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The Changing Function of River Deltas

Cross-Disciplinary Perspectives

Edited by Andrew J. Manning



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Meet the editor



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Preface

Occupying the dynamic interface between land and sea, river deltas are among the most intensively used and ecologically complex environments on Earth. They provide critical ecological functions and sustain vast human populations, while supporting essential economic activities, including agriculture, fisheries, industry, and urban development. However, this very importance renders them acutely vulnerable: the cumulative pressures of extraction, infrastructure, and climate-driven change continue to exert unprecedented stress on these sensitive aquatic systems. Effective stewardship of deltaic environments requires a nuanced, multidisciplinary understanding of the processes that govern them. Although deltas are predominantly shallow-water systems, their behaviour reflects the interplay of diverse physical, chemical, biological, and social factors operating across multiple spatial and temporal scales. Numerical models, now a cornerstone of delta research and management, allow scientists and practitioners to explore trends and predict outcomes. However, their effectiveness depends on a robust appreciation of local conditions, which can vary dramatically from one delta to another. Over the past half-century, scientists, engineers, hydrologists, and mathematicians have significantly advanced our understanding of deltaic systems, encompassing a range of topics from water quality, pollution, and tidal dynamics to geomorphodynamics, sediment transport, ecosystem structure, and habitat change.

This volume, *The Changing Function of River Deltas – Cross-Disciplinary Perspectives*, brings together international scholarship on a wide range of delta-related issues, including water quality and contamination, environmental disasters, climate change, land reclamation, geomorphology, biodiversity, flocculation, hydrodynamics, sediment dynamics, classification, circulation patterns, ecosystem processes, the social construction of deltaic landscapes, and anthropogenic stressors. Each topic is illustrated with case studies drawn from deltas around the world, providing a global perspective on local challenges. The book comprises five chapters authored by an international group of researchers specialising in geomorphology, sediment dynamics, water quality, hydrology, and numerical modelling. While most chapters focus on natural process-related issues, several also address the human dimensions of delta environments - for example, the social constructs shaping the Seine Estuary, or the impacts of urbanisation on the Maeander River of south-western Turkey. Other contributions examine hydrodynamic erosion of riverbeds, the mechanics of flocculation, and key features of deltaic environmental change. By assembling this research, the volume offers an up-to-date, interdisciplinary resource for scientists, engineers, and decision-makers concerned with the sustainable management of river deltas. I extend my

sincere gratitude to all contributing authors for their expertise and commitment, and I commend this book to readers seeking a deeper understanding of one of the planet's most vital and threatened systems.

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Introductory Chapter: River Deltas – An Overview of Key Features

Andrew J. Manning

1. Overview

A river delta is a dynamic geomorphological landform created where sediment-laden river water enters a standing body of water—such as a sea or lake—causing a rapid loss of flow energy and subsequent sediment deposition. Characterized by fan- or triangle-shaped plains and complex distributary networks, deltas distribute water and sediment across flat, fertile terrain. These features have long supported dense human populations due to their agricultural productivity, aquatic resources, and navigability. Approximately 25% of the global population inhabits deltaic and coastal wetland regions [1].

Deltas are globally widespread, with 21 of the world's 25 largest rivers forming well-developed deltaic systems that contribute approximately 31% of the total fluvial sediment delivered to the oceans [2]. While biologically rich and agriculturally productive, deltas are inherently dynamic and sensitive landscapes shaped by the interplay of sediment deposition, erosion, subsidence, and hydrological variability. Today, around 2400 river deltas exist globally, but just 295 account for ~95% of the total marine deltaic area, spanning roughly 855,000 km² [3]. The Ganges-Brahmaputra Delta—the world's largest and most populous—extends 350 km along the coast, covering approximately 60,000 km² across Bangladesh and eastern India. Formed by the confluence of the Ganges, Brahmaputra, and Meghna rivers and driven by intense monsoonal processes, this delta is among the most fertile regions globally and contains the Sundarbans, the largest mangrove forest on Earth and a UNESCO World Heritage Site. Major deltas like this serve as critical hubs for biodiversity, food production, and dense urban populations, but they are increasingly threatened by anthropogenic pressures and climate change.

