

Longitudinal dispersion in fluvial environments: new empirical formulations and applications to pollutant transport modeling

Ankit Kumar

Maulana Azad National Institute of Technology

Rajesh K. Mahato

rajesh@manit.ac.in

Maulana Azad National Institute of Technology <https://orcid.org/0000-0002-0334-2693>

Harsangeet Kaur

Maulana Azad National Institute of Technology

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Longitudinal dispersion in fluvial environments: new empirical formulations and applications to pollutant transport modeling

Ankit Kumar¹ · Rajesh K. Mahato¹ · Harsangeet Kaur¹

Highlights

- We present novel empirical formulations for longitudinal dispersion coefficients in narrow and wide channels.
- We discover that the dispersion in narrow and wide channels is governed by the channel aspect ratio and shear velocity ratio, respectively.
- One-dimensional advection–dispersion equation is numerically solved to examine transport dynamics for instantaneous and continuous pollutant release scenarios.

Abstract

In this paper, we analyze the transport dynamics of instantaneous and continuous release of pollutants in rivers. We begin with proposing new formulations for longitudinal dispersion coefficient in narrow and wide channels. Considering the observed trends in field-derived datasets, the channel aspect ratio to demarcate narrow and wide channels is set as 10. The analysis shows that the longitudinal dispersion coefficient depends nonlinearly on the channel aspect ratio and shear velocity ratio. Finally, the robustness of the proposed formulations is established through a comparative analysis with existing formulations available in the literature. To simulate the pollutant transport dynamics, the one-dimensional advection–dispersion equation is numerically solved using the proposed formulations of dispersion coefficient. The numerical simulations are performed for instantaneous and continuous pollutant release scenarios in both narrow and wide channels. The pollutant concentration profiles in a narrow channel with instantaneous release manifest a distinct peak concentration. Conversely, for continuous release scenario, the pollutant concentration remains at its maximum magnitude for a finite temporal interval and spatial extent. For instantaneous release case, the enhanced dispersion in wide channels causes the intensified attenuation of the concentration peak. In addition, the continuous release of pollutants in wide channels characterize a decay of peak concentration in downstream direction. The predicted pollutant concentration profiles are in agreement with the classical analytical solution and field observations of Atkinson and Devis (2000).

Keywords Pollutant transport · Open channel flow · advection–dispersion equation · Channel aspect ratio · Shear velocity ratio

Introduction

✉ Rajesh K. Mahato
rajesh@manit.ac.in

¹ Department of Civil Engineering, Maulana Azad National Institute of Technology Bhopal, Madhya Pradesh, India, 462003

Rivers are vital freshwater resources supporting drinking water supply, agricultural irrigation, industrial development, and ecological sustainability. However, in recent year, accelerated urbanization, industrialization, and agricultural development have contaminated natural water bodies including rivers (Noori et al. 2021). Consequently, reliable assessment of pollutant transport and mixing processes is crucial for water quality management, environmental conservation, and pollution mitigation strategies (Fischer et al. 1979; Chen et al. 2009; Parsaie and Haghiabi 2015; Noori et al. 2021).

The advection–dispersion equation has been extensively employed to model the pollutant transport dynamics in rivers (Wallis and Manson 2004; Abderrezzak et al. 2015; Moghaddam et al. 2017; Ramezani et al. 2019). Over the years, numerous software packages, such as SIMCAT, QUAL2Kw, COMSOL, MIKE 11, ADISTS, etc., have been developed to model pollutant transport dynamics in rivers (Pelletier et al. 2006; Ani et al. 2009; Launay et al. 2015). Pollutant discharges in streams usually occur in two forms—instantaneous and continuous. For continuous discharges, the concentration front propagates downstream and gradually approaches a steady-state condition (Abderrezzak et al. 2015; Ramezani et al. 2019). Conversely, an instantaneous discharge generates a concentration plume that travels downstream while spreading and attenuating, typically exhibiting a Gaussian distribution (Abderrezzak et al. 2015; Ramezani et al. 2019). For various initial and boundary conditions, van Genuchten and Alves (1982) compiled the existing analytical solutions for one-dimensional advection–dispersion equation. Moreover, de Smedt (2006) proposed an analytical solution for advection–dispersion equation coupled with transient storage and first order decay. Besides, Hunt (2006) presented asymptotic solutions for one-dimensional dispersion in rivers. For a mountainous stream featured by riffles and pools, Bencala and Walters (1983) found that a transient storage model performs well in simulating pollutant transport dynamics. Note that a transient storage model couples dead storage zones with the advection–dispersion equation (Bencala and Walters 1983). For a given real-world case, Schmid (2004) developed conditions in terms of Damköhler index and skewness coefficient for selecting a suitable modelling framework (transient storage or advection–dispersion) for pollutant transport dynamics. A numerical algorithm for simulating pollutant transport dynamics in unsteady flow regimes is proposed by Zhang and Aral (2004). The numerical experiments revealed that the k – ε turbulence closure captures the features of three-dimensional pollutant mixing in rivers (Wilson et al. 2007). Ani et al. (2009) found that the inclusion of a transient storage term improves the reliability of predicted concentration breakthrough curves. Employing a one-dimensional advection–dispersion model, the spatiotemporal distribution of pollutant concentrations resulting from accidental releases in rivers is examined by Guo and Cheng (2019). Zhang et al. (2026) developed a physics-informed neural network framework for simulating pollutant transport dynamics in vegetated flows. Literature suggests that the downstream transport of pollutants in rivers is primarily governed by advection and dispersion processes. The longitudinal dispersion coefficient plays a pivotal role in determining the accuracy and uncertainty of pollutant transport simulations (Chapra 1997). It accounts for the combined effects of channel geometry, velocity variations, turbulence, and transverse mixing (Chapra 1997). Accordingly, a reliable estimate of the longitudinal dispersion coefficient is required to simulate pollutant transport dynamics in rivers (Fischer 1967; Fischer et al. 1979; Noori et al. 2021).

The direct methods, such as the method of moments, routing procedure, Krenkel and Chatwin graphical method, crown of concentration method, etc., employ the field tracer concentration data to estimate longitudinal dispersion coefficient (Oliveira et al. 2017). The requirement of field concentration data in direct methods encourages the use of empirical formulations. The empirical formulations use hydraulic and geometric parameters to predict the longitudinal dispersion coefficient. The seminal work of Taylor (1953) demonstrated that

the spreading of solute in a laminar flow can be represented as an equivalent diffusion process. Subsequently, Taylor (1954) extended the theory to turbulent pipe flows and proposed a formulation to estimate the effective longitudinal dispersion coefficient. Building on Taylor's (1954) pioneering work, Elder (1959) proposed one of the earliest formulations of longitudinal dispersion coefficient for open channel flows. Presuming a uniform flow in an infinitely wide channel, he expressed longitudinal dispersion coefficient in terms of the shear velocity and flow depth. Nonetheless, owing to the negligence of the transverse velocity gradients, the Elder's (1959) formulation found limited applicability in natural scenarios. Employing field data from 18 watercourses, McQuivey and Keefer (1974) identified that the longitudinal dispersion coefficient remains inversely proportional to the longitudinal bed slope. Fischer (1967) recognized the influence of lateral mixing on longitudinal dispersion in natural streams. Employing multi-regression techniques, Seo and Cheong (1998) analysed concentration profile data from 26 watercourses in United States. They identified that, in addition to hydraulic parameters, the channel aspect ratio controls the magnitude of longitudinal dispersion coefficient. Using field data from literature, Wang and Huai (2016) employed log-linear regression to propose a formulation for the longitudinal dispersion coefficient.

