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REVIEW

Geophysical Controls on River Turbulence: Implications for Bank Erosion and Pollutant Dispersion

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ABSTRACT

Turbulence plays a critical role in the transfer of momentum, sediment, and pollutants in rivers. We review the state of knowledge on geophysical controls of river turbulence and their role in bank erosion and contaminant transport. Controlling factors, such as channel geometry, boundary roughness, flow conditions, and forcing, have been shown to affect not only the magnitude of turbulence but also its spatial structure and temporal dynamics. The review underscores the role of organized structures, intermittent bursts, and scale interactions in driving near-boundary mechanisms and mixing processes. For bank erosion, turbulence produces fluctuating stresses and pressures that interact with spatially varying bank materials, resulting in complex erosion processes that go beyond threshold-based models. Intermittent high-energy events, such as floods, are shown to play a significant role in erosion. In terms of pollutant dispersion, turbulence dictates mixing and transport processes and can lead to non-Fickian transport behavior in complex channels with temporary storage zones. The review highlights the link between erosion and dispersion, both of which are controlled by turbulence and partially by similar geophysical factors. It also discusses current shortcomings of the models and suggests the need for integrated, multi-scale models considering unsteady turbulence. The development of such approaches is critical to enhance predictions and inform river protection and management.

Keywords: River Turbulence; Bank Erosion; Pollutant Dispersion; Channel Morphology; Hydrodynamic Processes

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1. Introduction

Rivers are evolving systems where the interaction between flow, sediment and boundaries leads to complex flow patterns over multiple spatial and temporal scales [1]. Of the processes that govern river dynamics, turbulence is particularly important in setting momentum, sediment entrainment and channel change, as well as the transport and fate of dissolved and particulate matter [2]. Turbulent river flow differs from laminar flow in that it includes random fluctuations, organized structures and eddies of multiple sizes that have a significant impact on near-wall processes [3]. Accordingly, understanding the emergence and controls of turbulence in rivers is critical to improving predictive capabilities in fluvial geomorphology and environmental hydraulics. In the last few decades, significant advances have been made in describing river turbulence through analytical, laboratory and numerical studies. Traditional models have dealt with idealized channel shapes and steady uniform flow, offering insights into boundary layer dynamics, shear stress gradients and turbulence properties. Yet, real rivers are far from ideal. Channel geometry, bed and bank composition, vegetation and hydrodynamics drive strong spatial and temporal heterogeneity and create intricate turbulence patterns [4,5]. These geophysical factors not only influence the strength and structure of turbulence but also control processes like bank erosion and contaminant transport that are important for human and environmental systems.

For example, bank erosion is a key process governing landscape dynamics and sediment supply in rivers [6]. This impacts channel stability, floodplain evolution, and infrastructure integrity. Erosion rates are typically estimated using the mean flow velocity and shear stress, but emerging research indicates that turbulence, especially bursts, vortices and organized flow structures, is the dominant forcing mechanism for bank erosion at the bank-water interface [7]. The interplay between turbulence and bank properties, such as cohesive sediments and vegetation, adds further complexity to bank erosion that is not adequately accounted for in traditional models. Thus, bank erosion prediction remains a challenge, particularly under changing climatic conditions and growing human impacts. Likewise, turbulence regulates the transport and mixing of contaminants in rivers, affecting water quality and ecosystems [8]. The fate and transport of pollutants, including nutrients, sediments, metals, and other contaminants of emerging concern, are governed by advection and turbulent diffusion. Although traditional advection-dispersion models offer a first-order description, they may not capture the influence of channel geometry, flow separation, recirculation and hyporheic exchange. These processes, which are tightly coupled with geophysical controls, can give rise to anomalous dispersion such as increased mixing, temporal storage, and long-tailed concentration distributions [9]. As such, there is a need to understand the role of turbulence, modified by geophysical features, in the fate and transport of pollutants.

While the role of turbulence is acknowledged in both bank erosion and pollutant dispersion, these have been typically considered independently. Geomorphic and geotechnical factors have been the main focus of bank erosion studies, while pollutant transport studies have tended to focus on hydrodynamic and water quality controls. This focus has constrained the development of a holistic approach that integrates geophysical controls, turbulence structure, and its impact on river processes. In addition, many studies have been site-specific or have used laboratory settings that limit their application to real-world river systems. This review seeks to address these shortcomings by synthesizing the state of the art on the geophysical controls of river turbulence and clarifying their relevance to bank erosion and pollutant transport [10]. The original contribution of this work is its integrated approach, which highlights the relationships between physical controls, including channel geometry, solid boundaries and hydroclimatic variability, and both turbulence characteristics and relevant transport and erosion processes [11]. By bringing together insights from fluvial geomorphology, environmental fluid mechanics, and water quality science, this review highlights common mechanisms and feedbacks that are often overlooked when these topics are considered separately.

In particular, this article advances the field in three main ways. First, it synthesises the interactions between various geophysical factors influencing turbulence structure in rivers, transcending idealised descriptions of turbulence to more realistic representations of flow complexity [12]. Second, it considers the influence of turbulence not simply in terms of mean statistics (e.g., mean flow, Reynolds stresses) but also as coherent structures and intermittency, which are increasingly acknowledged as key drivers of boundary-layer processes and mixing [13]. Third, it brings together the consequences of turbulence for bank erosion and contaminant dispersion in a coherent conceptual framework, highlighting the interdependencies between these processes and their reliance on geophysical controls [14].

