x, 0) = c_1 - c_s(x)$$

For eliminating advection term, we are introducing

$$c_T(x, t) = e^{ax} u(x, t)$$

Now equation (2.7) becomes as

$$\frac{\partial u}{\partial t} = D \frac{\partial^2 u}{\partial x^2} - \lambda_0 u \quad (2.8)$$

$$\text{Where } \lambda_0 = k_a + \frac{v^2}{2D}$$

Now accordingly boundary conditions become

$$u(0, t) = 0, \quad \frac{\partial u(L, t)}{\partial x} + au(L, t) = 0, \quad u(x, 0) = e^{-ax} (c_1 - c_s)$$

We will solve it by separation of variables. For this purpose, we have consider

$$u(x, t) = X(x)T(t)$$

From equation (2.8), we get

$$\frac{T'}{T} - \lambda_0 = D \frac{X''}{X} = \text{Constant} = -D\lambda_n^2$$

Using boundary conditions, we the solution as

$$u(x, t) = \sum A_n \sin(\lambda_n x) e^{-\gamma_n t}$$

$$\text{Where } A_n = \frac{\int_0^L e^{-ax} (c_1 - c_s) \sin(\lambda_n x) dx}{\frac{L \sin(2\lambda_n L)}{2} - \frac{4\lambda_n}{\lambda_n}}, \quad \tan(\lambda_n L) = -\frac{2D\lambda_n}{v}, \quad \gamma_n = D\lambda_n^2 + k_a + \frac{v^2}{4D}$$

Now the final solution of concentration profile is

$$c(x,t) = c_s(x) + c_T(x, t)$$

$$c(x, t) = \frac{S}{k_a} + \left(c_0 - \frac{S}{k_a}\right) e^{ax} \left\{ \cosh \mu x - \left(\frac{\mu \sinh \mu L + a \cosh \mu L}{\mu \cosh \mu L + a \sinh \mu L} \right) \sinh \mu x \right\} + e^{ax} \sum A_n \sin(\lambda_n x) e^{-\gamma_n t}$$

(2.9)

3 RESULT AND DISCUSSION

In this section, The analytical solution was used to investigate the transient transport of microplastic pollutants in an aquifer under the combined effects of advection, dispersion, first-order attenuation, and a constant source or sink term. The concentration profiles were evaluated along the aquifer domain for different values of time, dispersion coefficient, advective velocity, attenuation coefficient, and source/sink strength. Figures 2–7 illustrate the influence of these parameters on the spatial and temporal distribution of microplastic concentration. we graphically examined the effects of the main parameters involved in the analytical solution given in equation (2.9). The MPs concentration in equation (2.9) was computed for the input data of $c_0=1.0$, $c_1=2.0$ and $L=10$.

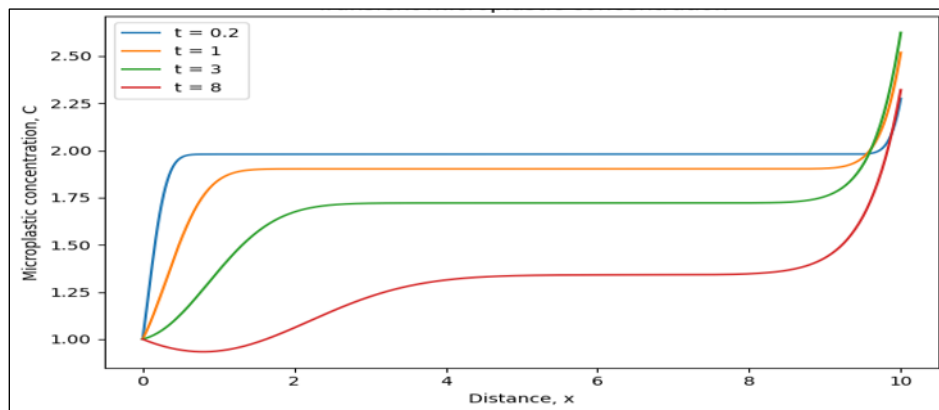


Figure 2: Transient concentration profiles of microplastic pollutants at different times.

