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NUMERICAL INVESTIGATION OF RIVER BED FORMS ON POLLUTION DISPERSION

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ABSTRACT

This study numerically investigates the effects of different riverbed forms (flat, ripple, and dune) on pollutant dispersion in open channels using the Flow-3D model and computational fluid dynamics (CFD). The numerical simulations were operated using the Reynolds-averaged Navier-Stokes (RANS) equations which was coupled with an advection-dispersion model for three distinct bed forms. Sodium chloride is used as a tracer material to track pollutant transport. The results reveal that bed forms profoundly influence pollutant dispersion rates in open channels. Ripple beds exhibited the fastest dispersion due to enhanced turbulence and mixing, promoting the breakdown and transport of pollutant particles throughout the water column. In contrast, flat beds displayed the slowest dispersion owing to minimal turbulence and mixing, resulting in higher pollutant concentrations near the source. Dune beds exhibited intermediate dispersion rates compared to ripple and flat beds, with complex flow patterns inducing both turbulence and stratification, leading to variations in dispersion based on flow conditions and pollutant properties. In addition, flow characteristics like velocity, and surface roughness played crucial roles, with higher velocities and rougher beds generally promoting faster dispersion through increased turbulence and mixing. However, excessively high velocities could also hinder dispersion by forming flow separation zones that trap pollutants.

Keywords: Bed form, Pollutant dispersion, Dune bed, Ripple bed, Flat bed

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INTRODUCTION

Rivers serve as vital water resources for human consumption, irrigation, and industrial activities (Aroua, 2022; 2023). However, the increasing use of chemicals and the generation of waste products have led to a growing concern regarding water pollution (Adjagodo et al., 2016; Baba Hamed, 2021; Zegait et al., 2021; Makhoukh et al., 2011). The dispersion of pollutants in rivers is a complex phenomenon influenced by various factors, including flow conditions, channel geometry, and bed form morphology (Bahroun and Kherici-Bousnoubra, 2011). Bed forms, the irregular patterns on the riverbed caused by sediment transport, play a significant role in pollutant dispersion by affecting turbulence, mixing, and flow patterns (Chabokpour and Azamathulla, 2022; Yuan et al., 2018). Access to clean, sufficient, and good-quality water is one of the most prominent conditions for achieving sustainable development (Remini, 2010; Faye, 2017; Faye et al., 2018; Ihsan and Desroya, 2024). Among water resources, rivers are among the most important sources of water supply used for drinking, agriculture, irrigation, and industry (Kumar et al., 2009). Unfortunately, today, with the advancement of industry and technology, surface waters and rivers are mainly used as the primary and major disposal sites for wastewater and effluents from industrial and agricultural activities. This leads to a reduction in the quality of water resources for various downstream uses of rivers (Neary and Odgaard, 1993). Recent studies have shown that continuous fluid exchange between the main river channel and bed sediments, river banks, and the saturated zone beneath the bed increases the likelihood of biological and chemical activities, while simultaneously causing the retention of dissolved matter in the water body, which delays the transport of pollutants downstream (Yuan et al., 2021). The dispersion of pollution in rivers has received particular attention in recent years due to its environmental consequences, especially the risks posed to humans. Accordingly, many researchers have focused on this issue. In general, the stages of pollution dispersion in rivers are divided into three main categories (Chabokpour, 2020).The first stage is depth mixing, the second stage is lateral mixing, and the final stage is longitudinal mixing. Given the importance of longitudinal mixing, studying this phenomenon is particularly important. One of the main characteristics of longitudinal pollutant dispersion in rivers and open channels is the longitudinal dispersion coefficient, which is a fundamental parameter in the hydraulic modeling of river pollution. Therefore, when a pollutant enters a flow, the processes that occur can be divided into three parts. these three parts can be categorized as follows: first) dispersion near the release point of the material due to the initial momentum and buoyancy force, second) lateral dispersion due to transverse dispersion, and third) longitudinal shear dispersion of the flow (Chao et al., 2004; Xin et al., 2010). (Hamidifar and Omid, 2013) investigated the geometric and behavioral structure of flow and the type of turbulence in compound channels interacting with rigid floodplain vegetation. Their laboratory study examined the mean flow structure and turbulent flow parameters in a straight prismatic compound channel. The experiments were conducted under two conditions, with and without vegetation, at three different relative depths. Ultimately, the comparison of results indicated that flow characteristics and vegetation cover have a significant interrelationship, and these flow characteristics, such as Reynolds number, Froude number, and mean flow velocity, are altered with higher or lower vegetation cover. Ansari (2015) simulated bed topography and flow around groynes using Flow-3D. He investigated scour and 3D flow patterns around permeable double-row and rock-mattress groynes. Effects of groyne spacing and porosity on scour and flow were studied. Flow-3D showed good capability in correlating with experimental data for scour depth and velocity profiles. Noori et al. (2011) developed a neural network model based on gradient descent with momentum and resilient back propagation training functions to predict the longitudinal dispersion coefficient in rivers. Parsaie et al. (2014) and Sukhodolov et al. (2002) modeled pollutant transport in waterways with dead zones using the fractional advection-dispersion equation. Numerical methods were used to solve the equation for non-uniform flow. Parameters influencing pollutant transport prediction were estimated by mathematical optimization. Real data from Boas Creek, California, were used to validate the model's accuracy. Results showed acceptable agreement between the model and observational data. The presented solution method was accurate for simulating pollutant transport in waterways with dead zones. Amiri et al. (2021) utilized the approximate inverse method to determine the spatial and temporal distribution of pollutant concentration inversely over time. The main objective of this research was to inversely solve the advection-dispersion equation and obtain information about the release time and time-series data of pollutant concentration discharged into rivers. In this study, the approximate inverse method was employed, which involves adding a stabilizing term (fourth-derivative term) to the advection-dispersion equation, allowing the equation to be solved inversely without causing instability in the solutions. This method was applied to a hypothetical example and a case study of the Karun River to determine the pollutant concentration at various points and intervals along the river. Hamidifar et al. (2020; 2024) studied the effect of vegetation zoning and the interaction between the main channel and the floodplain on the variations of the longitudinal dispersion coefficient in compound channels. In their study, by conducting laboratory experiments, the influence of various factors such as flow depth, vegetation arrangement, and the interaction between flow in the main channel and the floodplain on the longitudinal dispersion coefficient (**K**) in a compound channel was examined. Sukhodolov et al. (2002) investigated the Effect of groynes on the Dispersion of Pollution. Their study takes advantage of the unique characteristics of groynes in stimulating water turbulence to improve surface water quality and reduce pollution concentration in rivers. In this study, numerical simulation of flow in a rectangular channel was performed using the Flow-3D. (Gholami et al., 2023) studied the impact of longitudinal dispersion coefficient (LDC) on pollutant transport in rivers using Monte Carlo simulations. They found that LDC has a variable effect and can be challenging to determine accurately. This research presents a new method to identify scenarios where LDC significantly impacts pollutant transport. The method was validated using sensitivity analysis and a case study. The findings suggest that the temporal pattern of the pollution source is a key factor influencing LDC's impact on pollutant transport. In some cases, LDC can be disregarded with minimal impact on simulation results. Chabokpour, 2019) and Chabokpour and Amiri Tokaldany (2017) studied the longitudinal dispersion of non-reactive pollutants in granular media using electrical conductivity sensors. They found that experimental breakthrough curves were asymmetrical compared to theoretical curves due to pollutant storage and release. The analytical solution of the advection-dispersion equation could predict the general shape of the curves but not always the peak concentration.