Additionally, technological advances in measuring turbulence, such as acoustic Doppler velocimetry (ADV), particle image velocimetry (PIV) and high-resolution remote sensing, and in modeling turbulence processes, such as large-eddy simulation (LES) and data-driven approaches, have provided new avenues to capture turbulence in complex river settings [15,16]. This review evaluates how these have improved our understanding and highlights the challenges in resolving multi-scale interactions between flow, sediment, and boundaries.

Finally, advances in understanding of geophysical controls on river turbulence have implications for river management and restoration. Improved prediction of bank erosion can guide measures to reduce land erosion and safeguard infrastructure, and better models of contaminant transport can assist in managing water quality and associated risks [17,18]. Through this review, we aim to provide a synthesis of current understanding and outline future research needed to support more process-based approaches to managing river systems in a changing environment. In conclusion, this article views turbulence as a connecting process that links geophysical controls to geomorphic change and contaminant dispersion in rivers. It draws attention to the need for integrated strategies that consider the complexity of natural systems through an interdisciplinary perspective and sets the stage for future research to enhance prediction in fluvial science. The conceptual relationships between geophysical controls, turbulence dynamics, and river processes are illustrated in **Figure 1**.

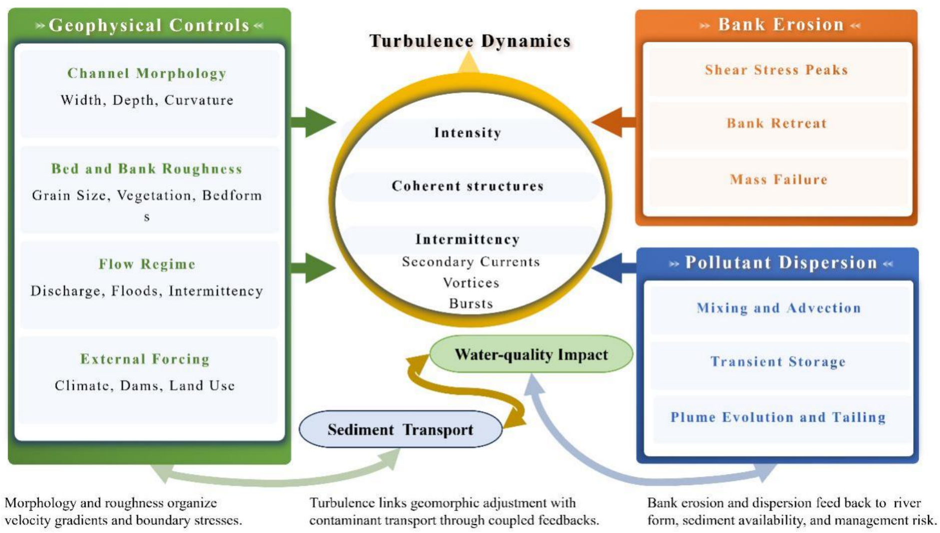

Figure 1. Conceptual framework.

Note: The conceptual framework illustrates the interactions between geophysical controls (channel morphology, roughness, flow regime, and external forcing), turbulence characteristics (intensity, intermittency, and coherent structures), and their implications for bank erosion and pollutant dispersion in river systems.

2. Geophysical Controls on River Turbulence

Turbulence in natural rivers is an outcome of the competition between flow inertia, boundary effects, and channel-scale variability [19]. In contrast to laboratory channels, where geometry and roughness are highly idealized, natural river channels are highly variable in terms of morphology, substrate, and forcing. These features shape the magnitude, structure, intermittency and coherent structure of turbulence [12]. As a result, a holistic approach is needed to describe turbulence in rivers that extends beyond the traditional boundary-layer theory, and that explicitly considers geomorphic complexity and hydrologic variability. This section reviews the main geophysical controls of river turbulence, and their interactive and scale-dependent impacts.

2.1. Channel Morphology

Turbulence generation and evolution are strongly influenced by channel morphology [20]. Changes in the shape, size, slope and planform of the channel create spatial gradients in velocity and pressure, leading to the generation of shear and secondary circulation. In channels that are relatively straight and have uniform cross-sectional areas, turbulence is largely controlled by bed shear and, to a certain degree, follows canonical open-channel flow dynamics [21]. But even small disturbances in bed topography or bank geometry can create accelerations and decelerations, leading to nonuniform turbulence distributions. Curvature in meandering channels plays a key role in turbulence dynamics via secondary flows [22]. This results in a helical flow that transports momentum across the channel and increases shear stress on the outer bank. This facilitates the development of large-scale coherent structures that enhance turbulence and drive sediment transport and bank erosion. Secondary flows are influenced by curvature, flow depth, and aspect ratio, suggesting that morphological factors such as these act on multiple scales.

The turbulent flow in braided rivers is even more complicated by the presence of multiple channels and ephemeral bars [23]. Channel confluences and divergences create regions of strong mixing, whereas regular channel re-arrangement results in highly dynamic turbulence structures. At channel junctions, interactions between flows with different velocities and sediment loads generate intense shear layers and large-scale instabilities, such as Kelvin-Helmholtz vortices, which govern local turbulence structures and affect downstream transport [24]. While there have been major advances in describing the interaction between morphology and turbulence, a major gap in existing approaches is the assumption of rigid channel geometry. However, channel geometry is dynamic and responds to turbulence, resulting in interactions between flow structures and channel morphology. Understanding this relationship remains elusive and is a key frontier in fluvial hydraulics.