In recent years, owing to advancements in computational intelligence, soft computing and machine learning techniques have been used for predicting the longitudinal dispersion coefficient. For instance, approaches such as artificial neural networks, fuzzy inference systems, support vector machines, adaptive neuro-fuzzy inference systems, and gene-expression programming have been employed to model the intricate nonlinear relationships between flow characteristics and longitudinal dispersion coefficient (Tayfur and Singh 2005; Tayfur 2006; Toprak and Cigizoglu 2008; Noori et al. 2009; Sahay and Dutta 2009; Sahay 2011; Etemad-Shahidi and Taghipour 2012). In addition, several studies explored hybrid optimization and evolutionary algorithms to further improve the prediction accuracy of the longitudinal dispersion coefficient (Najafzadeh and Tafarjnoruz 2016; Balf et al. 2018; Parsaie et al. 2018; Memarzadeh et al. 2020). However, considerable uncertainty remains regarding the reliability of existing formulations (Noori et al., 2016). To this end, Seifi and Riahi-Madvar (2019) compiled a comprehensive tracer study database comprising measurements from laboratory flumes and natural rivers worldwide. Subsequently, Noori et al. (2021) conducted a detailed reliability assessment and demonstrated that the relative importance of aspect ratio and friction depends strongly on channel geometry. It is observed that, in narrow streams, the pollutant transport dynamics is controlled by the channel aspect ratio (Etemad-Shahidi and Taghipour 2012, Noori et al. 2021). On the other hand, the shear velocity ratio governs the pollutant dynamics in wide channels (Etemad-Shahidi and Taghipour 2012, Noori et al. 2021). The findings suggest that a single universal dispersion equation is unlikely to be applicable across all river geometries.

The discussion reveals that numerous formulations were developed for longitudinal dispersion coefficient in rivers (Koussis and Rodríguez-Mirasol 1998; Iwasa and Aya 1991; Seo and Cheong 1998; Deng et al. 2001; Kashefipour and Falconer 2002). The existing formulations for the longitudinal dispersion coefficient are compiled in Ghaemi et al. (2021). In addition, the preceding discussion highlights the importance of pollutant transport dynamics in rivers, which motivated extensive investigation by researchers. However, there remains scope for further analysis. Most of the existing formulations for longitudinal dispersion coefficient used data from both narrow and wide channels. However, the underlying dispersion mechanism is sensitive to the channel regimes (Etemad-Shahidi and Taghipour 2012, Noori et al. 2021), making a unified treatment potentially inadequate. In addition, the numerical studies reveal that no single existing longitudinal dispersion coefficient formulation performs well for both experimental and field datasets (Abderrezzak et al. 2015). Some formulations are suitable for experimental conditions, while others provide better predictions for field conditions

(Abderrezzak et al. 2015). Moreover, the pollutant transport dynamics associated with instantaneous and continuous release scenarios across different channel geometries warrant detailed investigation.

Table 1 A few existing formulations for longitudinal dispersion coefficient $\tilde{K}$

Reference	Method	Longitudinal dispersion coefficient $\tilde{K}$
Elder (1959)	Empirical	5.93Ξ
Fischer (1967)	Empirical	$0.011\beta^2\Xi^{-1}$
Liu (1977)	Empirical	$0.18\beta^2\Xi^{-0.5}$
Koussis and Rodriguez-Mirasol (1988)	Empirical	$0.6\beta^2\Xi$
Iwasa and Aya (1991)	Empirical	$2\beta^{1.5}\Xi$
Seo and Cheong (1998)	Empirical	$5.92\beta^{0.62}\Xi^{-0.43}$
Li et al. (1998)	Empirical	$0.55\beta h^{-2}\Xi$
Kashefipour and Falconer (2002)	Empirical	$[7.428 + 1.775\beta^{0.62}\Xi^{0.572}]\Xi^{-1}$
Sahay and Dutta (2009)	Genetic algorithm	$2\beta^{0.96}\Xi^{0.25}$
Etemad-Sahidi and Taghipour (2012)	Model tree	$15.49\beta^{0.78}\Xi^{0.89}, \beta \leq 30.6$ $14.12\beta^{0.61}\Xi^{0.15}, \beta > 30.6$
Li et al. (2013)	Differential evolution algorithm	$2.28\beta^{0.76}\Xi^{0.47}$
Zeng and Huai (2014)	Empirical	$5.4\beta^{0.7}\Xi^{-0.13}$
Wang and Huai (2016)	Empirical	$17.65\beta^{0.36}\Xi^{-0.16}$
Alizadeh et al. (2017)	Particle swarm optimization	$5.32\beta^{1.21}\Xi^{0.925}, \beta \leq 28$ $9.93\beta^{0.19}\Xi^{-0.8}, \beta > 28$
Ukpaka and Agunwamba (2024)	Empirical	$21.16\beta^{-0.012}\Xi^{0.056}$

The present study therefore endeavours to propose new empirical formulations for longitudinal dispersion coefficient in narrow and wide channel regimes. The threshold separating narrow and wide channel regimes is determined from the observed trends in field-derived dispersion coefficients. Subsequently, the proposed formulation for dispersion coefficient is used in the one-dimensional advection–dispersion equation to simulate the pollutant transport dynamics for instantaneous and continuous release scenarios. Finally, the pollutant concentration profiles are compared with the existing studies.

A new formulation for longitudinal dispersion coefficient

The longitudinal dispersion coefficient K is a physical parameter used to model the spreading of pollutants in fluvial systems. The spreading of pollutants in natural scenarios is dependent on the geometric and kinematic properties of the flows (Seo and Cheong 1998). The dimensional analysis reveals that the dimensionless dispersion coefficient $\tilde{K} [= K(uh)^{-1}]$ can be expressed in terms of the shear velocity ratio $\Xi (= u_* u^{-1})$ and channel aspect ratio $\beta (= wh^{-1})$ (Seo and Cheong 1998; Wang and Huai 2016). Here, the u denotes the uniform flow velocity, h is the flow depth, u_* is the shear velocity, and w represents the channel width. A few existing formulations for the longitudinal dispersion coefficient are presented in Table 1. The hydraulic aspects of narrow channels—that manifests velocity dip phenomenon—differs from the wide channels (Dey 2024). Hence, herein, we propose a regime-based formulation for $\tilde{K}$. It reads

$$\tilde{K} = \wp \beta^a \Xi^b \quad (1)$$

where $\wp$ is a coefficient, and a and b are exponents. Note that, herein, the channels are classified as narrow and wide for $\beta \leq 10$ and $\beta > 10$, respectively (Isma et al. 2025). To obtain $\wp$, a and b , we perform a regression analysis employing ample field data from literature. The regression analysis employs 105 data plots characterizing a wide range of flow and geometric conditions (Sooky 1969; Godfrey and Frederick 1970; Yotsukura et al. 1970; Yotsukura and Cobb 1972; McQuivey and Keefer 1974; Nordin and Sabol 1974; Devens et al. 2006; Ribeiro et al. 2010; Oliveira 2013; Pereira et al. 2016; Wang and Huai 2016; Oliveira et al. 2017; Palu and Julien 2019). The employed data plots are made available as electronic supplementary material. For narrow and wide channels, the regression analysis offers $\wp$, a and b as (1.11, 12.98), (1.13, 0.18), and (0.27, -0.65), respectively. The overall coefficient of determination and root mean square error are found to be 0.83 and 35.14, respectively. These estimates advocate that the proposed model is more reliable compared to the existing ones (Alizadeh et al. 2017).

Numerical framework

The pollutant transport in fluvial systems is governed by the advection–dispersion equation. Literature suggests that the pollutant transport in fully developed flows can be modelled employing a one-dimensional approach (da Silva et al. 2025). The advection–dispersion equation in one-dimensional form reads

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} = K \frac{\partial^2 c}{\partial x^2} \quad (2)$$

where c denotes the depth-averaged pollutant concentration, t is the time, and x measures the longitudinal distance. The advection and diffusion terms in Eq. (2) model the transport and spreading of pollutants, respectively. Herein, we solve Eq. (2) numerically employing finite difference method. The discretized equation reads

$$c_i^{n+1} = c_i^n - 0.5\lambda_1(c_{i+1}^n - c_{i-1}^n) + (0.5\lambda_1^2 + \lambda_2)(c_{i+1}^n - 2c_i^n + c_{i-1}^n) \quad (3)$$

where (i, n) represent spatial grid point and time level, respectively, $\lambda_1 [= u\Delta t(\Delta x)^{-1}]$ and $\lambda_2 [= K\Delta t(\Delta x)^{-2}]$ are Courant number and dispersion number, respectively, and Δt and Δx are temporal and spatial step size. Note that the advection term, owing to hyperbolic nature, is discretized employing the explicit Lax–Wendroff scheme (Hoffman and Chiang 2000). A full Lax–Wendroff treatment needs higher order derivatives and longer stencil. Hence, the diffusion term uses central difference with forward Euler time stepping (Hoffman and Chiang 2000). The discretization of advection term is second-order accurate in time and space, whereas the diffusion term discretization is first-order accurate in time. Accordingly, the employed scheme has first and second-order accuracies in time and space, respectively.