We plotted fig. 2 presents the spatial concentration profiles at different times. At the initial stage, the concentration distribution is strongly influenced by the prescribed initial concentration and the inlet boundary condition. As time increases, the transient component of the solution gradually decreases because of the combined effects of dispersion, advection, and first-order attenuation. The concentration profile becomes progressively smoother with time, indicating the redistribution of microplastic particles throughout the aquifer. The effect of the initial condition is dominant at early times, whereas the long-time concentration distribution is increasingly controlled by the steady-state balance between transport, attenuation, and the source term. Thus, the analytical solution clearly demonstrates the transition from the initial transient state toward a quasi-steady or steady concentration distribution. The decrease in the transient component is mathematically associated with the exponential decay of the eigenmodes in the analytical solution. Higher-order modes decay more rapidly, resulting in a smoother concentration profile at larger times. This behavior is physically realistic because dispersion tends to reduce sharp concentration gradients, while attenuation continuously removes microplastic particles from the mobile phase.

The effect of the dispersion coefficient (D) is shown in **Figure 3**. The dispersion coefficient controls the spreading of the microplastic concentration along the aquifer. For a small value of (D), the concentration distribution remains relatively steep, indicating limited spreading of the pollutant plume. As (D) increases, the concentration profile becomes smoother and the pollutant is distributed over a wider region of the aquifer. The increased dispersion also reduces sharp spatial concentration gradients. This occurs because the dispersive flux is proportional to the concentration gradient, and a larger (D) enhances the redistribution of microplastic particles from regions of high concentration toward regions of lower concentration. The results indicate that dispersion plays an important role in determining the spatial extent of microplastic contamination. A low-dispersion aquifer tends to retain a relatively localized concentration plume, whereas a highly dispersive medium promotes broader pollutant distribution. Therefore, accurate estimation of the

dispersion coefficient is important when predicting the migration distance and concentration of microplastics in groundwater systems.

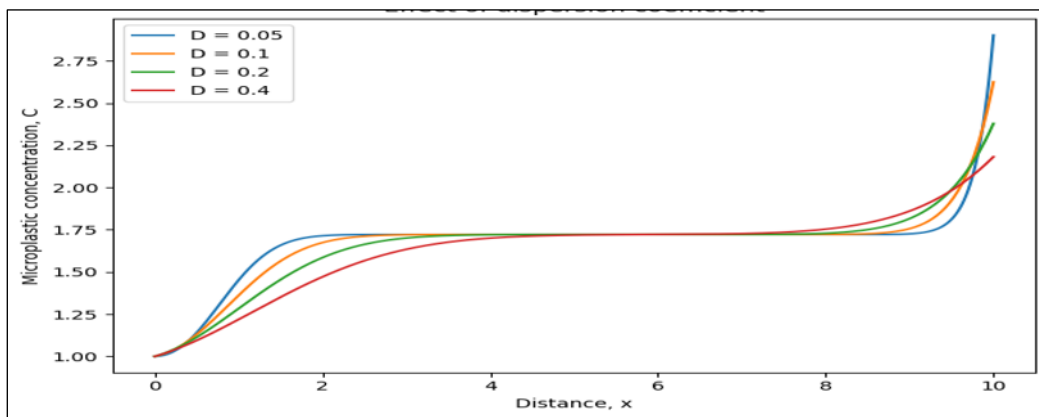


Figure 3: Effect of the dispersion coefficient (D) on the spatial distribution of microplastic

The influence of the advective velocity (v) is presented in **Figure 4**. Advection represents the transport of microplastic particles with the moving groundwater. An increase in (v) enhances the downstream movement of the pollutant and modifies the spatial concentration distribution. For smaller values of (v), the pollutant remains comparatively concentrated near the inlet region because the advective transport is weaker. As the velocity increases, microplastic particles are transported more rapidly into the aquifer, producing a greater downstream penetration of the contaminant. The results demonstrate that groundwater velocity is one of the major controlling parameters for microplastic migration. The interaction between advection and dispersion determines the shape and position of the concentration profile. When the advective effect is dominant, transport occurs primarily in the direction of groundwater flow, whereas stronger dispersion produces a more distributed concentration profile.