2.2. Bed and Bank Roughness

Rough boundaries are a key control on turbulence generation because they mediate the transfer of momentum between the flow and the bed [25]. The characteristics of bed roughness (sediment size, shape and configuration) affect the structure and thickness of the turbulent boundary layer [26]. In gravel-bed rivers, protruding roughness elements create wakes and flow separations, which increase turbulence mixing and dissipation. The size and spatial distribution of these elements generate variations in turbulence, resulting in a mosaic of high- and low-energy pockets. Bedforms like ripples and dunes add another layer of complexity by creating regular flow separation and reattachment [27]. A dune is generally accompanied by a recirculation zone on the downstream slope where turbulent eddies are generated, then advected downstream into the main flow. This helps to develop coherent structures that facilitate vertical mixing and can affect sediment transport. The coupling between bedforms and flow is unsteady and highly flow dependent, especially for high-discharge events that may induce bedform evolution.

Bank roughness is also important, especially in the near-bank region where turbulence affects erosion [28]. Plants, roots and bank irregularities increase flow resistance and disturb flow structures, promoting turbulence [29]. In vegetated banks, flexible stems oscillate in the flow and generate turbulence. This turbulence production alters turbulence intensity and structure, making the conventional representation of roughness based on grain-scale characteristics alone more complex. A key finding of recent studies is that river roughness is multi-scale. Rivers typically include multiple scales of roughness features, including both fine and coarse sediment particles, bedforms and vegetation. These interactions may have non-linear effects on turbulence, such as amplification or filtering of energy at certain frequencies. For instance, fine sediment embedded in a coarse bed can influence flow structures and turbulence in complex ways that cannot be explained solely by single-scale roughness [30].

Traditional models often adopt simplistic representations of roughness, such as equivalent sand roughness or empirical drag coefficients. Although they can be effective for engineering purposes, these expressions do not account for the dynamic and multi-scale characteristics of natural roughness, and can be ineffective at predicting turbulence dynamics in natural river systems.

2.3. Flow Regime and Hydrological Variability

In river systems, turbulence is tightly connected to the flow regime, which is characterised by the magnitude, variability and evolution of flow. In steady, low flows, turbulence is generally limited to the vicinity of boundaries and has more stable structures [3]. Increasing flow leads to more dynamic conditions, increased turbulence intensity, and broader regions of intensified turbulence. Floods play a prominent role in controlling turbulence. Higher flow velocities and depths during these periods increase shear production and contribute to the formation of large-scale coherent structures that play important roles in sediment transport and channel dynamics. Floods also erode bed sediment and change the boundary roughness, providing further feedbacks that affect turbulence.

Another characteristic of turbulence under unsteady flow is intermittency. Turbulent burst, sweep and ejection events are more frequent during rapidly varying discharge, promoting increased momentum and mass exchange [11,31]. Intermittent events become particularly important in triggering bed and bank erosion. The occurrence and magnitude of these events are controlled not only by the magnitude of the flow, but also by the rate of change of discharge, which highlights the importance of the shape of the hydrograph. Turbulence can also be affected by stratification, especially in rivers with temperature or density gradients [32]. Stable stratification can dampen turbulence and create stratified flow, while unstable stratification can promote turbulence through convection. While not as prevalent as in lakes or estuaries, stratification can occur in low-slope rivers or during certain times of the year.

Turbulence is also influenced by secondary currents, which are caused by channel bends or variations in the velocity distribution [33]. These currents lead to momentum redistribution and the formation of hotspots of increased turbulence not parallel to the main flow direction. They interact with unsteady flow to produce strongly three-dimensional turbulence structures that are difficult to model.

One key shortcoming of existing predictive models is their use of time-averaged flow characteristics and quasi-static approaches. These methods can over-simplify the transient and multi-scale nature of turbulence under unsteady flow conditions, including the impact of short-lived, high-magnitude events that have a disproportionate impact on sediment transport and erosion [34].

2.4. External Forcing Factors

River turbulence is strongly influenced by forcing factors such as climate variability and human activity. Climate influences, including rainfall and temperature fluctuations and extreme events, impact the magnitude and variability of river discharge [35]. Variations in these factors can affect the occurrence, magnitude and duration of turbulence regimes, which are critical for sediment transport and mixing.

Seasonality can result in cyclical changes in turbulence [36]. For instance, the snowmelt-dominated flows in mountain regions can generate sustained high-discharge flows with higher levels of turbulence, while low-energy flows in the dry seasons can have more stable turbulence structures. These patterns interact with bed structure to create seasonal erosion and deposition.

Human actions have further influenced river dynamics [37]. Dams and reservoirs alter natural flow patterns through flow regulation and changes to sediment loads [38]. Lower sediment inputs downstream of dams can cause channel incision and modifications to bed roughness, affecting turbulence production. Regulated releases may also generate unnatural variations from natural hydrologic cycles, resulting in different turbulence characteristics. Channelization and bank stabilization, often used for flood mitigation or navigation, modify channel morphology and boundary roughness. Channels with reduced meanders and bank erosion tend to have less complex morphology and secondary currents, leading to more uniform but potentially stronger turbulence at channel boundaries. Such measures may meet engineering goals, but they may also alter natural feedback mechanisms and have downstream consequences, such as erosion and loss of habitat complexity.