The literature review highlights the importance of understanding pollutant dispersion in rivers for effective water quality management and environmental protection. Previous studies have investigated various factors affecting pollutant transport, such as flow conditions, channel geometry, and bed form morphology. Researchers have employed numerical simulations, experimental studies, and analytical solutions to model pollutant dispersion and estimate parameters like the longitudinal dispersion coefficient. The review covers work on the influence of vegetation zoning, groyne fields, and dead zones on pollutant transport, as well as the application of neural networks and inverse methods in predicting dispersion coefficients. Overall, the literature emphasizes the need for comprehensive studies on the impact of bed forms on pollutant dispersion to inform pollution control strategies and remediation efforts. By focusing on previous studied the primary objectives of current study was arranged to numerically investigate the effects of different riverbed forms (flat, ripple, and dune) on pollutant dispersion in open channels. Also, it was tried to analyze the flow dynamics and pollutant transport processes using Navier-Stokes equations coupled with a dispersion-advection model. Moreover, tried to evaluate the dispersion rates and pollutant concentrations associated with each bed form to understand the role of turbulence, mixing, and flow patterns in influencing pollutant dispersion for different bed forms.

MATERIAL AND METHODS

The Flow-3D model, based on the principles of CFD, has been widely used for simulating a variety of flow phenomena, including pollutant dispersion (Ghasemi Asl and Heidarnejad, 2023). Its ability to handle complex geometries, multiphase flows, and non-Newtonian fluids makes it a versatile tool for a broad range of applications. In this study, the Flow-3D model is utilized to investigate the impact of bed forms on pollutant dispersion in open channels. Numerical simulations were conducted using the FLOW3D software package to investigate the effects of different bed forms on pollutant dispersion in open channels. The simulations employed the Reynolds-averaged Navier-Stokes (RANS) equations coupled with a dispersion-advection model to capture the flow dynamics and pollutant transport processes. Three distinct bed forms were considered: flat bed, ripple bed, and dune bed. The simulations were performed for a range of flow conditions and pollutant injection locations.

Numerical solution of the governing equation

The governing equations for modeling open-channel flow transport and dispersion in Flow-3D software can be summarized as follows:

Continuity Equation

The continuity equation expresses the conservation of mass principle, ensuring that the mass of fluid entering a control volume is equal to the mass of fluid exiting the control volume. Eq. (1) represents it.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

Where ρ is the fluid density, t is time, v is the fluid velocity vector.

