

Rivers, Estuaries, and Coastal Zones: Sediment Transport and Morphodynamical Models

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1. Introduction to the Special Issue

Sediment transport and the resulting bed changes are a crucial process shaping river channels, estuaries, and coastal zones. In dynamic fluvial and coastal systems, sediment transport depends on numerous physical factors. Particle movement begins when a critical flow-induced shear stress is exceeded—a phenomenon first described by Shields [1]. Since classical laboratory experiments on sediment transport [2], it has been known that entrained material creates characteristic bottom formations (e.g., ripples, dunes) and undergoes continuous transformations as flow conditions change. Rivers that deliver sediment to the ocean influence the morphology of deltas and coastlines and supply ecosystems with nutrients, thereby determining their productivity and biodiversity [3,4]. Various hydrodynamic conditions—from steady river flows to wave action and tidal cycles—determine the mechanisms of sediment transport and the associated morphodynamic changes in the bed. For example, tidal asymmetry can generate periodic mass transport towards the upper part of the estuary, favouring the formation of a zone of increased suspended material concentration. In turn, wave action can temporarily increase the mechanical impact on the bottom, thus increasing the susceptibility of bottom sediments to erosion [5,6].

This Special Issue is devoted to the full spectrum of sediment mobilisation conditions—from the initial initiation of grain movement to the state of full bed mobilisation. Particular attention is paid to various forms of bottom material transport: bedload transport and transport in the so-called contact layer in the immediate vicinity of the bed, as well as transport of suspended sediments further from the bed. Fractions of suspended material near the bed, in the so-called bottom layer, play a significant role in channel-bed morphodynamic processes, although they have received less attention to date than total transport [7]. Experimental and modelling studies, therefore, cover both grains rolling on the bed and those entrained in the bottom layer, from critical conditions, when particle movement is just beginning, to states of intense transport, with grains moving throughout the channel. Laboratory wave experiments have confirmed that the oscillatory nature of waves initiates sediment transport in both directions of the wave cycle [8], with the presence of the finest particles potentially determining the resulting transport direction [7,8]. The effect of fine-grained material admixtures (cohesive-free fractions) on sand transport was also investigated under steady-state flow and wave motion conditions. The results indicate a significant contribution of the finest particles [8,9] to the overall transport of unconsolidated sediment mixtures. Such experimental approaches, combined with numerical modelling, contribute to comparative morphodynamics by integrating laboratory and field analyses with simulations, enabling a better understanding of the spatiotemporal variability of processes [10,11].



Received: 10 December 2025

Accepted: 11 December 2025

Published: 15 December 2025

Citation: Kaczmarek, L.M.; Pietrzak, M. Rivers, Estuaries, and Coastal Zones: Sediment Transport and Morphodynamical Models. *Water* **2025**, *17*, 3545. <https://doi.org/10.3390/w17243545>

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This Special Issue focuses particularly on the transport of fine-grained material and complex processes occurring in suspension, as well as on the transport of cohesive-free sediments in the bottom layer [12]. The transport of fine, cohesive sediments (silts, clays) is primarily determined by flocculation, the formation of loose agglomerates of particles. This process remains one of the most complex elements of sediment dynamics—it is simultaneously influenced by physical, chemical, and biological factors, which requires further in-depth interdisciplinary research [13]. Previous studies indicate that flocculation affects the effective diameter and settling velocity of grains, and thus the sediment concentration in the water column and the rate of accumulation at the bottom. However, many aspects (e.g., the influence of organic matter, turbulence, and impingement on flocculation processes) remain insufficiently explained, leaving a significant research gap that needs to be filled [14].

The broader context of global changes—both climatic and those driven by human impacts—that strongly affect sediment systems cannot be ignored. Climate warming and the accompanying changes in precipitation patterns, temperatures, and the frequency of extreme hydrological events are leading to modifications in the sediment transport regime in rivers. Many regions are already observing more extended periods of low water levels and less frequent floods, resulting, among other things, in a reduction in the annual transport of river-suspended solids [15]. Human activity over the past few decades has also significantly altered the sediment balance. The construction of dams and retention reservoirs has dramatically reduced the sediment flow to river mouths—estimates indicate local reductions exceeding 95% (e.g., in the Nile and Ebro river basins) and a global decline in total river transport by approximately 25–30% [16,17]. As a result, many deltas and coasts are suffering from sediment deficits, which translate into accelerated coastal erosion, backwater formation, and the degradation of coastal ecosystems. Furthermore, climate projections predict further declines in river flows and sediment transport potential: by the mid-21st century, these reductions could reach $\sim 30\%$, and by the end of the century, even 50%, depending on the climate scenario and water management measures [17].

Therefore, an integrated approach to sediment resource management is becoming necessary to counteract the adverse effects of these changes. Fortunately, modern measurement and modelling methods are rapidly developing, supporting sediment transport research. Numerous technological innovations have been introduced in recent years, enabling the tracking of sediment transport in the aquatic environment with unprecedented resolution. Advanced sensors and measurement platforms—from unmanned drones with lidars, through flotillas of floating gliders equipped with probes (ADCPs, optical sensors, etc.), to observation satellites with high-frequency imaging—provide data with a precision and frequency previously unattainable, enabling the observation of rapid changes in seabed shape and suspended solids concentration in near-real-time [18,19]. Simultaneously, the development of numerical models—increasingly complex yet widely available as open-source software—capable of simulating coupled hydrodynamic-sedimentary phenomena on local and regional scales [20] is progressing.