Anthropogenic activities, such as urban development and deforestation, also affect river turbulence through changes in runoff and sediment delivery [39]. Greater impervious surfaces in urban environments result in faster runoff and more variable discharge, creating flashy flows with increased turbulence during extreme events. Simultaneously, vegetation changes influence sediment supply and bank stability, and thus boundary roughness and turbulence production. It is important to note that external forcing factors and intrinsic geophysical controls interact in a non-linear fashion. The effects of a given hydrological event on turbulence depend not only on the magnitude of the event but also on the "legacy" of past channel morphology and roughness. Likewise, the impact of human activities is constrained by long-term channel responses and feedback loops.

To conclude, geophysical controls on river turbulence are a result of interactions between channel morphology, boundary roughness, flow regime, and external forcing factors[40]. These controls act at a range of spatial and temporal scales and interact in complex (nonlinear) ways. Progress in this field requires more holistic approaches that explicitly consider these interactions and offer a more reliable basis for assessing bank erosion and pollutant transport in natural rivers. The main geophysical controls on river turbulence and their impacts are summarised in **Table 1**.

Table 1. Summary of main geophysical controls on river turbulence, their characteristics, and their influence on turbulence structure and scale.

Geophysical Control	Characteristics	Influence on Turbulence	Scale of Impact
Channel Morphology	Width, depth, curvature, planform	Generates secondary flows, shear layers, coherent structures	Reach to basin scale
Bed Roughness	Grain size, bedforms, sediment heterogeneity	Enhances turbulence production, flow separation, eddy formation	Grain to channel scale
Bank Roughness	Vegetation, irregular geometry	Modifies near-bank turbulence, local shear stress distribution	Local to reach scale
Flow Regime	Discharge magnitude and variability	Controls turbulence intensity, intermittency, and structure	Temporal (event to seasonal)
External Forcing	Climate, dams, land use	Alters flow variability and boundary conditions	Basin to long-term scale

3. Turbulence and Bank Erosion Processes

Riverbank erosion is a critical process that controls river channel morphology, sediment transport, and channel evolution[41]. Conventionally, erosion has been modelled using time-averaged flow properties like mean velocity and bed shear stress. But recent research suggests that turbulence, especially its intermittent and coherent structures, is the dominant factor driving initiation and maintenance of erosion at the bank surface. The interplay between turbulent eddies and the diverse bank materials adds to the complexity and defies traditional deterministic approaches. Here, we explore the influence of turbulence on bank erosion processes, the effects of material properties and biophysical feedbacks, and the spatial and temporal variability of bank erosion in natural river systems.

3.1. Mechanisms of Turbulence-Induced Erosion

Traditionally, bank erosion is associated with the exceedance of a critical shear stress, at which sediment particles or cohesive bank materials are removed[42,43]. This approach is a good first approximation, but it does not account for the variability of turbulence. In reality, the stresses on the bank are variable, with short-duration, high-amplitude events that can be much greater than the mean shear stress. These large, short-lived events are associated with turbulent bursts and coherent flow structures, and may initiate erosion, even when the mean flow is sub-critical. Turbulence adjacent to the bank involves large velocity gradients between the main flow and the slow-moving fluid adjacent to the bank. This region gives rise to a number of coherent structures, such as vortices and eddies that impinge on the bank. Sweeps and ejections are of particular significance. Sweeps carry high momentum fluid towards the bank, which leads to localized spikes in shear stress that can dislodge sediment particles or cause them to break apart[44]. Ejections transport low-momentum fluid away from the bank, contributing to suspension[45]. This creates an oscillating bed stress that allows for cyclic suspension.

In meandering channels, turbulence is complemented by secondary and helical flow. In meanders, the outer bank has a high flow momentum and turbulence intensity due to centrifugal effects. This promotes the development of large vortices that impact the bank, increasing shear stress and pressure fluctuations. These eddies are often spatially coherent and persistent and play a key role in long-term erosion of the outer bank[46].

Pressure fluctuations associated with turbulence also contribute to erosion processes[47]. Rapid changes in pressure at the bank surface can induce seepage forces within permeable or partially saturated materials. These modify the internal stress state, decrease the effective strength, and trigger failure. This process illustrates the interaction between external hydrodynamic forces and geotechnical processes, which are frequently neglected in erosion models. While there is growing awareness of the role of turbulence, its effects on erosion are difficult to quantify. There are few field observations of high-frequency fluctuations of velocity and pressure near eroding banks, and laboratory experiments may not capture the full spectrum of variability. This means there is a need for better observation methods and models that can capture the stochastic and multi-scale aspects of turbulence-driven erosion. The main turbulence mechanisms that drive bank erosion are listed in **Table 2**.

Table 2. The turbulence mechanisms driving bank erosion, their physical characteristics, and their effects on bank stability under different flow conditions.