Navier-Stokes Equations

The Navier-Stokes equations describe the momentum balance of the fluid, considering both inertial and viscous forces. They are represented by the three momentum equations for the x, y, and z directions as Eqs. 2 to 4.

$$\rho \left(\frac{\partial u}{\partial t} + \nabla \cdot (uv)\right) = -\frac{\partial p}{\partial x} + \mu \nabla^2 u + \rho f_x \tag{2}$$

$$\rho \left(\frac{\partial v}{\partial t} + \nabla \cdot (vv)\right) = -\frac{\partial p}{\partial y} + \mu \nabla^2 v + \rho f_y \tag{3}$$

$$\rho \left(\frac{\partial w}{\partial t} + \nabla \cdot (vw)\right) = -\frac{\partial p}{\partial z} + \mu \nabla^2 w + \rho f_z \tag{4}$$

where: u, v, w are the velocity components in the x, y, and z directions, respectively, p is the fluid pressure, μ is the dynamic viscosity of the fluid, f_x, f_y, f_z are the body forces per unit mass in the x, y, and z directions, respectively

Flow-3D incorporates various turbulence models to account for the effects of turbulent fluctuations in the flow field. These models introduce additional terms into the momentum equations to represent the Reynolds stresses, which are the average turbulent momentum fluxes.

Advection-Dispersion Equation

The advection-dispersion equation describes the transport and dispersion of pollutants in the flow field. It is represented by Eq. (5).

$$\frac{\partial C}{\partial t} + \nabla \cdot (vC) = \nabla \cdot (D \nabla C) \tag{5}$$

Where C is the pollutant concentration and D is the dispersion tensor, representing the combined effects of advection (transport by the mean flow) and dispersion (diffusion due to turbulence).

In this research, three different bed conditions are modeled including flat surface, ripples, and dunes. The modeled channel has a length of 20 meters, a width of 1 meter, and height of 1.2 meters. Additionally, the bed thickness is 0.2 meters, the side wall thickness is 0.1 meters, and the inlet flow discharge for this research is considered to be 5 l/s. The modeling was performed under turbulent flow conditions. It is evident that the dimensions of the tested ripples should be consistent with the dimensions of dunes present in natural river flows to consider them as models of natural flows. Based on studies, ripples found in the reaches have wavelengths less than 30 centimeters, and their heights range from 0.5 to 2 centimeters. The maximum observed ripple height is 5 centimeters. In the longitudinal section of a river, ripples are approximately triangular shape. Fig. 1(a) illustrates a schematic of a rippled bed and its associated parameters. In river engineering, dunes are one of the important bed forms and significantly influence the formation of hyper concentrated exchanges in river flows. Dunes are found in rivers, tidal inlets. The formation of complete dune bed forms increases turbulence due to the irregularity of flow lines around the bed form, turbulence in front of the bed forms, and in the flow separation region, thereby increasing the mixing rate. The upstream face slope of these dunes is relatively gentle and long, while the downstream face slope is steep and short, approximately equal to the angle of repose of the bed material. Fig. 1 (b) shows the modeled geometry of the dune bed form.

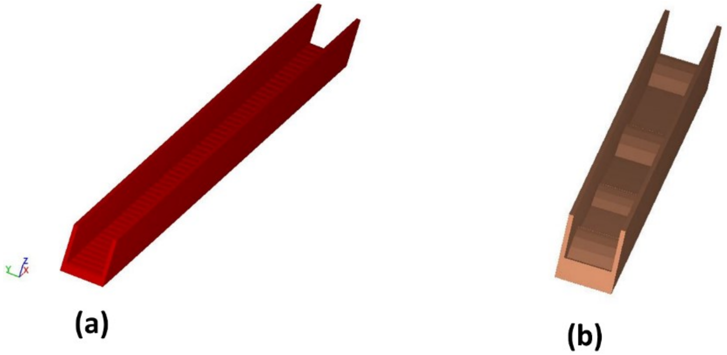


Figure 1: (a) schematic of geometric configuration for ripple bed form, (b) schematic of geometric configuration for dune bed form

Formation of Mesh Grid (Flow Equation Solution Grid)

One of the most important and sensitive stages of modeling in the Flow3D is mesh generation for the model geometry (Kulkarni and Hinge, 2023). Generally, increasing the mesh size reduces the accuracy of equation solving and decreases the approximate time for problem analysis. Conversely, if the mesh sizes are reduced, both the accuracy and simulation analysis time increase. The smaller cell sizes that enable more accurate simulations require a more powerful and professional computer. Appropriate mesh generation may also be achieved through trial and error. The mesh is defined based on the size of each cell, which was set to 0.2 cm the software. Fig.2 illustrates the above explanations and their application to the modeled geometry in the numerical model environment.

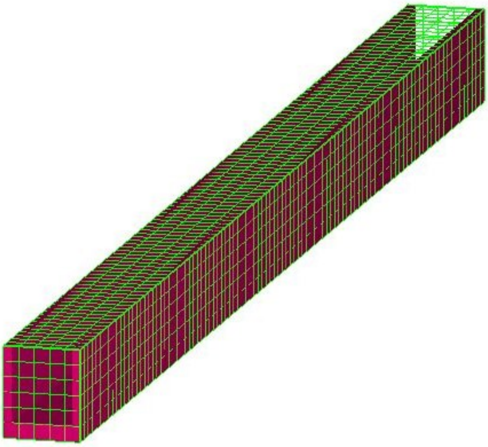


Figure 2: Schematic of generated mesh for solution of flow field

Tracer Material Used for Determining the Dispersion Coefficient and Length

To track fluid flow vectors and particles, various materials can be utilized. Considering the experimental conditions and the available instruments for measuring the concentration of that material and other parameters is one of the most fundamental and principled steps that must be taken. In brief and general terms, the tracer should not readily react chemically with other substances and have a weak adsorption rate. Additionally, this material and its decomposition products should not be toxic, must be traceable, readily available and economical, soluble, and easily and quickly analyzable. Organic dyes, chloride salts, bromides, sulfates, chlorocarbons, gases, stable isotopes, radioactive materials, selected ions in solution, and microorganisms can be cited as examples of various tracer types. In this research, sodium chloride was used as the tracer material. Salt is an ionic compound formed from equivalent proportions of sodium and chlorine. Sodium chloride is the primary compound that constitutes table salt and is also the primary contributor to the salinity of ocean water. The properties of this material include safety, ease of accessibility, ease of measurement, and cost-effectiveness.