A von Neumann stability analysis suggests that the Lax–Wendroff scheme coupled with explicit diffusion is conditionally stable. The stability criteria reads $\lambda_1^2 + 2\lambda_2 \leq 1$. Note that the derived stability criteria is used to select a suitable computational time step. The discretized equation is employed to simulate pollutant transport for two cases: instantaneous release of pollutants and continuous release of pollutants. For instantaneous release of pollutants, the initial condition is presumed in the form of a Gaussian function centered at x_0 . It reads

$$c(x, 0) = c_0 \exp[-0.5\sigma^{-2}(x - x_0)^2], 0 < x < L \quad (4)$$

where c_0 is the initial peak concentration, σ indicates the standard deviation of the Gaussian function modelling the initial spread of pollutants, and L denotes the length of the stretch. In addition, the boundary conditions for the instantaneous release case are taken as $c(0, t) = 0$ and $dc/dx|_{x=L} = 0$. The initial condition for the continuous release case is presumed as $c(x, 0) = 0$ for $0 < x < L$. Besides, for continuous release, the boundary conditions are taken as follows: $c(0, t) = (c_s, 0)$ for $(0 < t \leq t_d, t > t_d)$, where c_s denotes the pollutant concentration at source and t_d indicates the time interval for release. Akin to the instantaneous release case, we consider a vanishing concentration gradient at the downstream. Finally, we perform a grid sensitivity analysis. It is observed that the results become independent of the grid size for $\Delta x < 2$ m. Hence, the computations are performed considering Δx equalling 1 m.

Results and discussion

Firstly, we examine the robustness of the proposed model for the longitudinal dispersion coefficient. To this end, Fig. 1 furnishes a comparison of the predicted and observed values of the dimensionless dispersion coefficient $\tilde{K}$. The observed field data are taken from Sooky (1969), Yotsukura et al. (1970), Godfrey and Frederick (1970), Yotsukura and Cobb (1972), McQuivey and Keefer (1974); Nordin and Sabol (1974), Devens et al. (2006), Ribeiro et al. (2010), Oliveira (2013), Pereira et al. (2016), Oliveira et al. (2017), and Palu and Julien (2019). The considered dataset includes both narrow and wide regimes of the streams. The solid line highlights the line of best agreement. Conversely, the broken lines manifest $\pm 20\%$ error bands. We observe that most of the field data plots fall within the error bands. The inset presents an enlarged view of the data plots clustered up to $\tilde{K}$ equalling 20. In general, the predictions are congruent with the field observations. The deviations may be ascribed to the uncertainties in the field measurements.

It is interesting to compare the proposed formulation for dimensionless dispersion coefficient $\tilde{K}$ with existing relations. Towards that end, Figs. 2–3 present the variations of $\tilde{K}$ with the shear velocity ratio Ξ for narrow and wide channels, respectively. The channel aspect ratios β for narrow and wide channels are taken as 5 and 20, respectively. The formulations proposed by Elder (1959), Fischer (1967), Liu (1977), Koussis and Rodríguez-Mirasol (1998),

Iwasa and Iya (1991), Seo and Cheong (1998), Li et al. (1998), Kashefipour and Falconer (2002), Sahay and Dutta (2009), Etemad-Shahidi and Taghipour (2012), Li et al. (2013), Zeng and Huai (2014), Wang and Huai (2016), Alizadeh et al. (2017), and Ukpaka and Agunwamba (2024) are considered for comparison (also in Fig. 4). We observe that the $\tilde{K}$ manifests differing behavior in narrow and wide channels. In a narrow channel, the $\tilde{K}$ augments as the $\mathcal{E}$ increases. Conversely, the $\tilde{K}$ in a wide channel decline with an augmentation in $\mathcal{E}$. An increase in $\mathcal{E}$ is associated with an amplification in the near-bed velocity gradient (Dey et al. 2023; 2024). Consequently, the reinforcement of differential advection between adjacent fluid layers enhances shear-induced dispersion. The shear-induced dispersion promotes the longitudinal spreading of pollutants causing an increase in $\tilde{K}$. The contrasting behavior observed in wide channels may be owing to the dominance of transverse turbulent mixing over shear-induced spreading. The augmented lateral and vertical mixing in a wide channel promotes rapid homogenization of the pollutant concentration across the channel cross-section. Consequently, the $\tilde{K}$ diminishes. A look at Figs. 2–3 reveal substantial variability in the $\tilde{K}$ obtained from the various existing relations. Moreover, it is evident that the existing relations fail to capture the contrasting behaviors of the $\tilde{K}$ in narrow and wide channels. The observation suggests that, compared to the existing relations, the proposed formulation provides a more reliable representation of dispersion behavior, particularly in distinguishing between narrow and wide channel regimes.

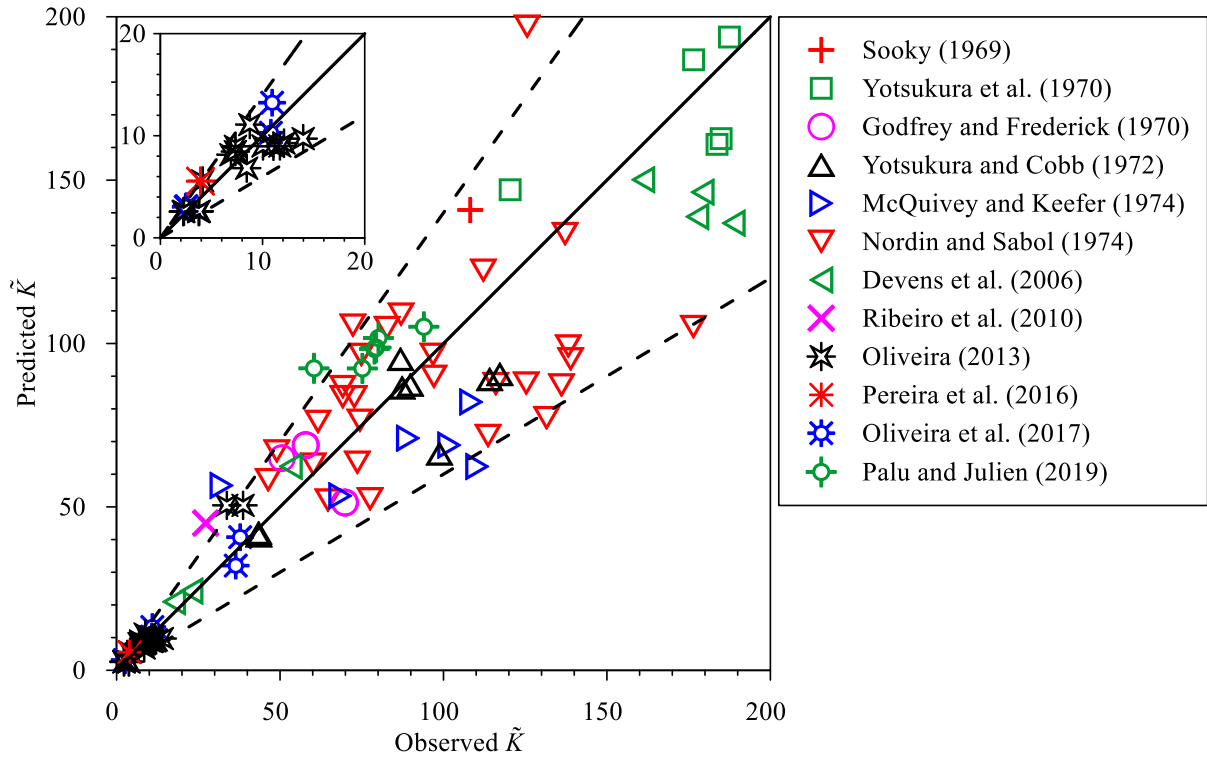


Fig. 1 Comparison of the predicted dimensionless dispersion coefficient $\tilde{K}$ with the observed field data of various authors.