2. Formation

River deltas form where sediment-rich rivers discharge into standing bodies of water such as oceans, seas, or lakes. This transition causes a sharp reduction in flow velocity, which diminishes the river's capacity to transport sediment. Consequently, suspended sediments—ranging from coarse sand to fine clay—begin to settle and accumulate at the river mouth. Over time, this leads to the creation of a deltaic landform, typically fan- or triangle-shaped, and characterized by distributary channels

that further spread and deposit sediment. For instance, the Mississippi River delivers approximately 200 million tonnes of sediment annually, facilitating land-building processes across an area exceeding 25,000 km². Delta morphology depends on the balance among fluvial inputs, sediment load, wave and tidal energy, and relative sea-level changes.

3. Sediment dynamics

These processes in river deltas involve complex interactions of transport, deposition, erosion, and flocculation. Rivers carry a spectrum of sediment grain sizes: gravel, sand, silt, and clay. Coarser sediments typically settle near the delta front, forming bars and foreset beds (i.e., sloping sediment layers deposited as river flow decelerates and sediments settle at a delta front—seaward edge of the delta), while finer particles travel farther offshore into the prodelta region (i.e., the submerged, outermost seaward zone). Fine-grained sediments, particularly clay and silt, often undergo flocculation—where electrochemical attraction and turbulence cause particles to aggregate and settle more rapidly than they would individually. This process is especially significant in estuarine zones where freshwater meets saline water, enhancing deposition rates in brackish zones. Active delta lobes may accumulate sediment at rates of 10–20 mm/year, with the Amazon River contributing over 1.2 billion tonnes of sediment annually. However, sediment erosion due to tidal currents (often >1 m/s in tide-dominated deltas like the Ganges or Mekong), wave reworking, and sea-level rise frequently counteract these gains. The Mississippi Delta, for example, loses about 45 km² of land per year due to a combination of subsidence, sediment deficit, and coastal erosion.

4. Hydrodynamics, human impact, and delta stability

Delta evolution is heavily influenced by hydrodynamical forces and anthropogenic pressures. River discharge volumes and seasonal variability—such as the Ganges reaching over 20,000 m³/s during monsoon—govern sediment flux and distribution. Tidal ranges vary widely: less than 1 m in wave-dominated systems like the Rhône, to over 6 m in tide-dominated deltas such as the Amazon or Ganges-Brahmaputra. Coastal wave energy, which may exceed 10 kW/m during storm events, shapes shoreline configuration by redistributing sediments or causing erosion. Human activities have severely altered sediment budgets; for example, global damming has trapped an estimated 60–70% of fluvial sediment upstream [4], while sand mining and dredging further exacerbate sediment starvation. Sea-level rise gradually results in submergence and land loss. Vegetation such as marsh grasses and mangroves, which can enhance local sediment deposition by up to 50%, provides crucial stabilization. Ensuring long-term delta resilience requires integrated sediment management strategies, including controlled flooding, sediment diversions, and restoration of vegetated buffers, and adaptive planning.

5. Biogeochemical and ecosystem features

River deltas are biogeochemically active and ecologically complex systems shaped by interacting chemical, physical, and biological processes. Chemically, deltas are

transitional zones where freshwater meets saline or brackish water, triggering processes such as flocculation, redox transformations, and nutrient cycling. Flocculation, driven by ionic interactions between fine sediments and saltwater cations (e.g., Ca^{2+} , Mg^{2+}), along with biological cohesion from extracellular polymeric substances, promotes rapid sediment settling [5]—a key mechanism in delta formation. Redox reactions in sediments, regulated by microbial decomposition of organic matter, govern the cycling of nutrients and trace metals such as nitrogen, phosphorus, iron, and sulfur, affecting both sediment chemistry and water quality. These processes are further modulated by tidal mixing, temperature, discharge variability, and anthropogenic stressors such as damming and pollution.