RESULTS

The numerical simulations revealed that bed forms have a substantial impact on pollutant dispersion. Ripples, characterized by their small, regular waves, exhibited the fastest dispersion rate due to their enhanced turbulence and mixing characteristics. The increased turbulence in ripple beds promoted the breakup and transport of pollutant particles, leading to a more rapid diffusion of pollutants throughout the water column. In contrast, flat beds, with their smooth, uniform surfaces, exhibited the slowest dispersion rate. The lack of turbulence in flat beds resulted in minimal mixing and dispersion, leading to higher pollutant concentrations near the source. Dune beds, characterized by their larger, more irregular waves, displayed intermediate dispersion rates compared to ripple and flat beds. The findings of this study highlight the importance of considering bed form morphology when assessing pollutant transport in rivers and designing remediation strategies. Ripples, with their rapid dispersion properties, can be utilized to promote natural pollutant attenuation in rivers. Conversely, flat beds should be avoided in areas with high pollutant loads, as they may lead to localized contamination. The understanding of bed form effects on pollutant dispersion can inform the placement of pollutant sources, the design of water treatment systems, and the development of effective pollution control strategies.

Fig. 3 illustrate the distribution, velocity, dispersion pattern, and movements of the particles over a smooth bed at the beginning of the simulation process, the middle of the simulation process, and the end of the simulation process. It can be seen that at 1.5 seconds, the tracer particle concentration is very high, and since the bed form is completely smooth with no specific processes occurring along the channel bottom, the particles move in a concentrated group in the middle of the channel toward the end of the channel. The second figure clearly shows that the concentrated particles in the middle of the channel have the highest velocity, dispersing longitudinally at a speed close to 3 m/s. In the third figure, it can be seen that the particles have generally passed with a slight concentration dispersing at the end of channel. In addition, it can be stated that the higher velocity resulted in a faster transfer of the tracer particles.

As observed in the set of Fig. 4, the tracer particles move in a turbulent manner over the rippled bed surface, experiencing greater dispersion compared to smooth bed form. This phenomenon causes some tracer particles to continue their motion along the channel sides, resulting in an increase in dynamic viscosity near the channel walls, breakage of tracer grains, and consequently, greater lateral and longitudinal dispersion. On the other hand, in comparison with the smooth bed, it is observed that the tracers passes more quickly over the rippled bed, such that a substantial portion of the pollutant mass has left the solution domain by the middle of the simulation time, with only a very small percentage of tracer particles continuing their motion along the path.