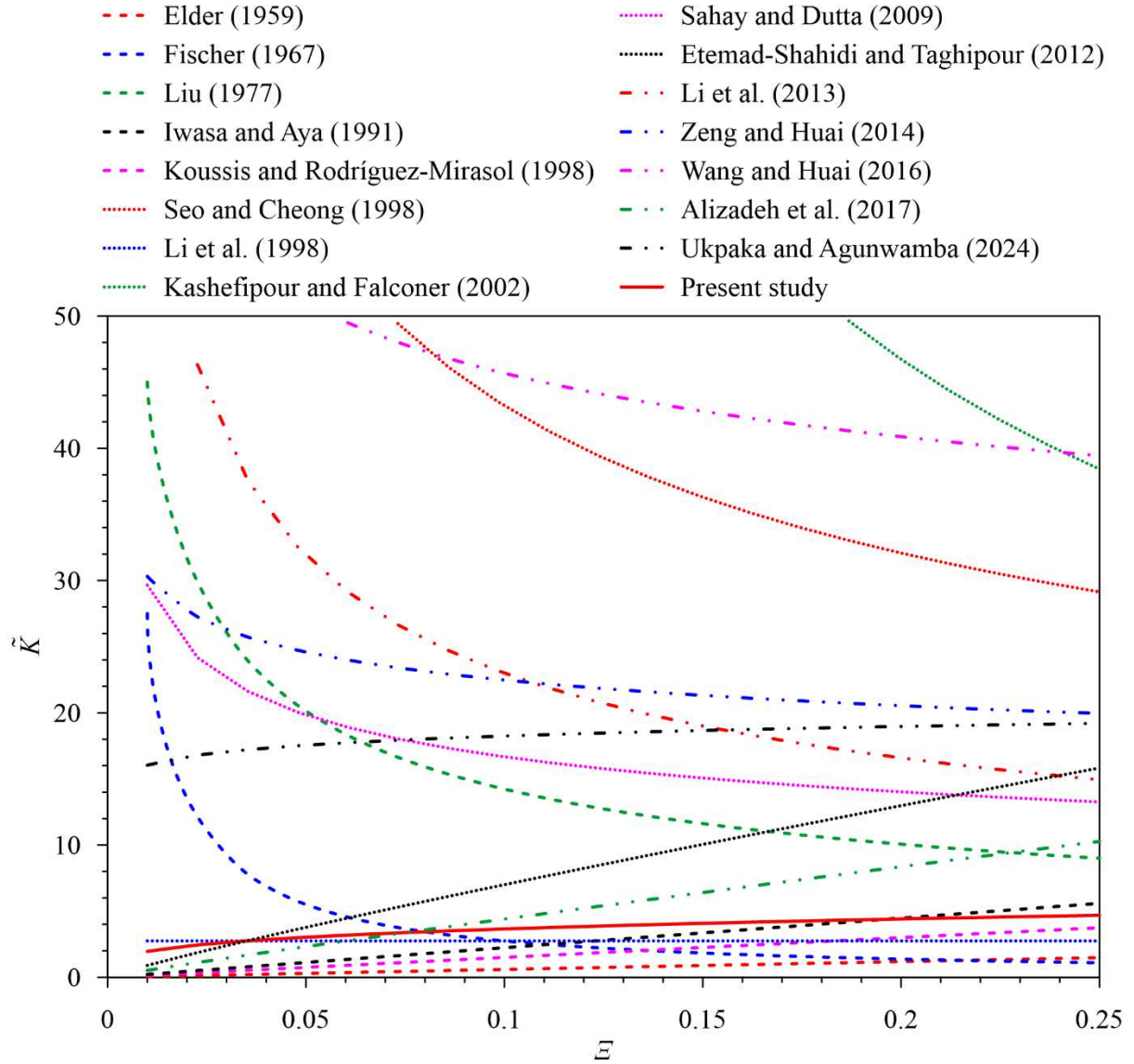


Fig. 2 Variations of the predicted dimensionless dispersion coefficient $\tilde{K}$ with the shear velocity ratio $\mathcal{E}$ in a narrow channel. The formulations proposed by Elder (1959), Fischer (1967), Liu (1977), Iwasa and Iya (1991), Koussis and Rodríguez-Mirasol (1998), Seo and Cheong (1998), Li et al. (1998), Kashefipour and Falconer (2002), Sahay and Dutta (2009), Etemad-Shahidi and Taghipour (2012), Li et al. (2013), Zeng and Huai (2014), Wang and Huai (2016), Alizadeh et al. (2017), and Ukpaka and Agunwamba (2024) are considered for comparison.

The comparison with the considered existing relations reveals that, in narrow channels for selected range of the shear velocity ratio, the formulations proposed by Seo and Cheong (1998), Kashefipour and Falconer (2002), Sahay and Dutta (2009), Li et al. (2013), Wang and Huai (2016), Zeng and Huai (2016), and Ukpaka and Agunwamba (2024) overpredict the $\tilde{K}$ (Fig. 2 and 4). On contrary, the formulations proposed by Elder (1959) and Koussis and Rodríguez-Mirasol (1998) underpredicts the $\tilde{K}$ in narrow channels (Fig. 2 and 4). Besides, the formulations of Iwasa and Iya (1991), Etemad-Shahidi and Taghipour (2012), and Alizadeh et al. (2017) underpredicts and overpredicts the $\tilde{K}$ for lower and higher values, respectively, of

the selected range of the shear velocity ratio (Fig. 2 and 4). Conversely, the reverse is true for Fischer (1967) and Li et al. (1998) (Fig. 2 and 4).

For wide channels in selected range of the shear velocity ratio, majority of the considered formulations for comparison—Elder (1959), Fischer (1967), Iwasa and Iya (1991), Li et al. (1998), Sahay and Dutta (2009), Etemad-Shahidi and Taghipour (2012), Li et al. (2013), Zeng and Huai (2014), Alizadeh et al. (2017), and Ukpaka and Agunwamba (2024)—underpredicts the $\tilde{K}$ (Fig. 3 and 4). Conversely, Liu's (1977) formulation overpredicts the $\tilde{K}$ (Fig. 3 and 4). In addition, the relations proposed by Koussis and Rodríguez-Mirasol (1998), Seo and Cheong (1998), and Wang and Huai (2016) underpredict and overpredict the $\tilde{K}$ for lower and higher magnitudes of the shear velocity ratio, respectively (Fig. 3 and 4). On the other hand, the reverse is true for Kashefipour and Falconer (2002) (Fig. 3 and 4).