Consequently, regions having higher groundwater velocity may experience faster migration of microplastics and potentially greater contamination at downstream locations. This observation is particularly important for assessing the transport time and spatial extent of microplastic pollution in aquifers.

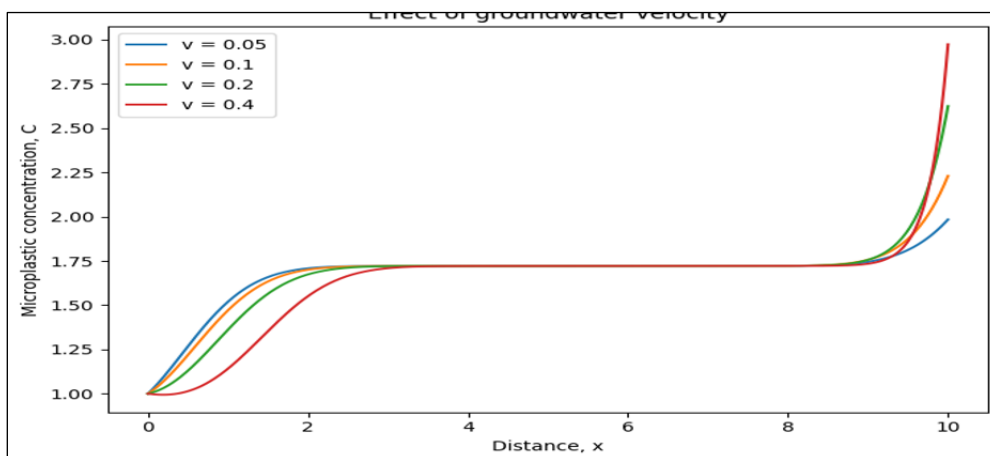


Figure 4: Effect of advective velocity (v) on the microplastic concentration profile.

The attenuation term ($-kC$) represents the overall removal of microplastic particles from the mobile aqueous phase through processes such as attachment, filtration, retention, deposition, or other first-order removal mechanisms. The concentration decreases as the attenuation coefficient increases. For a small value of (k), the pollutant remains in the mobile phase for a longer period and consequently travels farther through the aquifer. Increasing (k) enhances pollutant removal and reduces the concentration throughout the domain. The influence of attenuation becomes particularly important at larger transport times because the attenuation contribution accumulates with time. In the analytical solution, the transient modes contain an exponential decay contribution associated with (k). Therefore, increasing (k) results in faster temporal decay of the microplastic concentration. These results indicate that the attachment and retention characteristics of the porous medium can substantially reduce the mobility of microplastic particles. Hence, the attenuation coefficient provides an important measure of the interaction between microplastics and the aquifer matrix.