Turbulence Mechanism	Description	Effect on Bank Stability	Dominant Conditions
Sweep Events	High-momentum fluid moving toward the bank	Increases instantaneous shear stress, particle detachment	High flow, near-bank zones
Ejection Events	Low-momentum fluid moving away from boundary	Enhances sediment suspension and mixing	Moderate to high turbulence
Coherent Vortices	Organized rotating flow structures	Induce localized erosion and pressure fluctuations	Meanders, confluences
Pressure Fluctuations	Rapid changes in flow pressure near bank	Promotes seepage and internal weakening	Permeable banks
Secondary Flow	Helical motion due to curvature	Concentrates erosion at outer bends	Curved channels

3.2. Interaction between Flow and Bank Materials

River bank responses to turbulent forcing are highly dependent on their physical properties, such as grain size, cohesion, structure and biology [48]. In non-cohesive banks, such as those made of sand or gravel, the response of banks to changes in flow conditions is generally quick. In these materials, erosion is controlled by particle entrainment processes, where the turbulent component of the flow exerts a fluctuating force on the grains, exceeding the gravitational and frictional forces acting on the particles. The turbulence governs the frequency and intensity of events that can mobilise particles, and thus controls the erosion rate. Cohesive banks, made of fine-grained clays and silts, respond in a more complex manner because of interparticle cohesion and strength. Such sediments can withstand higher average shear stresses, but are vulnerable to repeated turbulent events. Repeated turbulent events can fatigue cohesive bonds, resulting in delayed erosion under relatively low flows. This time lag complicates conventional models that assume instantaneous erosion once a threshold is reached [49].

Vegetation can influence bank erosion. Plants can strengthen the bank material, enhancing its shear strength [50]. Simultaneously, vegetation above the surface interacts with the flow, affecting turbulence. Bending stems and leaves can introduce further turbulence through oscillations, and affect the velocity distribution. These effects can either reinforce the bank or increase erosion, depending on factors such as vegetation density and type, and flow regime. This combination makes predictions challenging and underscores the need to consider biophysical processes in erosion modelling. Another key factor in erosion is pore-water pressure. Fluctuations in water pressure due to turbulence at the bank surface can enter the bank and influence seepage gradients and effective stress. For example, during rapid drawdown, such as flood recession, the hydrostatic pressure outside the bank drops but the pore pressure inside the bank remains high, destabilizing the bank. Turbulence may further contribute to this instability by providing further variations in pressure, promoting mass failure [51].

One difficulty in studying bank erosion is the interplay between hydrodynamic and geotechnical factors [52]. Hydraulic models typically consider variables such as velocity and shear stress, whereas geotechnical models consider soil strength and stability. The interaction between these fields, facilitated by turbulence, is currently poorly understood. Recent methods that integrate fluid and solid mechanics show promise but are data and computationally intensive.

3.3. Spatial and Temporal Patterns of Erosion

The spatial and temporal variability of bank erosion is considerable, reflecting the variability of turbulence and its controlling factors. Spatially, erosion often occurs in areas of high turbulence, such as the outside of meanders, channel constrictions, and at river confluences [53]. Here, velocity gradients, secondary flows and coherent structures are intense, leading to increased shear stress and mixing[54]. The migration of meanders in rivers is an example of the spatial distribution of erosion. The outer bank is exposed to higher energy flow and turbulence, resulting in erosion, while the inner bank receives lower flow and deposition. This process can be influenced by variations in bank strength, vegetation, and channel shape, leading to dynamic erosion and deposition processes.

Temporal variability in bank erosion is equally important[55]. During low-flow periods, erosion is typically steady and measured by the effects of sustained but low-level turbulence. However, high-flow conditions (e.g., floods) often provide the majority of sediment yield[56]. These events are associated with increased turbulence and an increase in the frequency of very large stress events, triggering rapid and sometimes catastrophic bank erosion. The effects of a single flood event can be greater than those of prolonged low-flow erosion, highlighting the intermittent nature of erosion. Temporal variation in erosion is also related to thresholds. Banks can be stable across a wide range of flows until a threshold is exceeded in terms of turbulence, duration, and bank weakening. Once the threshold is surpassed, bank failure may occur suddenly in the form of mass wasting. Turbulence is important in both approaching and passing these thresholds through the distribution and intensity of instantaneous turbulent forcing.

Erosion is also affected by antecedent conditions. The history of flow events, soil moisture, and previous erosion can affect the current susceptibility of a bank to turbulent forcing. For instance, a bank previously weakened may succumb to relatively low levels of turbulence, whereas an undamaged bank may withstand higher levels[56]. This history-dependence makes erosion processes difficult to model, and stresses the need to better understand long-term system dynamics.

Technological improvements in monitoring bank erosion, such as high-resolution topographic monitoring and time-lapse photography, have enabled better observations of erosion events[57]. These data indicate that erosion often proceeds in bursts linked to specific episodes of turbulence, rather than continuously. These observations highlight the limitations of existing models based on time-averaged quantities, and suggest the need for event or stochastic models. However, there are still many challenges in connecting erosion patterns to turbulent dynamics. Observations of three-dimensional flow structures around eroding banks in the field remain scarce, and it is difficult to extrapolate laboratory results to the field. And interactions between human activities and climate change add further complexity to the analysis of erosion events.

In conclusion, bank erosion is controlled by the interaction of turbulent flow structures and bank material properties[47]. Turbulence is responsible for the detachment of sediment particles and facilitates feedback interactions between flow, form and bank materials. To understand these processes in detail, an approach that explicitly incorporates the intermittent, multi-scale and three-dimensional characteristics of turbulence is needed. This is crucial to enhance prediction models and to design strategies to manage and restore rivers.

4. Turbulence and Pollutant Dispersion

Contaminant transport and fate in rivers are controlled by advective and turbulent processes acting at various scales. Advective transport is responsible for the longitudinal movement of pollutants downstream, while turbulent mixing, dispersion, and dilution are responsible for the transverse movement of pollutants[10,58]. In real rivers, where the channel configuration, boundary conditions and flow variability are highly variable, turbulent dispersion is significantly different to that assumed under idealized conditions in traditional transport models. This section considers the underlying physics of turbulent mixing, the role of geophysical processes in dispersion, and their effects on contaminant transport in rivers.