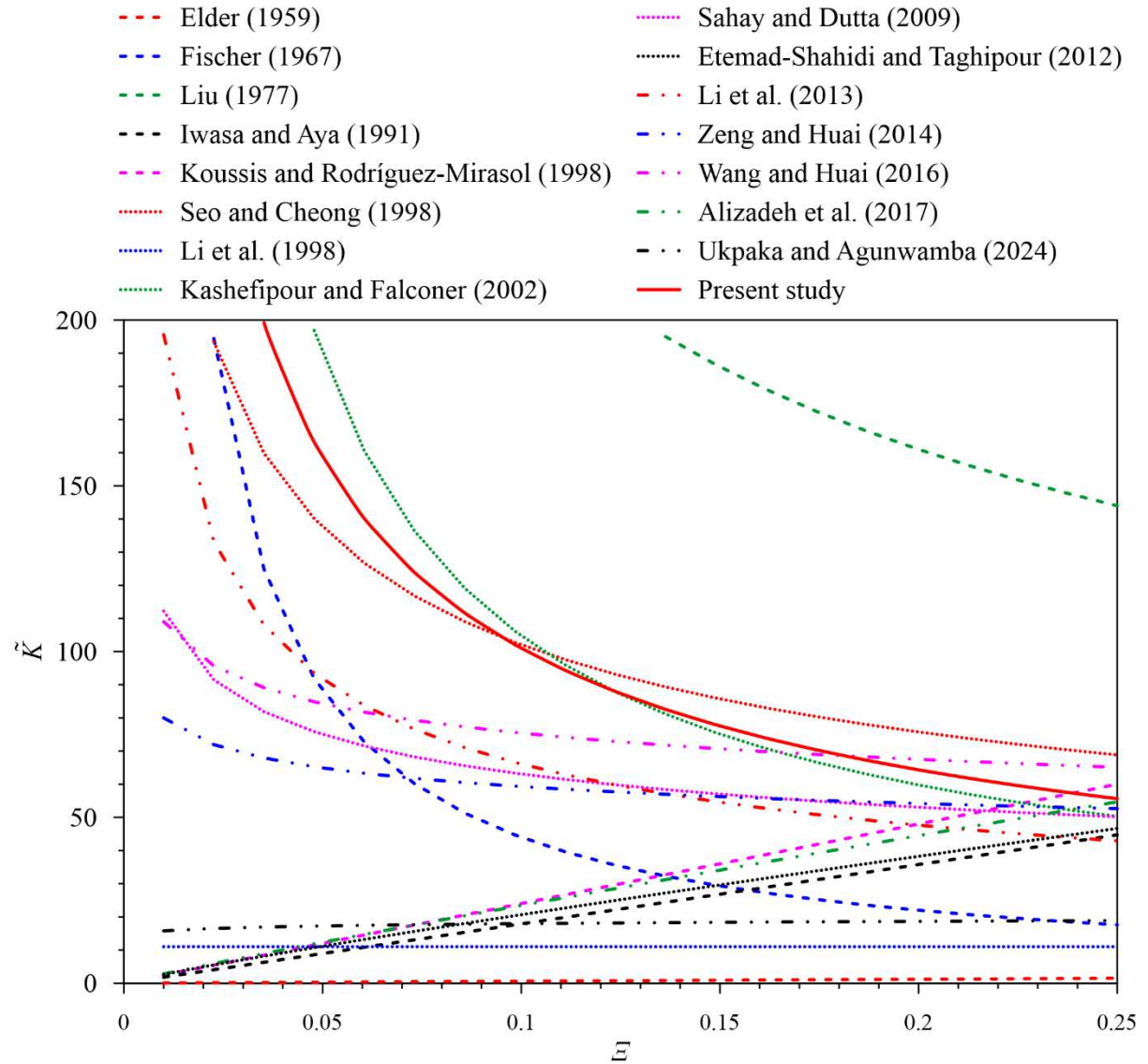


Fig. 3 Variations of the predicted dimensionless dispersion coefficient $\tilde{K}$ with the shear velocity ratio Ξ in a wide channel. The formulations proposed by Elder (1959), Fischer (1967), Liu (1977), Iwasa and Iya (1991), Koussis and Rodríguez-Mirasol (1998), Seo and Cheong (1998), Li et al. (1998), Kashefipour and Falconer (2002), Sahay and Dutta (2009), Etemad-Shahidi and Taghipour (2012), Li et al. (2013), Zeng and Huai (2014), Wang and Huai (2016), Alizadeh et al. (2017), and Ukpaka and Agunwamba (2024) are considered for comparison.

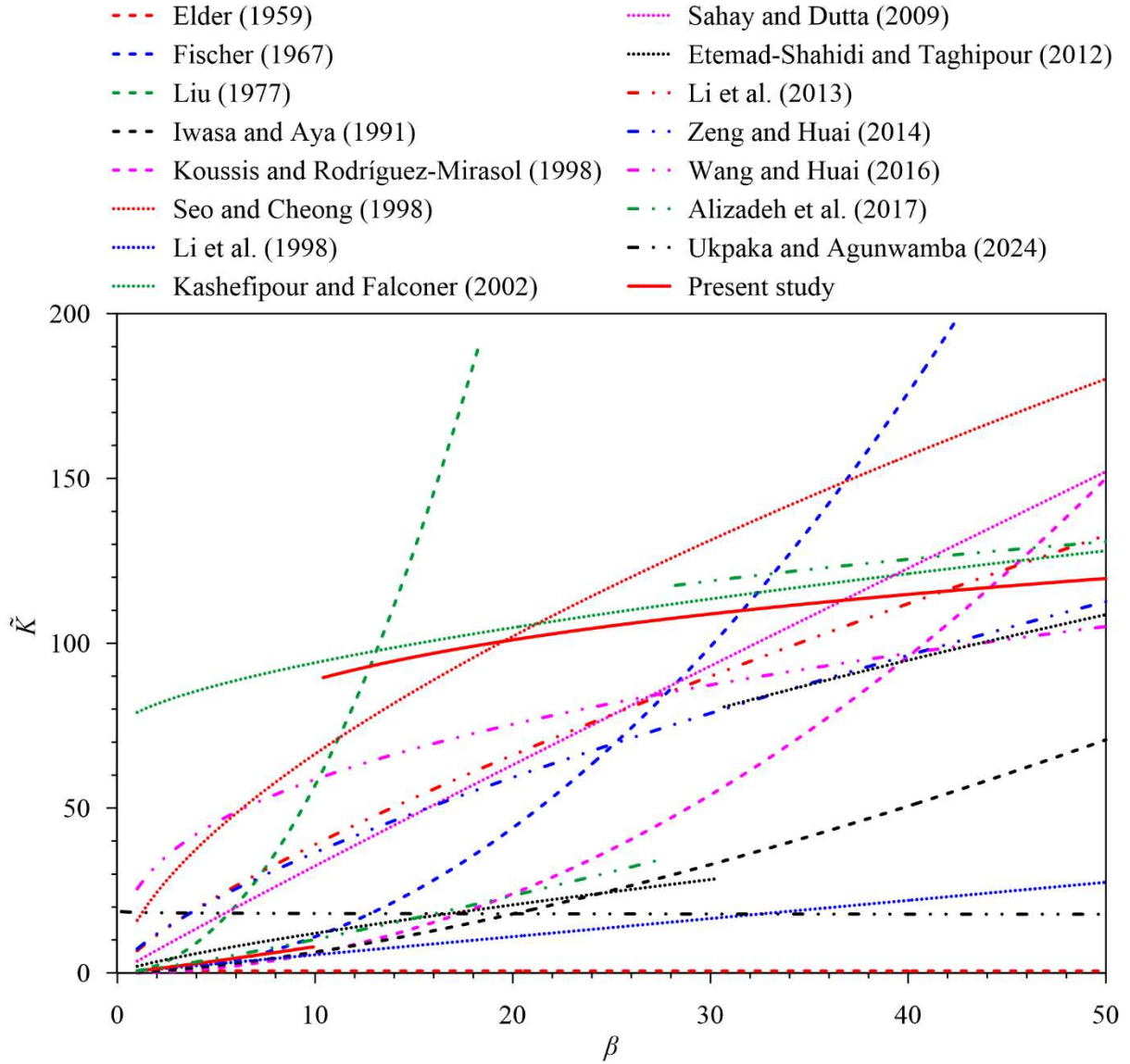


Fig. 4 Variations of the predicted dimensionless dispersion coefficient $\tilde{K}$ with the channel aspect ratio β . The formulations proposed by Elder (1959), Fischer (1967), Liu (1977), Iwasa and Iya (1991), Koussis and Rodríguez-Mirasol (1998), Seo and Cheong (1998), Li et al. (1998), Kashefipour and Falconer (2002), Sahay and Dutta (2009), Etemad-Shahidi and Taghipour (2012), Li et al. (2013), Zeng and Huai (2014), Wang and Huai (2016), Alizadeh et al. (2017), and Ukpaka and Agunwamba (2024) are considered for comparison.

It is intriguing to examine the sensitivity of the dimensionless longitudinal dispersion coefficient $\tilde{K}$ with the channel aspect ratio β . To this end, Fig. 4 furnishes the variations of the dimensionless dispersion coefficient $\tilde{K}$ with the channel aspect ratio β . The shear velocity ratio $\mathcal{E}$ is considered equalling 0.1. We find that, for a given $\mathcal{E}$, an increase in β leads an amplification in $\tilde{K}$. The observation may be ascribed to the amplified differential advection triggered by the lateral velocity non-uniformity. The abrupt change in the predicted dispersion coefficient at β equalling 10 reflects the threshold employed in the proposed model to delineate narrow and wide channel regimes. Note that Etemad-Shahidi and Taghipour (2012) and Alizadeh et al. (2017) considered this threshold equal to 30.6 and 28, respectively. However, the present study

presumes narrow-wide threshold at 10. The consideration indeed offers better alignment with the available field data as discussed in the previous section. For narrow channels, the present predictions closely resemble with Fischer (1967), Iwasa and Iya (1991), Li et al. (1998), Koussis and Rodríguez-Mirasol (1998), and Alizadeh et al. (2017). On the other hand, for wide channels, the predictions are close to Kashefipour and Falconer (2002) and Alizadeh et al. (2017). The observed inconsistencies in the predictions of existing relations may be attributable to their neglect of the threshold governing the transition from narrow to wide channel behavior.