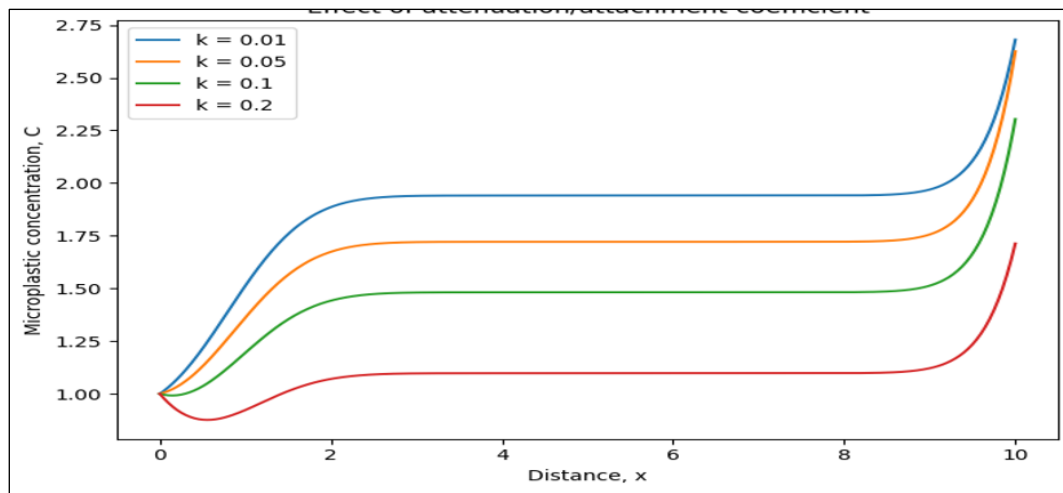


Figure 5: Effect of the attenuation coefficient (k) on microplastic concentration.

The effect of the source strength (S) is presented in **Figure 6**. The source term represents continuous addition of microplastic pollutants into the aquifer system. A positive value of (S) increases the concentration because microplastics are continuously introduced into the transport domain. For ($S=0$), the concentration is controlled only by the initial condition, inlet concentration, advection, dispersion, and attenuation. When a positive source is introduced, the concentration profile increases relative to the source-free case. A further increase in (S) produces a corresponding increase in concentration. The results demonstrate that continuous pollutant loading can maintain elevated microplastic concentrations even when attenuation is present. The source term therefore acts against the removal effect of the attenuation mechanism. At steady state, the concentration distribution is determined by the balance between pollutant input through the source, transport by advection and dispersion, and removal through attenuation. This behavior is relevant to practical aquifer systems where microplastics may continuously enter groundwater through wastewater infiltration, landfill leachate, urban runoff, agricultural drainage, or other anthropogenic sources.

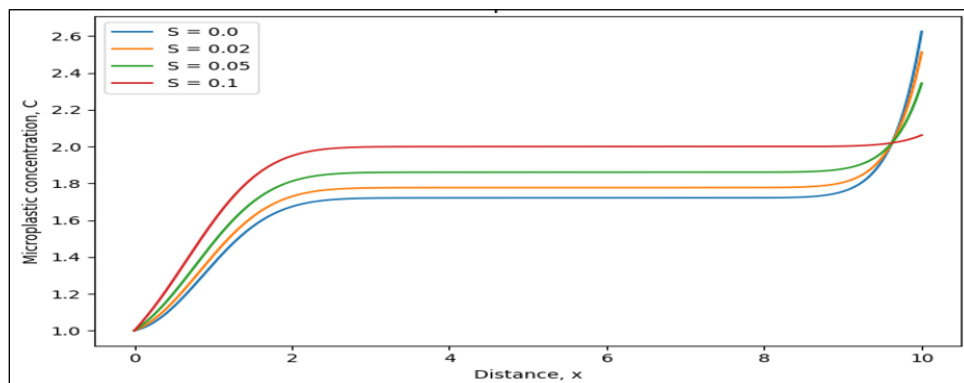


Figure 6: Effect of the positive source strength (S) on microplastic concentration.

The influence of positive, zero, and negative source/sink terms is shown in **Figure 7**. A positive value of (S) represents a net source and increases the microplastic concentration, whereas ($S=0$) corresponds to the absence of external loading or removal. A negative value of (S) represents a net sink and results in additional removal of microplastic pollutants. The concentration profile for the positive source case lies above the source-free profile, demonstrating continuous pollutant addition. In contrast, the negative source/sink case produces a lower concentration because the sink removes microplastics from the system. Thus, the magnitude and sign of (S) have a direct influence on the pollutant concentration. The results emphasize that source and sink processes can significantly modify the natural transport behavior of microplastics. Even when groundwater velocity, dispersion, and attenuation remain unchanged, a persistent source can maintain contamination, while an effective sink can accelerate pollutant reduction. The source/sink term is therefore an important component of a realistic mathematical representation of microplastic transport in aquifers.