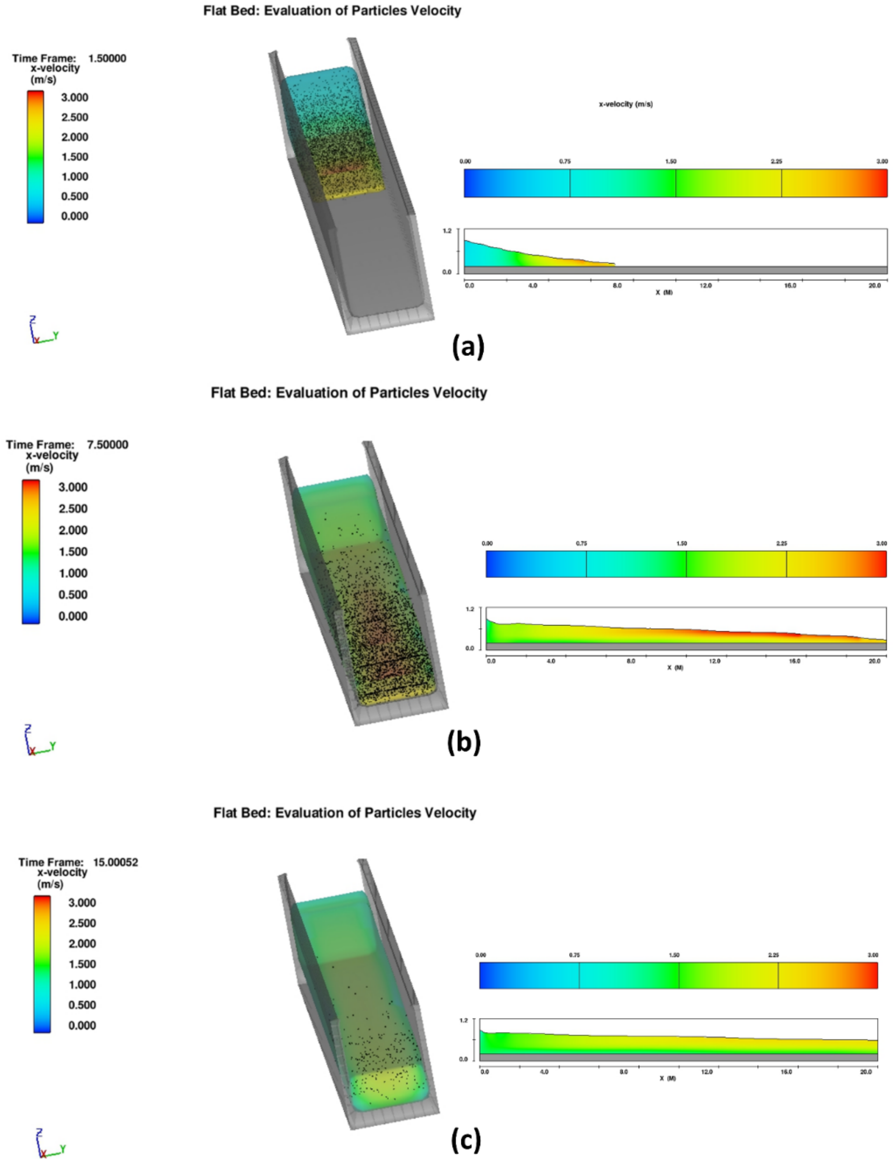


Figure 3: (a) Schematic of pollution particle spread at the beginning of simulation time over flat bed. (b) Schematic of pollution particle spread at the middle of simulation time over flat bed. (c) Schematic of pollution particle spread at the end of simulation time over flat bed

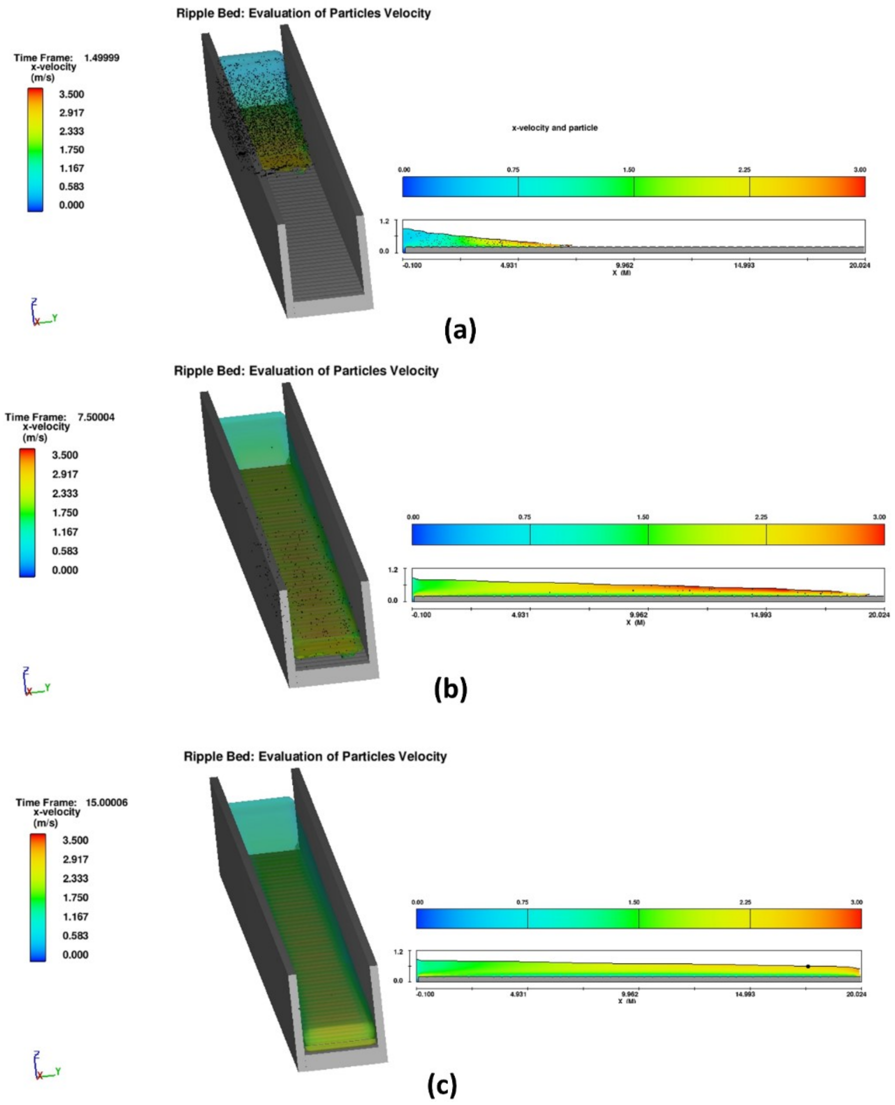
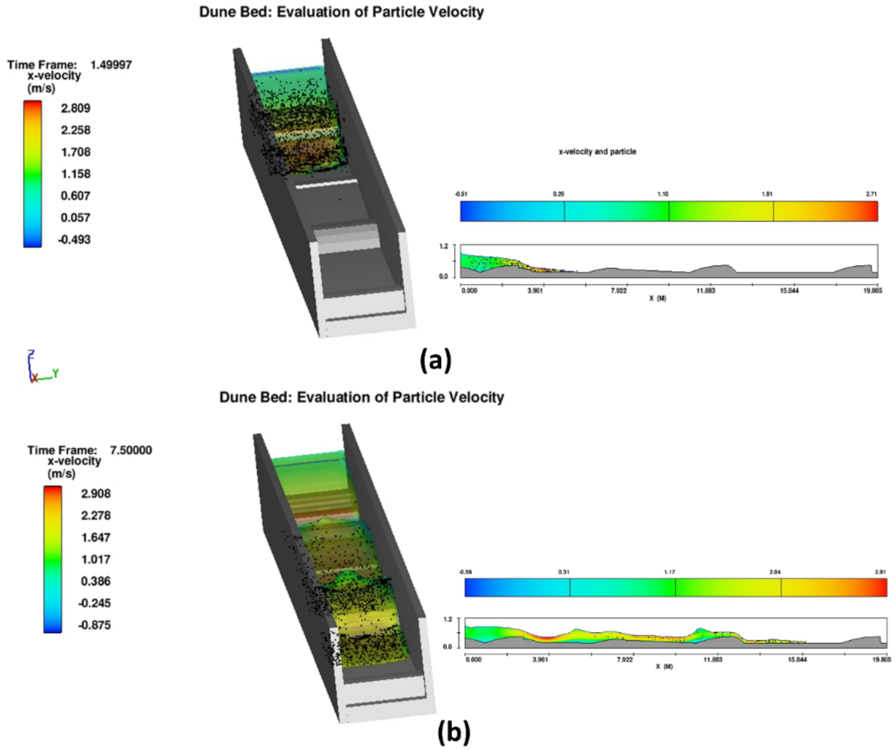