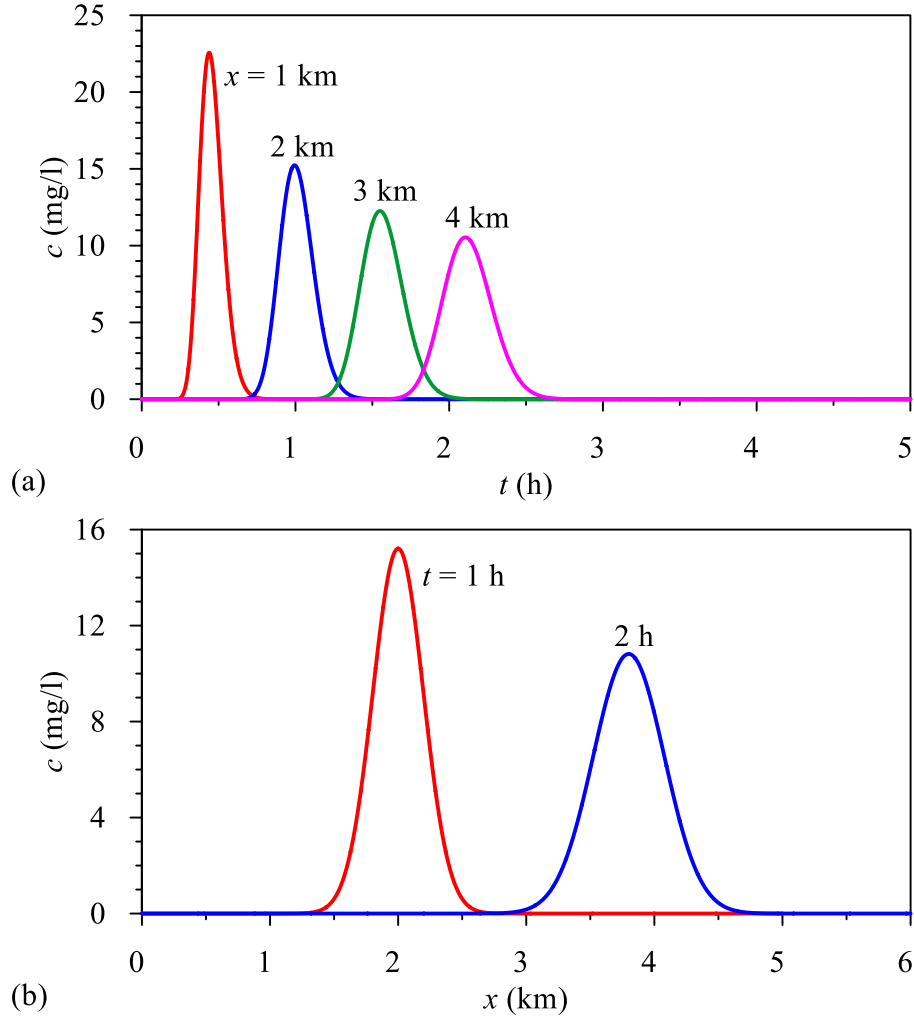


Fig. 5 Pollutant concentration profiles in a narrow channel with instantaneous pollutant release: (a) at various spatial locations and (b) at different time instants.

We now employ the proposed formulation for dimensionless dispersion coefficient to model the pollutant dispersion in streams. Herein, we consider two pollutant release scenario: instantaneous release and continuous release. Firstly, we consider the instantaneous release case. The pollutant release scenarios, such as accidental chemical spills, leakage of hazardous materials from pipelines, untreated wastewater release due to treatment failure, etc., are typical examples of instantaneous release. We found that the dynamics of dispersion differ in narrow and wide channels. Accordingly, the pollutant dispersion in narrow and wide channels are simulated separately. Fig. 5 presents the pollutant concentration profiles at various spatial locations and time instants for a narrow channel with aspect ratio β equalling 6. The length of the reach is taken as 6 km. The initial peak concentration c_0 and the standard deviation of the

Gaussian function σ are presumed as 100 mg/l and 30, respectively. The Gaussian function is considered to be centered at x_0 equal to 200 m. The shear velocity ratio $\mathcal{E}$ is taken as 0.08. We observe that, for a given spatial location or time instant, the concentration profile manifests a peak magnitude. However, the dispersion induced spreading causes the concentration peak to decline as the pollutant plume travels downstream.

For continuous release of pollutants, Fig. 6 furnishes pollutant concentration profiles in a narrow channel with aspect ratio β equal to 6. The consideration resembles intermittent effluent discharges in streams. The shear velocity ratio $\mathcal{E}$ is presumed to be 0.08. We consider a continuous pollutant release for 1.5 h with concentration at source equalling 100 mg/l. A look on the concentration profiles reveal that the dispersion dynamics for continuous release case differs than that of the instantaneous release case. The continuous pollutant release in a narrow channel does not exhibit a well-defined concentration peak. Rather, the concentration remains at its maximum magnitude over a finite temporal interval and spatial extent, forming a broad plateau due to the sustained supply of contaminant mass. For the considered duration of simulation, we do not observe any decay in the pollutant concentration peak. This may be ascribed to the dominance of advection over diffusion for continuous release scenarios in narrow channels.

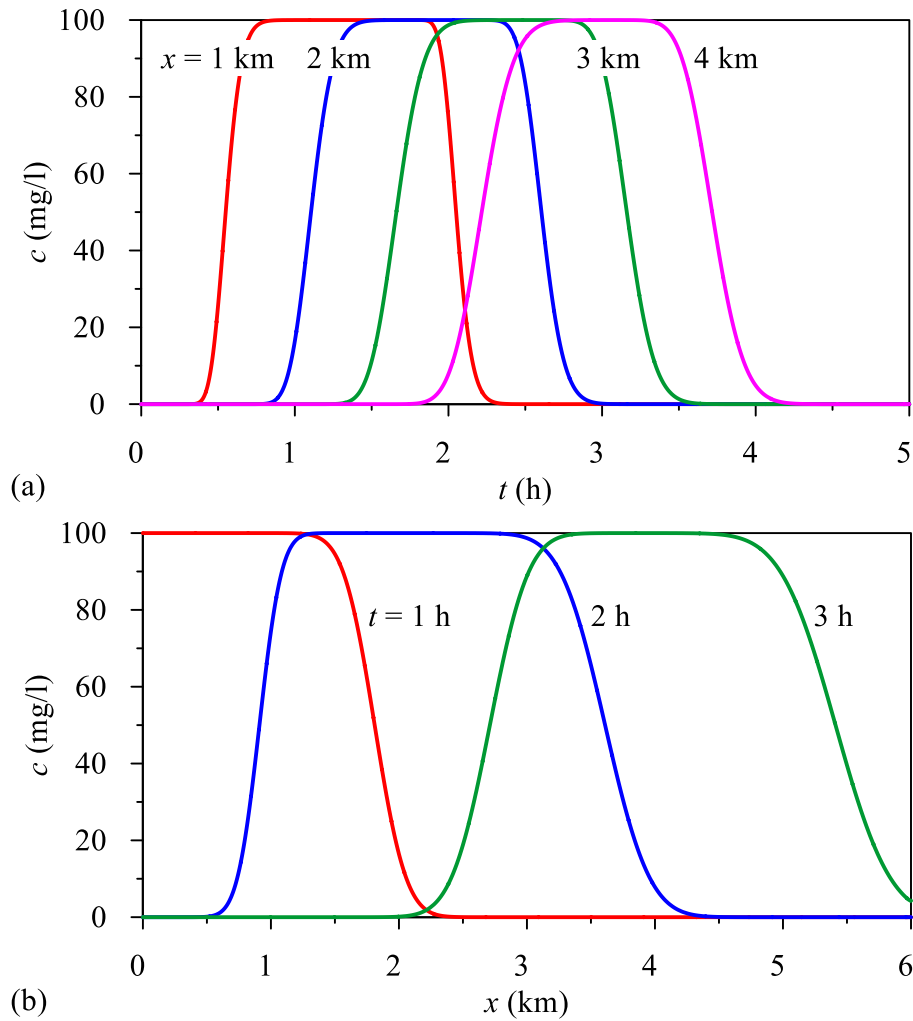


Fig. 6 Pollutant concentration profiles in a narrow channel with continuous pollutant release: (a) at various spatial locations and (b) at different time instants.