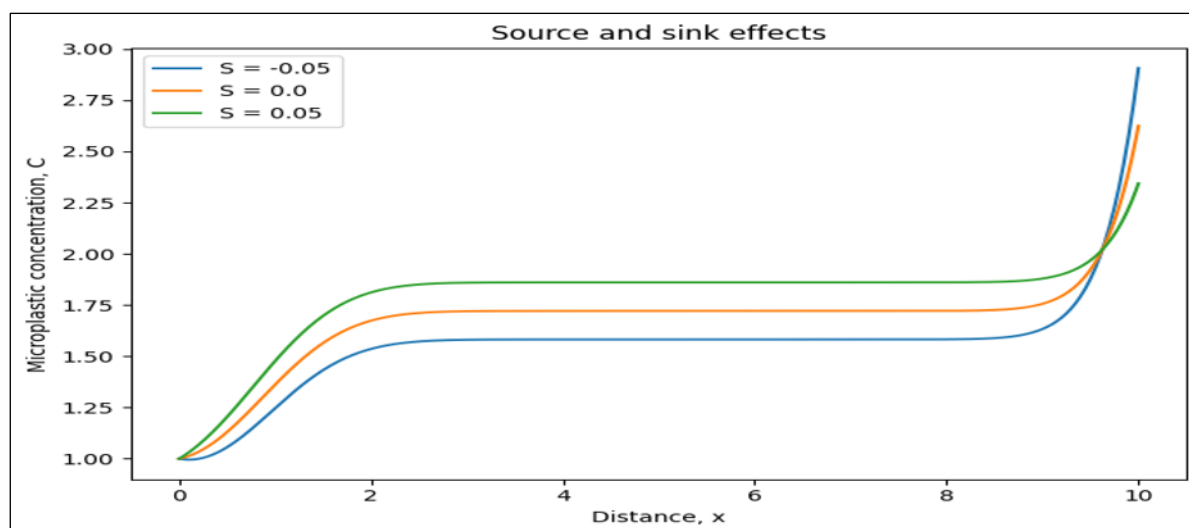


Figure 7: Comparison of microplastic concentration profiles for positive source, zero source, and negative source/sink conditions.

4 CONCLUSION

The main objective of this work is to develop and analyze an analytical solution for microplastic pollutant transfer through an aquifer in the presence of source/sink effects. The study specifically aims to: (i) formulate a one-dimensional advection–dispersion–reaction model for microplastic transport; (ii) incorporate first-order attenuation/attachment and a source/sink term; (iii) derive an analytical transient solution using steady-state decomposition, exponential transformation, separation of variables, and eigenfunction expansion; and (iv) investigate the influence of groundwater velocity, dispersion, attenuation, and source/sink strength on the spatial and temporal distribution of microplastic concentration. The resulting analytical framework is intended to provide a theoretical basis for understanding microplastic migration in groundwater and a benchmark solution for future numerical and experimental investigations. The combined interpretation indicates that the concentration of microplastics at any location is determined by the balance between advection, dispersion, attenuation, and external pollutant loading or removal. In particular, a high groundwater velocity may promote rapid downstream migration, whereas a high attenuation coefficient can restrict this migration. Similarly, increased dispersion broadens the contaminant plume, while a positive source maintains pollutant concentrations despite attenuation.

An important advantage of the present analytical formulation is that these effects can be investigated independently by varying the corresponding model parameters. The analytical solution therefore provides a useful framework for understanding the physical mechanisms controlling microplastic transport and can also serve as a benchmark for numerical models of more complicated aquifer systems. Overall, the results establish that source/sink processes cannot be neglected when predicting microplastic contamination in groundwater. The proposed analytical model provides a mathematical basis for evaluating transient microplastic transport and for examining how changes in aquifer properties and pollutant loading conditions affect the concentration distribution.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors report no potential conflicts of interest.

Data availability statement

Data supporting the conclusions of this study are available from the corresponding author upon reasonable request.

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