Figure 4: (a) Schematic of pollution particle spread at the beginning of simulation time over ripple bed form. (b) Schematic of pollution particle spread at the middle of simulation time over ripple bed form. (c) Schematic of pollution particle spread at the end of simulation time over ripple bed form.

When the bed form is a dune (Fig. 5), the motion pattern of pollutant particles differs significantly. As is evident from the simulation results, these particles exhibit very high dispersion, and due to the velocity fluctuation, they do not tend to exit the solution domain rapidly. This continuous velocity fluctuation causes the tracer particles to occasionally move backward, and this rotational cycle ultimately results in the dispersion of pollutants in both longitudinal and lateral directions, effectively trapping the pollutant mass and expanding the extent of the pollutant. It is observed that at the beginning of the simulation, the distribution of tracer particles is relatively uniform and regular in height. In the carrying flow, the concentration and dispersion of particles have a larger volume. An important point to note is the protrusions on the dune bed surface, which can act as force-absorbing obstacles, reducing the fluid and particle velocities. This phenomenon leads to longer paths and transit times for the tracer particles to pass through the solution domain. The maximum velocity can reach approximately 2.9 m/s, which is predictable considering the intense turbulence of the fluid in this type of bed form. It is expected that the particles will continuously move at different velocities within the fluid, resulting in a significant concentration of pollutant particles remaining in the fluid. Evidently, the maximum time for the particles to reach the end of the path in this bed form is the highest. Moreover, the flow depth also varies constantly, causing changes in particle concentration at different times. It is evident that a decrease in flow depth will increase the concentration and compactness of the tracer particles.



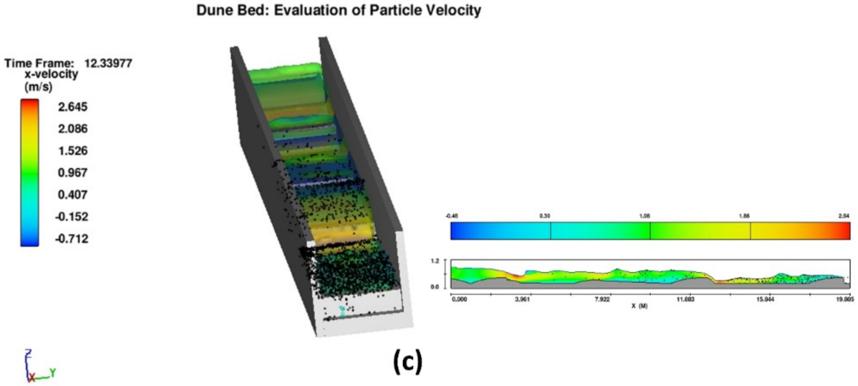


Figure 5: (a) Schematic of pollution particle spread at the beginning of simulation time over dune bed form. (b) Schematic of pollution particle spread at the middle of simulation time over dune bed form. (c) Schematic of pollution particle spread at the end of simulation time over dune bed form.