Recent studies summarise these achievements, suggesting new approaches and formulas for describing sediment transport in streams. These tools allow scientists to understand better the complex interactions between water flow and sediment movement, thereby enabling more accurate predictions of changes in channel and coastal morphology. We hope that such interdisciplinary and innovative work, combining field observations, experiments, and modelling, will provide practical knowledge for managing rivers, estuaries, and coastal zones in the era of climate change and increasing human pressure.

2. Special Issue Summary

This Special Issue of the journal *Water* comprises eight scientific articles presenting the latest advances in sediment transport and morphodynamic modelling in rivers, estuaries, and coastal zones. The papers cover a broad range of topics, encompassing both theoretical and applied research. The authors address topics such as modelling the transport of heterogeneous sediments in river channels, the influence of shoreline geometry on beach nourishment efficiency, improving calibration methods for hydrodynamic models, the formation of bedforms (rippling), the use of advanced acoustic measurements to assess suspended solids transport, seasonal variability of transport in a large river estuary, sediment monitoring in a macrotidal bay, and the reconstruction of historical changes in sediment delivery to the coast based on sediment archives.

Biegowski et al. proposed a three-layer model for the transport of a mixture of grains in a steady flow over a moving, inclined bed. The model distinguishes a lower bed layer, a contact layer, and an upper layer, enabling continuous vertical profiles of velocity and sediment concentration. A key element of the new approach is the inclusion of the additional gravity effect in the bed layer during downslope flow. This effect, which has often been neglected in previous studies, increases velocity in the moving-bed sublayer and influences the concentration distribution in the upper flow layers. The model was experimentally verified under various conditions (variable bed slope, grain diameters, and densities, from initial movement to full mobilisation), achieving good agreement with experimental data. The proposed theoretical description increases the reliability of sediment transport calculations and can be applied in the design and operation of hydraulic infrastructure (e.g., dams, canals, and seabed revetments).

Liu et al. analysed how foreshore slope affects sediment transport across the beach and the formation of sandbars during shore nourishment. The study used Bagnold's energy approach and the small-angle method to formulate the relationship between shoreline steepness and sediment transport across the beach profile. The authors demonstrated the existence of a feedback mechanism: for small slope angles (below 10°), a lower initial steepness results in lower sediment losses, and as the process progresses, the profile flattens and reaches an equilibrium state favouring the formation of offshore rifts. Numerical simulations, conducted for Guanhu Beach in Dapeng Bay, among others, confirmed that profiles with a gentler slope experience less sediment loss in the initial phase and form protective rifts more effectively. The obtained results provide guidance for the design of beach nourishment treatments—a properly selected slope angle can limit early material losses and improve the durability of artificial nourishment.

Rivera-Trejo et al. proposed an innovative methodology for iterative calibration of a two-dimensional river hydrodynamic model using flow velocity measurements at multiple cross-sections. Traditional calibration approaches typically rely on fitting the model to the observed water surface profile, which is effective for 1D models but insufficient for 2D models. The presented method utilises ADCP data and 3D sonar-derived seabed bathymetry to assess simulation quality. These data are compared with model results for compatible spatial locations. Quantitative error measures (including relative mean error, absolute error, and RMS) are used to assess the accuracy of 2D simulations objectively. The procedure was tested using the TELEMAC-2D model for a section of the White River (USA) encompassing a developing, cut-off meander. It was demonstrated that including detailed velocity data improves calibration, enabling better tuning of model parameters (e.g., bed roughness, boundary conditions) and increasing the reliability of the flow simulation.

Zanke and Kloker addressed the fundamental issue of rippling—small ripples in the sandy bottom that form spontaneously when currents or waves set grains in motion. This phenomenon has significant practical significance (affecting bottom roughness and

sediment transport) and paleohydrological significance, enabling the reconstruction of flow conditions based on fossil sedimentary structures. Previous research has primarily focused on describing mature rippling and dune formations and their migration conditions, while the mechanism of initial rippling formation remains unclear. In their paper, the authors proposed an explanation for the genesis of rippling by invoking hydrodynamic flow instability. The presented theory indicates that a regular pattern of initial rippling with uniform wavelengths is formed by Tollmien–Schlichting waves in the bottom layer, leading to periodic disturbances that result in local sediment accumulation. Classical laboratory experiments have confirmed this model and represent a significant step forward in understanding how and why rippling occurs.