We now switch our attention to the case of wide streams. Fig. 7 presents the pollutant concentration profiles in a wide channel with instantaneous release of pollutant. Akin to the instantaneous release in narrow channels, the peak initial concentration c_0 , standard deviation of the Gaussian function σ , and center of the Gaussian function x_0 are considered as 100 mg/l, 30, and 200 m, respectively. The length of the stretch is presumed to be 10 km. The shear velocity ratio Ξ and channel aspect ratio β are taken as 0.08 and 30, respectively. We observe that the attenuation of the concentration profile peaks is more pronounced in wide channels than in narrow channels. This is owing to the augmented dispersion coefficient, which promotes greater spreading and dilution of the pollutant plume. Moreover, we found that the concentration profiles recorded at a given location display a shorter rising limb and a longer falling limb. This implies a relatively rapid arrival of the pollutant plume followed by a gradual decline in concentration due to dispersion and dilution.

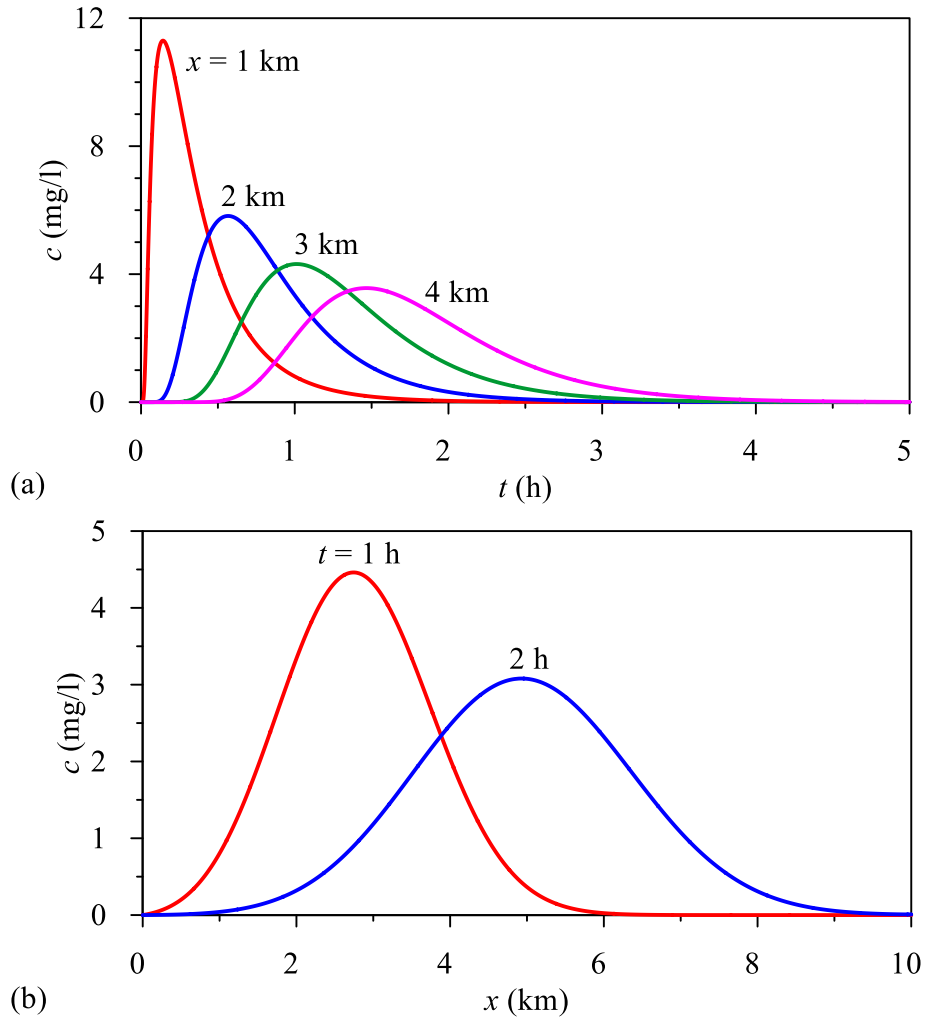


Fig. 7 Pollutant concentration profiles in a wide channel with instantaneous pollutant release: (a) at various spatial locations and (b) at different time instants.

Finally, we examine the continuous pollutant release scenario in a wide channel with channel aspect ratio β equalling 30 (Fig. 8). The shear velocity ratio Ξ is presumed to be 0.08. The pollutant with concentration 100 mg/l is released for 1.5 h. Unlike continuous release scenario in narrow channels, the concentration profiles herein manifest a significant decay of peak concentration. This is due to the augmentation in dispersion coefficient for wide channels.

Moreover, we observe a sharp front in concentration profile at x equal to 1 km. This may be ascribed to the initial dominance of advection over dispersion. The appearance of the sharp front is congruent with the canonical observations (Wallis and Manson 2004; Ani et al. 2009). The continuous release of pollutants maintains a higher peak concentration than that observed in the instantaneous release case due to the sustained input of contaminant mass into the flow.

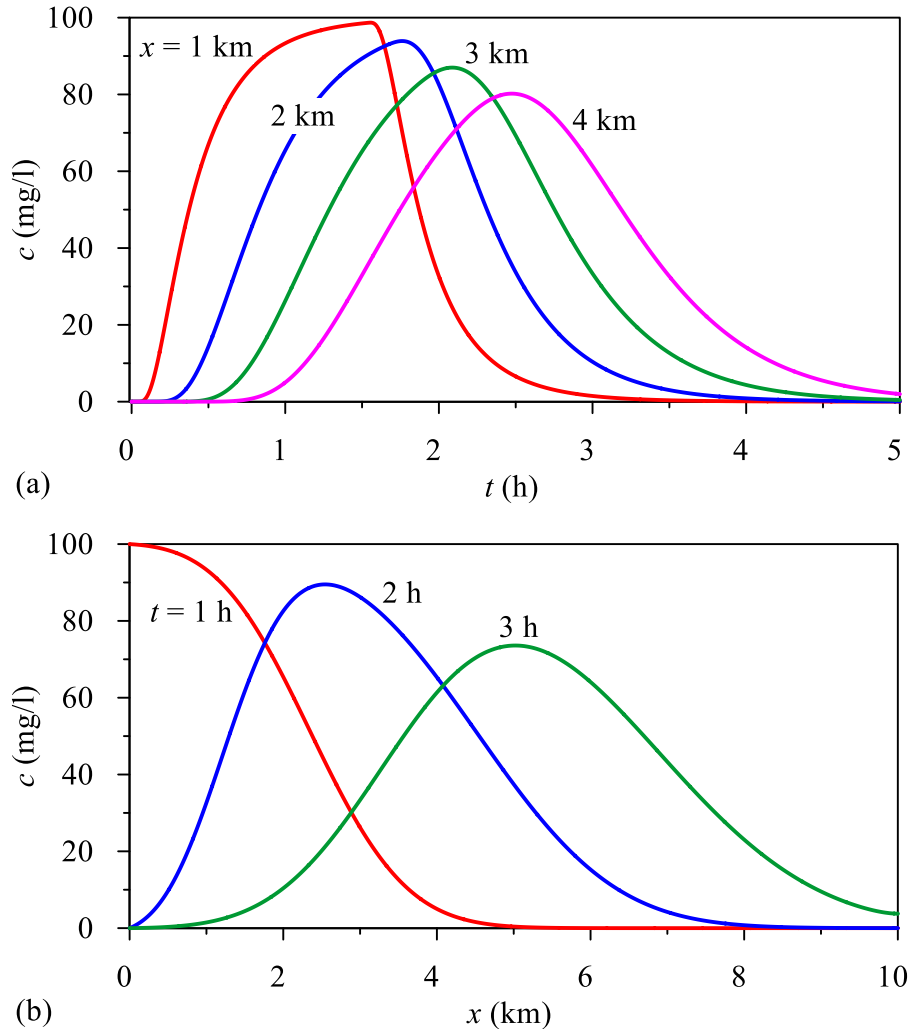


Fig. 8 Pollutant concentration profiles in a wide channel with continuous pollutant release: (a) at various spatial locations and (b) at different time instants.

It is pertinent to compare the predictions of the employed numerical model with the existing analytical solution (Guymer 1998; Jirka and Weitbrecht 2005; Chin 2006) for the instantaneous pollutant release scenario. To this end, Fig. 9 furnishes a comparison of the numerical predictions on concentration profiles with the classical analytical solution. The length of the reach, initial pollutant concentration, channel aspect ratio, and shear velocity ratio are considered as 25 km, 49.88 $\mu\text{g/l}$, 20, and 0.1, respectively. The standard deviation of the Gaussian function is taken as 100. We discover that the numerical predictions with the proposed formulation for dispersion coefficient are congruent with the analytical solution. This highlights the reliability of the proposed model for dispersion coefficient. The numerical solution predicts slightly lower peak concentrations than the analytical solution, which may be attributed to the numerical diffusion introduced by the discretization scheme. Numerical diffusion smoothens the concentration gradients, resulting in attenuation of the concentration

peak and a broader pollutant plume. Furthermore, the analytical concentration profiles exhibit a slight lag relative to the numerical profiles. This discrepancy may arise from the differences in the treatment of advection and dispersion processes in analytical and numerical approaches.