It was seen that flat beds, with their smooth, uniform surfaces, exhibit minimal turbulence and promote the formation of longitudinal streaks, leading to slower pollutant dispersion and higher pollutant concentrations near the source. In contrast, ripple beds, characterized by their small, regular waves, enhance turbulence and mixing, resulting in faster pollutant dispersion and lower pollutant concentrations. The increased turbulence in ripple beds promotes the breakup and transport of pollutant particles, leading to a more rapid diffusion of pollutants throughout the water column. Dune beds, with their larger, more irregular waves, exhibited intermediate dispersion rates compared to ripple and flat beds. The complex flow patterns over dune beds induce both turbulence and stratification, leading to variations in pollutant dispersion rates depending on the flow conditions and pollutant properties. It was seen that the flow characteristics, such as velocity and turbulence, played a crucial role in pollutant dispersion and transport. Higher flow velocities generally lead to faster pollutant transport, while increased turbulence enhances mixing and dispersion. However, the relationship between flow velocity and dispersion is not always straightforward, as high velocities may also lead to the formation of secondary currents and flow separation zones, which can trap pollutants and hinder dispersion. Furthermore, the surface roughness parameter, which represents the irregularities of the bed surface, also influences pollutant dispersion. Rougher beds, characterized by larger surface irregularities, promote turbulence and mixing, leading to faster dispersion. Conversely, smoother beds, with smaller surface irregularities, exhibit reduced turbulence and slower dispersion.

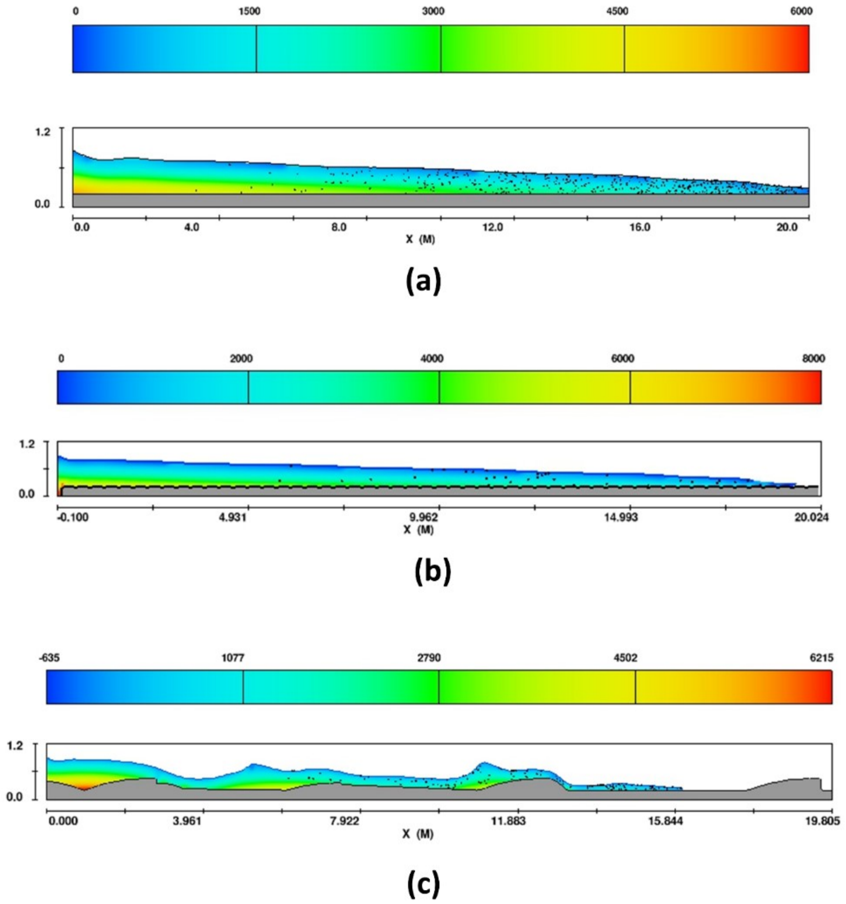


Figure 6: (a) Pressure distribution and pollution particle spread at the middle of simulation time over flat bed form. (b) Pressure distribution and pollution particle spread at the middle of simulation time over ripple bed form. (c) Pressure distribution and pollution particle spread at the middle of simulation time over dune bed form

Hydrostatic pressure also influences pollutant dispersion and transport. In deeper flows, higher hydrostatic pressure can suppress turbulence and hinder pollutant dispersion, particularly in areas with flat beds. However, in shallower flows with lower hydrostatic pressure, turbulence tends to be more pronounced, leading to enhanced pollutant dispersion. Ripple and dune bed forms, prevalent in open channel flows, significantly influence both hydrostatic pressure and the flow Froude number, playing a crucial role in pollutant dispersion dynamics. These bed forms, characterized by their distinct shapes and sizes, alter the flow patterns, turbulence characteristics, and bed shear stresses, leading to variations in hydrostatic pressure distribution and Froude number values. Ripple bed forms, with their small, regular waves, induce minimal changes in hydrostatic pressure distribution compared to flat beds. The smooth transitions of ripple crests and troughs maintain a relatively uniform pressure distribution across the bed surface. Dune bed forms, with their larger, more irregular waves, exert a more significant impact on hydrostatic pressure distribution. The steep slopes and sharp crests of dunes can cause variations in pressure along the bed surface, with higher pressures at the base of dunes and lower pressures at the crests. These pressure variations can influence sediment transport processes, as higher pressures can mobilize loose sediments, while lower pressures can promote sediment deposition (Fig. 6).

Ripple bed forms, with their enhanced turbulence and mixing, tend to reduce the flow Froude number compared to flat beds. The increased friction caused by the ripples decreases the flow velocity, leading to a lower Froude number. This reduction in Froude number can promote the formation of additional ripples, as the flow conditions become more favorable for ripple development. Dune bed forms can have a more variable impact on the flow Froude number. In some cases, dunes can increase the Froude number due to the acceleration of flow over the dune crests. However, in other cases, dunes can decrease the Froude number due to the increased friction caused by the bed form roughness. The net effect of dunes on Froude number depends on the specific flow conditions and dune characteristics (Fig. 7).