4.1. Fundamentals of Turbulent Mixing

The advection-dispersion model is widely used to describe the transport of pollutants in rivers, where a contaminant is transported by the mean flow and dispersed by turbulent mixing[59]. Dispersion results from the interaction of velocity gradients and turbulence, which mix solute or particulate material in the flow. The longitudinal dispersion process is greatly affected by the coupling of transverse velocity gradients and turbulent mixing, resulting in greater spreading than would be achieved solely through molecular diffusion.

Open-channel turbulence is anisotropic and inhomogeneous, with varying degrees of mixing in the longitudinal, lateral and vertical directions [60]. Lateral mixing is often slower than vertical mixing, especially in a wide, shallow channel where there are smaller gradients of velocity in the transverse direction. Consequently, contaminants released into a river may not be well mixed across the channel for a long time, resulting in longitudinal variations in concentrations.

One potential weakness of traditional dispersion theory is its use of time-averaged quantities (such as dispersion coefficients) that are intended to capture the influence of turbulence. But turbulence is inherently transient and comprises intermittent coherent structures that can play a dominant role in the mixing process. Coherent structures such as large eddies, shear-layer instabilities and secondary flows can transport pollutants over greater distances than would be expected if mixing were purely diffusive, resulting in non-Fickian transport [59]. Recent experimental and numerical research has shown the role of coherent structures in mixing. Separation vortices formed at bedforms or other irregularities in the channel can capture and transportpollutants, resulting in concentration hotspots [61]. Such results highlight the need for a shift from traditional diffusive models of pollutant transport to include the structured and dynamic nature of turbulence.

4.2. Influence of Geophysical Controls on Dispersion

Turbulent dispersion in rivers is significantly influenced by geophysical factors such as channel geometry, bed and bank roughness, and variability of flow [53,62]. The shape of the channel affects the distribution of flow velocity and turbulence intensity, which in turn, affects the pathways of contaminant transport. In simple, uniform channels, dispersion processes may be fairly predictable and accurately modelled by conventional theories. However, natural rivers with complex shapes and cross-sectional variability display complex mixing dynamics.

For instance, meandering channels create large transverse velocity gradients as a result of secondary flows [22]. Such flows improve lateral mixing by redistributing pollutants, and may accelerate the rate at which complete mixing is approached. But recirculation zones on the inner banks can also temporarily retain contaminants, slowing their downstream movement and introducing non-uniformity in contaminant distributions. The interaction between mixing and storage is influenced by channel geometry, water depth and flow rate.

Dispersion is also affected by bedforms and other boundary roughness features, which affect flow structure and turbulence. Separation at dunes or large roughness elements creates eddies and recirculation zones, contributing to vertical mixing, but also to local trapping of pollutants [63]. The size, arrangement, and mobility of these features affect the overall dispersion process, with larger or more irregular features resulting in more intense and complex mixing.

Hydrological variability and flow regime add further complexity. Low-flow conditions are associated with lower turbulence intensity, which can limit mixing, resulting in concentration gradients and reduced dilution potential. By contrast, high-flow conditions enhance turbulence and mixing, often leading to more homogeneous distributions [64]. But they can also resuspend sediments and associated contaminants, adding sources and changing flow pathways.

Transient flow conditions, such as those typical of storm events or controlled dam releases, may lead to dynamic mixing that deviates from steady-state conditions [65]. Discharge fluctuations can create shear layers and instabilities that increase mixing in some areas but decrease mixing in others. Such conditions complicate the use of steady-state dispersion models and require time-dependent approaches. The role of geophysical controls on pollutant dispersion processes is listed in **Table 3**.

Table 3. Influence of geophysical controls on pollutant dispersion, including their effects on flow structure, mixing processes, and resulting transport behavior.

Control Factor	Effect on Flow Structure	Impact on Dispersion	Resulting Behavior
Channel Curvature	Induces secondary circulation	Enhances lateral mixing	Faster cross-sectional mixing
Bedforms	Causes flow separation and recirculation	Promotes vertical mixing and temporary storage	Non-uniform concentration fields
Flow Variability	Unsteady discharge conditions	Alters mixing rates and transport pathways	Transient dispersion patterns
Roughness Heterogeneity	Creates localized turbulence zones	Enhances or suppresses mixing locally	Patchy dispersion
Dead Zones/Storage Areas	Low-velocity regions	Delays pollutant release	Long-tail concentration profiles

One key feature of geophysical control is the existence of transient storage zones, such as dead zones, side channels and the hyporheic zone [66]. These zones have low velocities and low exchange with the main flow, where contaminants can be stored and then released. Turbulence helps to regulate exchange with the main flow, affecting both residence time and dispersion. This can lead to long tails in concentration distributions due to the storage and subsequent release.

4.3. Implications for Contaminant Transport

Turbulence-geophysical control interaction has important implications on the transport and fate of river system pollutants [67]. Among the consequences is the non-adherence of the classical dispersion behaviour, which can give inaccurate predictions of contaminant spreading and dilution unless accounted accordingly. Coherent structures and temporary storage areas may lead to delayed transportation, focal storage, and extended contaminant persistence.