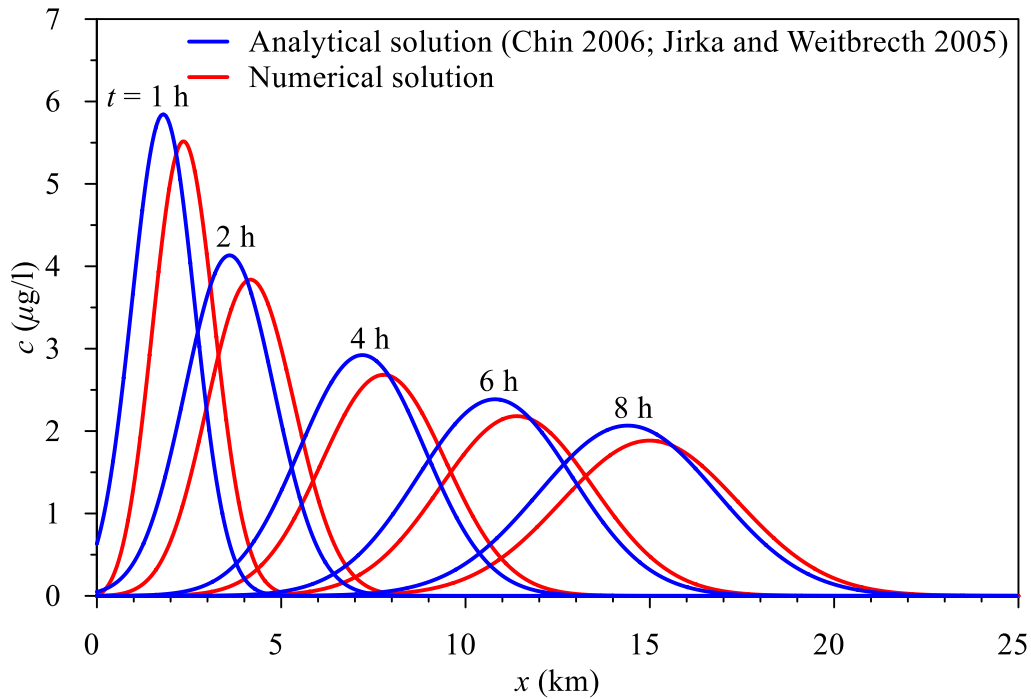


Fig. 9 Comparison of the numerically estimated pollutant concentration profiles with the existing analytical solution for instantaneous release scenario.

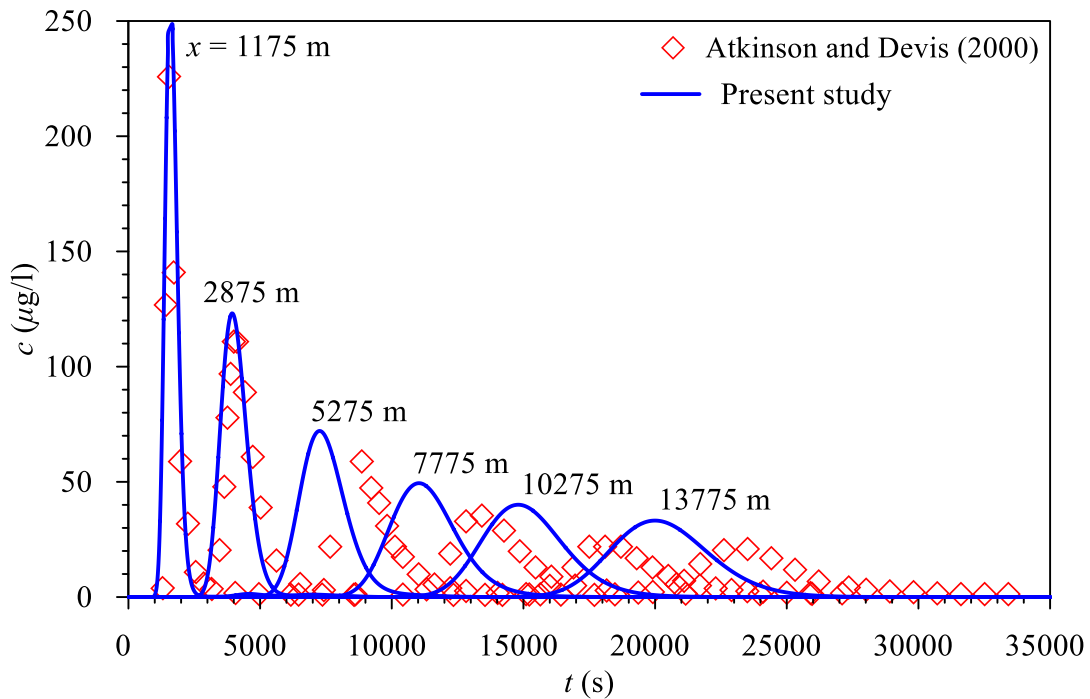


Fig. 10 Comparison of the numerically estimated pollutant concentration profiles with the field observations of Atkinson and Devis (2000).

Finally, we compare the numerical predictions with the field observations of Atkinson and Devis (2000) (Fig. 10). Atkinson and Devis (2000) performed field tracer studies in a selected reach of the Severn River. The field measurements are taken over a stretch of 13.775 km. Note that the numerical predictions are obtained considering field measurements at x equal to 210 m as initial condition. In general, the numerical predictions are in agreement with the field observations. However, compared to numerical predictions, the field observations manifest slightly lower magnitudes of peak concentration. Moreover, the observed concentration profiles appear to lead the concentration profiles obtained from the numerical framework. The discrepancy may be attributed to the enhanced dilution, transient storage, lateral inflows, and other mixing processes that are disregarded in the numerical framework. The leading concentration profiles suggest faster pollutant transport in the field, possibly due to spatial variability in flow velocity, preferential flow paths, or uncertainties in the estimated hydraulic and dispersion parameters.

Conclusions

We examine the pollutant transport dynamics in rivers. Firstly, we propose new formulations for longitudinal dispersion coefficient in narrow and wide channels. Based on the observed trends in field-derived datasets, the threshold for demarcating narrow and wide channels is set at channel aspect ratio equalling 10. The developed formulations unveil that the longitudinal dispersion coefficient has a nonlinear dependency on the channel aspect ratio and shear velocity ratio. Finally, the robustness of the proposed formulations is evaluated through comparison with several existing formulations reported in the literature.

We then employ the proposed formulations of dispersion coefficient in one-dimensional advection–dispersion equation to simulate the pollutant concentration profiles. The numerical simulations are performed for instantaneous and continuous pollutant release scenarios in narrow and wide channels. The pollutant concentration profiles in a narrow channel with instantaneous release manifest a distinct peak concentration. Conversely, for continuous release scenario, the pollutant concentration remains at its maximum magnitude for a finite temporal interval and spatial extent. The observation may be ascribed to the sustained input of pollutant and dominance of advection compared to dispersion in narrow channels. For instantaneous release case, the enhanced dispersion in wide channels causes the intensified attenuation of the concentration peak. Unlike the observed peak concentration for finite time interval and spatial extent for continuous release case in narrow channels, the wide channels characterize a decay of peak concentration. The predicted pollutant concentration profiles are congruent with the classical analytical solution and field observations of Atkinson and Devis (2000).

In essence, this study offers a reliable formulation for longitudinal dispersion coefficient. Moreover, the study unveils the dynamics of pollutant transport for instantaneous and continuous pollutant release scenarios in narrow and wide channels. However, herein, the effects of river curvature, floodplain exchange, and vegetation resistance are disregarded. In addition, this study does not account for reactive transport processes such as decay, transformation, or biogeochemical interactions. Besides, the omnipresent three-dimensional aspects are not considered herein. These aspects may be explored in future studies to further enhance the applicability and robustness of the proposed framework.

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Declarations

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Data availability The datasets generated and analyzed during the current study are made available as supplementary material.

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