The interplay between ripple and dune bed forms, hydrostatic pressure, and flow Froude number has significant implications pollutant dispersion dynamics. The variations in pressure and Froude number over bed forms can influence the mobilization and deposition of sediments, affecting the overall transport patterns. Additionally, these variations can affect the transport and dispersion of pollutants, as they influence turbulence, mixing, and flow interactions with the bed. Ripple bed forms, with their enhanced turbulence and mixing, promote faster pollutant dispersion compared to flat beds. The increased turbulence breaks down pollutant particles and enhances their diffusion throughout the water column. Dune bed forms, on the other hand, can exhibit more complex dispersion patterns due to their irregular topography and flow patterns. In some cases, dunes can enhance dispersion, while in other cases; they can create zones of reduced dispersion due to flow separation and recirculation.

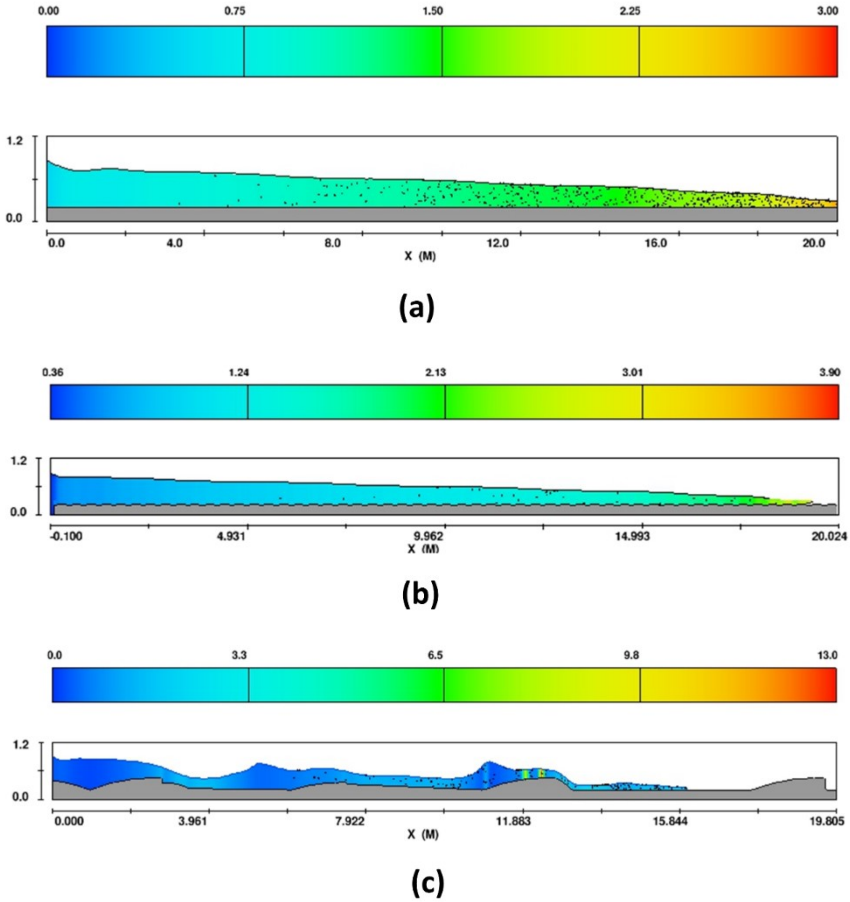


Figure 7: (a) Fr number and pollution particle spread at the middle of simulation time over flat bed form. (b) Fr number and pollution particle spread at the middle of simulation time over ripple bed form. (c) Fr number and pollution particle spread at the middle of simulation time over dune bed form.

CONCLUSION

The results revealed that ripples exhibit the fastest dispersion rate, while flat beds exhibit the slowest. These findings underscore the importance of considering bed form morphology when assessing pollutant transport and designing remediation strategies. As the Froude number tends to increase, causing the subcritical flow to transition to supercritical flow, the tracer particles also exhibit a greater tendency for increased velocity and concentration. This indicates the severe impact of the simple bed form in the initial stages of flow and pollutant particle dispersion, and the significant influence of the dune bed form on pollutant particles at locations with changes in elevation. Based on numerical modeling, it can be stated that there is an inverse relationship between the bed roughness coefficient and the rate of pollutant dispersion because if the bed form has a high roughness coefficient, it will act as a resistant force against fluid velocity. The reduction in velocity leads to a decrease in the Froude number and a decrease in velocity, resulting in an increase in the time required for pollutant dispersion. Considering the velocity profiles for the flat, ripple, and dune bed forms, the maximum flow velocity is 3.35 meters per second for the flat bed, 3.40 meters per second for the ripple bed, and 2.95 meters per second for the dune bed. Therefore, pollutant dispersion occurs more rapidly and in a shorter time for the ripple bed. Moreover, injecting the tracer material at the centerline of the channel and at, approximately, half the water depth results in the highest dispersion coefficient of the flow.

Declaration of competing interest

The authors declare that they have no know competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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