Pollutants are of various kinds and they react differently to turbulent mixing based on their physical and chemical characteristics. Particulate matter is also subject to the action of settling, resuspension, and aggregation processes, whereas the dissolved substances are mainly affected by advection and turbulent diffusion. Turbulence may also increase the transport distance of fine particles, allowing them to be carried further, although it may also increase deposition in low-velocity areas. These counter-acting processes make predictions of contaminant fate and distribution difficult. In the case of reactive pollutants, turbulence is found to exert not only a transport effect but also a transformation. Increased mixing can elevate the rate of reactions by increasing contact between reactants, as well as influence the distribution of temperature, oxygen, and other controlling factors. Turbulence can affect the uptake of nutrients in the case of nutrients by controlling the supply of nutrients to aquatic organisms. On the same note, the lack of mixing may cause the local regions of high concentration, and the ecological consequences may be expected [10,68].

Management-wise, the turbulence variability poses a problem in monitoring and risk assessment. The spatial and temporal heterogeneity of the pollutant distributions can be missed by traditional sampling techniques that are often based on discrete measurements or time-averaged concentrations. This may lead to erroneous measurements of exposure and environmental risk, especially where systems have a high transient storage or intermittent mixing. Transport predictive modeling of pollutants therefore requires consideration of the intricate interactions between turbulence and geophysical controls [69]. Although the one-dimensional advection dispersion models are still popular because of their simplicity, their drawbacks are also increasingly being realized. More sophisticated models, such as multi-dimensional numerical models and stochastic models, provide a better representation of mixing processes but demand detailed data and significant computing power.

The latest advances in technologies of measurements, including high-resolution velocity profiling and experiments with tracers, have contributed to the improvement of the possibility to observe and measure dispersion processes in natural rivers [70,71]. Such techniques offer useful information on the importance of turbulence and can guide the creation of more precise predictive models. Nevertheless, it is still difficult to extrapolate such observations to larger river systems and to incorporate them into the working management tools.

In short, a major aspect of turbulence that regulates the dispersion of pollutants in rivers is that it mediates the interplay between channel morphology, boundary conditions, and flow variability [72]. Transport processes that result are complicated due to the characteristic non-Fickian nature and intense spatial and temporal dissimilarity. These complexities demand integrative, process-based solutions that explicitly consider the dynamics of turbulence and its response to geophysical controls. These are necessary advances in enhancing prediction and control of the transportation of contaminants in riverine systems. **Table 4** compares the existing ways of modeling and their shortcomings. The multi-scale feedbacks are conceptually summarized in **Figure 2**.

Table 4. Comparison of modeling approaches used to simulate turbulence, bank erosion, and pollutant dispersion in river systems, including their advantages, limitations, and typical applications.

Model Type	Features	Advantages	Limitations	Applications
1D Advection–Dispersion Models	Simplified transport equations	Computationally efficient	Cannot capture spatial heterogeneity	Large-scale river studies

Table 4. *Cont.*

Model Type	Features	Advantages	Limitations	Applications
2D/3D Hydrodynamic Models	Resolves flow field in space	Captures complex flow structures	Data and computation intensive	River engineering, restoration
Large Eddy Simulation (LES)	Resolves large turbulence structures	High accuracy in turbulence representation	High computational cost	Research-scale studies
Empirical Models	Based on observed relationships	Easy to apply	Limited generalizability	Preliminary assessments
Coupled Hydro-Geomorphic Models	Integrates flow, sediment, and bank stability	Captures feedback mechanisms	Complex calibration	Erosion prediction

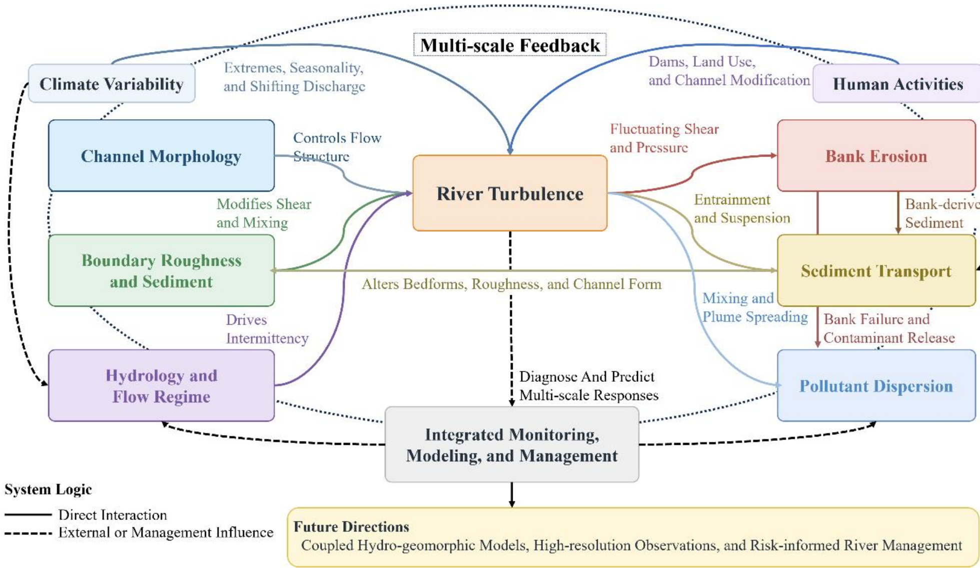

Figure 2. Integrated framework.

Note: The integrated framework shows feedback between turbulence, channel morphology, sediment dynamics, bank erosion, and pollutant dispersion, including the influence of external drivers such as climate variability and human interventions.