Creane et al. focused on estimating suspended sediment concentrations in a tidally dominated continental shelf environment to better validate numerical models. The lack of sufficient field data often limits confidence in sediment transport simulation results in the coastal zone. In this study, four methods were used to estimate suspended sediment concentrations from acoustic signals from an ADCP (current profiler) and were compared with direct water-sample measurements. The analysis was conducted for a two-dimensional sediment transport model in the southwestern Irish Sea. The authors obtained a spatiotemporally consistent dataset of suspended-solids concentrations from ADCP, which showed a high degree of correlation ($R^2 \approx 0.87$) with in situ measurements. Of the four validation techniques evaluated, three proved particularly useful and are recommended: validation of 2D model results using suspended solids concentrations measured in water samples, comparison of suspended solids transport characteristics (ebb/flow direction, variability over the tidal cycle) simulated in the 2D model with ADCP data, and comparison of peak sediment concentrations in the model during a complete tidal cycle with values determined from ADCP data. The proposed methods significantly increase confidence in sediment model validation while remaining relatively inexpensive due to the use of existing acoustic measurements. This approach makes a valuable contribution to the development of tools for assessing sediment transport models for marine engineering and coastal protection projects.

Lu et al. conducted a numerical study of seasonal variability of sediment transport in the Pearl River estuary (China), emphasising the importance of different hydrodynamic conditions between the wet and dry seasons. Using a well-calibrated numerical model of the estuary, the authors investigated how changes in river discharge and meteorological factors affect the dispersion of suspended solids and the rate of sediment export from the estuary to the sea. They demonstrated that during the wet season, the intense freshwater flow creates substantial outflows, which, combined with the Coriolis force and the bottom relief, direct the majority of sediment transport towards both banks of the estuary and further out to sea—particularly through the western part of the estuary. The sediment transport time (the so-called sediment age) is relatively short: it takes an average of 30 days to leave the estuary along the eastern channel, and about 45 days through the western flank. During the dry season, reduced river flow and prevailing northeasterly winds weaken sediment export; most material remains deposited within the estuary, and the average particle residence time increases to approximately 50 days or more. Winds appear to be an essential modifying factor: summer southerly winds weaken suspension dispersion and prolong transport times, while winter northerly winds enhance estuarine circulation and accelerate sediment export to the sea. The results of this study provide valuable insights into the mechanisms behind seasonal changes in sediment transport. They can aid estuarine management by indicating when and where sediments accumulate or are washed away.

Lee et al. focused on suspended solids transport processes in the macrotidal Gomso Bay (west coast of South Korea), part of the UNESCO World Heritage Site (“Getbol, Korean

Tidal Flats”). A 13 h series of stationary measurements was conducted in the bay’s main outflow channel over the tidal cycle, yielding a unique set of high-resolution vertical data. A set of sensors, including current metres (RCMs), CTD probes, water-level sensors, and manual water sampling, was used to analyse total suspended matter (TSM) concentration. Measurements were taken simultaneously at the surface, mid-depth, and bottom at 15–30 min intervals. The results showed a strong linear relationship between turbidity (NTU) and TSM concentration ($R^2 = 0.94$), confirming the suitability of optical probes for rapid estimation of suspended solids concentration under dynamic tidal-channel conditions. The local net transport balance of suspended solids was also calculated. The studied profile showed a predominance of seaward sediment export (approximately 5500 kg per metre of cross-sectional width throughout the entire cycle), consistent with the observed dominance of ebb currents. The authors note that this value is specific to a particular location and a short observation period, so it is not representative of the entire bay; elsewhere, opposing net transport directions may occur (e.g., local landward transport over shallow areas). Nevertheless, the study provided valuable reference material and serves as a starting point for further analyses, for example, in building a “digital twin” of the bay’s sedimentary system and in conservation management of this dynamic ecosystem.

Hadour et al. used sediment archives to reconstruct changes in fluvial–marine sediment transport in the Wadi Cheliff estuary region in Algeria, analysing the impact of climatic factors (precipitation) and anthropogenic factors (large dams) on reducing sediment delivery to the sea. Three river sediment cores collected in the lower Cheliff Valley, downstream of the main dam reservoirs, were analysed. The granulometric and geochemical profiles of the sediment cores were compared with historical data on regional rainfall totals and the construction schedules of large dams on the river. The analysis revealed a distinct difference between sediment layers from around 1980 and those from more recent times. In older cores (reflecting a period of higher rainfall before intensive river regulation), coarser sand fractions predominate, arranged in numerous layers, and deposition occurred at approximately 16 mm/year. In the upper sections of the cores, corresponding to the recent decades of decreasing rainfall and the construction of successive dams, the sediments are fine-grained (predominantly silt and clay) and deposited much more slowly, approximately 1.3 mm/year. The disappearance of the sand fraction in the younger sediments clearly indicates that the dam reservoirs intercepted material. The results of the study show that the sedimentary record faithfully reflects changes in sediment transport at the river mouth, driven by both natural climate fluctuations (wet and dry periods) and intense anthropogenic pressure from water damming.

Author Contributions: The two authors contributed equally to the preparation of the article. Conceptualization, M.P. and L.M.K.; writing—original draft preparation, M.P. and L.M.K.; writing—review and editing, M.P. and L.M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank the editors of the journal and the authors who contributed their articles to the Special Issue. Finally, special thanks are given to the anonymous reviewers who have contributed to improving the quality of the articles.

Conflicts of Interest: The authors declare no conflicts of interest.

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