Biological activity is equally central to delta stability. Nutrient-rich, sediment-laden waters fuel high primary productivity by phytoplankton and aquatic plants, forming the base of productive food webs. Wetland vegetation (e.g., mangroves, salt marshes; [6]) stabilizes sediments, aids nutrient retention, and supports carbon sequestration. Microbial processes—such as nitrification, denitrification, and methanogenesis—operate under varied redox conditions, facilitating organic matter decomposition and nutrient turnover. Deltas also host high biodiversity [7] across salinity gradients, supporting fisheries, migratory birds, and estuarine fauna. However, rising pressures from land-use change, water regulation, eutrophication, and habitat fragmentation threaten these critical functions. Integrated management that preserves hydrological connectivity and promotes ecological restoration is essential to sustain the multifunctional role of deltas under accelerating environmental and climatic change.

6. Geological characteristics

River deltas are dynamic sedimentary landforms formed at the interface between fluvial and marine or lacustrine systems, where riverine sediments are deposited as flow velocity declines upon entering standing bodies of water. The stratigraphy of a typical delta exhibits a tripartite structure comprising bottomset, foreset, and topset beds. Bottomset beds are composed of fine-grained particles transported furthest from the river mouth and laid down in horizontal layers under low-energy conditions. Above them, foreset beds form the bulk of the delta front and consist of coarser sediments deposited at an angle of repose as the delta progrades seaward. Finally, topset beds, consisting of finer sediments again, accumulate on the delta plain and are influenced by both riverine and tidal processes. The internal architecture of these strata reflects shifts in energy regimes and sediment supply, with smaller-scale features such as crossbedding offering insight into episodic depositional events. The geomorphology of deltas—whether arcuate, cusped, or bird's-foot—is governed by a complex interplay of sediment load, river discharge, tidal amplitude, wave energy, and basin slope.

The geological evolution of river deltas is shaped by both short-term depositional dynamics and long-term tectonic, climatic, and eustatic influences. For example, the Ganges-Brahmaputra Delta began forming around 11,000 years B.P., when rising sea levels inundated the Bengal Basin, trapping river discharge near the coast. Between 11,000 and 7000 years B.P., approximately $5 \times 10^{12} \text{ m}^3$ of sediment accumulated, indicating a sustained mean sediment load of 2.3×10^9 tonnes per year—more than twice the modern rate of $\sim 1 \times 10^9 \text{ t/yr}$ [8]. This elevated flux aligns with evidence of an intensified southwest monsoon during the early Holocene. The scale and duration

of this discharge highlight a strong monsoon-sedimentation linkage, mirrored in other tropical and subtropical systems, with the Ganges-Brahmaputra serving as a key example of climate-driven fluvial response.

Sediment accumulation often begins in estuarine settings, transitioning through stages of aggradation and progradation as sediment fills available accommodation space. Over millennial timescales, processes such as lobe switching (avulsion), subsidence, and relative sea-level changes sculpt deltaic landscapes. The Holocene epoch marks a major phase of delta expansion globally, facilitated by stabilized sea levels and increased sediment delivery from post-glacial river systems. Tectonics plays a central role by influencing subsidence rates and sediment routing pathways, thereby regulating delta stability and stratigraphic development. Sedimentological records from deltas like the Nile and Mississippi reveal the imprint of glacial-interglacial cycles and anthropogenic interventions on deltaic morphology. As both repositories of stratigraphic complexity and vital socio-ecological zones, deltas offer key insights into sedimentary processes, coastal evolution, and the challenges posed by climate change and human modification.

7. Comparison with estuaries

River deltas and estuaries, while both located where rivers meet larger water bodies, exhibit distinct geomorphological and sedimentary characteristics. Globally, there are about 1178 river deltas larger than 1 km², compared to roughly 4464 river basins that discharge into estuaries or estuarine-deltaic systems. River deltas primarily form through rapid sediment deposition as river velocity decreases abruptly upon entering standing water, resulting in broad, fan-shaped landforms with multiple distributary channels and active land-building. In contrast, estuaries are shaped predominantly by tidal mixing and hydrodynamic forces, producing elongated, funnel-shaped basins with sediment dynamics dominated by tidal pumping and fine sediment flocculation rather than large-scale fluvial sediment accumulation [9]. This leads to estuaries emphasizing habitat complexity and nutrient cycling, whereas deltas are more focused on sediment-driven land formation and agricultural productivity.