5. Conclusions

This review has discussed the basic importance of geophysical control in determining turbulence in river systems and has pointed out the implication of such dynamics on bank erosion and pollutant dispersion. Turbulence is identified to be a unifying process, which connects the morphology of channels, boundary roughness, hydrological variability, and external forcing to essential geomorphic and transport events. Instead of being a by-product of flowing, turbulence is a major cause of energy reallocation, exchange of momentum and mass transfer that affects the stability of river banks and the destiny of contaminants.

One key study finding of this synthesis is that turbulence in natural rivers cannot be well captured with simplified, time-averaged representations. The variability created by the presence of coherent structures, intermittent bursts, and multi-scale interactions is a strong control of near-boundary processes and mixing behavior. They are a systematic effect of geophysical controls like channel curvature, bedform geometry, vegetation and flow regime. Consequently, turbulence is spatially organized and also temporally variable and this fact has to be factored in explicitly within the predictive framework. The turbulence in the situation of bank erosion is decisive because it produces varying levels of shear stresses and pressure fields, which interplay with heterogeneous bank materials. Hydrodynamic forcing and geotechnical response are coupled, resulting in non-traditional threshold-based erosion mechanisms. Transient high-intensity turbulent events, especially in floods, are frequently attributed to the disproportionate contributions to the overall erosion, and capturing the transient dynamics is important. Moreover, turbulence and biological processes, including vegetation, also bring about other feedbacks that may stabilize or destabilize banks based on the local conditions.

Likewise, the dispersion and mixing of pollutants are controlled by turbulence and mediate the effects of channel geometry and flow variability on contaminant transportation. It has been highlighted in the review that classical advection-dispersion models are not always appropriate in describing transport in natural rivers with complex morphology and transient storage processes. The interaction between turbulence and features of recirculation zones, dead zones and hyporheic exchange results in non-Fickian behavior, such as skewed distributions of concentrations and long residence times. Such processes contain significant implications to the water quality management because they influence the spatial distribution and persistence of pollutants. A theme significant in this article is the interrelation between erosion and dispersion processes. They both share the same underlying turbulence dynamics, and are both subject to common geophysical controls. This interdependence implies that the issue of prediction and full comprehension of river systems requires integrated approaches. Indicatively, the morphology of channels that can change the turbulence structures can also change the pathway of pollutants and the stability of the banks. These linkages are important to understand so as to come up with effective river management and restoration strategies.

Although there have been tremendous improvements in the observational methods and numerical models, there are still considerable challenges. Turbulence measurement in natural rivers has not been extensively done in high-resolution, especially at boundaries where erosion and mixing occur most actively. Likewise, although the computational models have evolved to be complex, they are usually simplified and are only applicable in large-scale or long-term forecasting. The need to narrow the gap between a detailed understanding of processes and practical modeling tools is one of the priorities.

Despite substantial advances in observational methods and numerical models, considerable challenges remain. To move beyond generic calls for "integrated models" and "more observations," we propose specific, testable hypotheses and quantitative directions to guide future research. In meandering channels, we hypothesize that secondary flow will dominate over bed roughness effects on turbulence when the curvature ratio (R_c/B) is less than three and the aspect ratio (B/H) exceeds five, with a turbulence intensity ratio $I_{secondary}/I_{roughness}$ greater than 1.5. Under these conditions, outer-bank erosion rates will exceed inner-bank deposition by a factor greater than two during bankfull flows. For cohesive banks, we propose that erosion will initiate when the product of turbulent sweep event magnitude (u'_{sweep}/u^*) (where, u' for sweep-event velocity pulses; u* is the friction velocity, a mean shear scale) and event duration ($T_{event}/T_{integral}$) exceeds 0.8, even when the mean boundary shear stress is 30% below the critical threshold, with fatigue failure following ten to fifty high-frequency events (frequency greater than 0.1 Hz). Regarding pollutant dispersion, the departure from Fickian transport, measured as a skewness of concentration breakthrough curves greater than 0.5, will occur when the ratio of transient storage zone volume to main channel volume exceeds 0.15 and the Damköhler number for exchange ($\tau_{advection}/\tau_{exchange}$) is less than 0.3.

Quantitative research directions should include the following targets. Future field studies should acquire high-frequency (at least 50 Hz) velocity and pressure data within 0.1 m of eroding banks over complete hydrographs, capturing at least fifty turbulent burst events per monitoring period. Pressure fluctuation amplitudes exceeding 15% of the mean shear stress should be considered primary erosion triggers requiring explicit representation in predictive models. For model validation, hydrodynamic models should achieve root-mean-square errors below 0.1 m per second for all velocity components and predict Reynolds stresses within ±20% of acoustic Doppler velocimetry measurements. Models that fail to reproduce organized structures such as sweep-ejection cycles with a correlation above 0.6 should be considered inadequate for erosion prediction. Laboratory flume studies should systematically vary curvature ratio (R_c/B from 2 to 10), relative roughness height (k_s/H from 0.05 to 0.5), and hydrograph rising limb duration (from 1 to 24 h) in full factorial designs to quantify interaction effects on turbulence anisotropy and erosion efficiency.

Specific attention should be given to climate change and human activities, which are altering flow regimes, sediment supply, and channel morphology. We hypothesize that a 20% increase in flood frequency will amplify bank erosion by 40–60% in systems where turbulence intermittency currently limits sediment entrainment. This prediction is testable with existing long-term monitoring datasets. These hypotheses and quantitative benchmarks provide a concrete roadmap for future research, moving the field beyond descriptive calls toward falsifiable, process-based advances.

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