Estuarine deltas occupy a middle ground, combining features of both systems. They form where deltaic sedimentation occurs within tidal, saline-influenced estuarine environments, resulting in highly dynamic and spatially variable landscapes shaped by the interplay of fluvial sediment supply and tidal currents. For example, the Ganges-Brahmaputra-Meghna estuarine delta experiences both high river discharges (>30,000 m³/s) and strong tidal currents (~1.5 m/s), causing continuous reshaping of channels and sediment distribution. In comparison, river deltas tend to have more stable progradation due to dominant fluvial input, while estuaries focus on hydrodynamic mixing with limited land-building. These differences highlight the importance of tailored management strategies: estuaries are vulnerable to salinity intrusion and nutrient imbalances, whereas deltas face sediment deficits and subsidence risks, especially under the impacts of climate change and human activities such as damming and coastal development.

8. Classification

River deltas are primarily classified based on the dominant physical forces shaping their formation [10]—*fluvial*, *wave*, or *tidal* processes—alongside geographic setting

and sediment grain size, which collectively influence their morphology and dynamics. *Fluvial-dominated deltas* typically occur in environments with tidal ranges less than 1 m and wave heights under 0.5 m, where river processes dominate over marine influences. These deltas exhibit flow regimes including homopycnal (rapid mixing with equal densities), hyperpycnal (river water density exceeding basin water by up to 10–15%, generating bottom-hugging turbidity currents), and hypopycnal (lighter river water spreading as surface plumes). For example, the buoyancy-dominated Mississippi River Delta has formed long, narrow distributaries extending 20–50 km offshore, with channel avulsions occurring roughly every 100–500 years over the past 5000 years. *Gilbert deltas*, a fluvial subtype, deposit coarse sediments (often >2 mm grain size) in three characteristic zones—topset beds (flat, up to several km wide), steep foreset beds (slopes of 10°–30°), and bottomset beds extending several km into deeper water. These deltas are common in mountainous freshwater settings such as Lake Bonneville and Okanagan Lake. *Wave-dominated deltas* develop where significant wave energy prevails, with average offshore wave heights often exceeding 1 m and periods of 6–12 seconds, resulting in smooth, arcuate shorelines and sediment redistribution causing shoreline retreat rates up to 5 m per year, as observed in parts of the Ganges Delta. *Tide-dominated deltas* experience tidal ranges frequently exceeding 4–6 m and strong tidal currents surpassing 1.5 m/s, fostering dendritic distributary networks, tidal sandbars, and channel bifurcations; the Ganges-Brahmaputra Delta is a prime example, with tidal channels penetrating more than 100-km inland.

Additional categories include *tidal freshwater deltas* at the freshwater-estuarine interface, *inland deltas* such as the Inner Niger Delta (~30,000 km²) and Okavango Delta (~15,000 km²), which disperse water in arid or flat basins far from the coast, and *mega deltas*—like the Yangtze, Mekong, Indus, and Ganges-Brahmaputra—that exceed 100,000 km² in area, transporting sediment loads surpassing 500 million tons annually and supporting population densities often exceeding 1000 people per km².

Estuarine deltas are transitional geomorphological systems formed where fluvial sedimentation interacts with tidal and saline processes in semi-enclosed coastal basins [11]. These hybrid landscapes exhibit characteristics of both river deltas and estuaries, resulting in highly dynamic, spatially heterogeneous environments. Two principal morphogenetic types exist: (1) deltas forming within open-ended, funnel-shaped estuaries—typically in macrotidal regimes with tidal ranges of 1–5 m and bidirectional currents of 0.5–2 m/s; and (2) deltas forming in barrier-enclosed lagoons, where wave-built coastal barriers attenuate marine energy and favor fluvial sedimentation. Unlike purely fluvial deltas—such as the Indus—estuarine deltas experience significant sediment reworking by tides and waves, producing depositional features such as tidal ridges, mudflats, salt marshes, and midchannel islands. Sediment grain sizes vary spatially, from <4 µm clays in marsh zones to >2 mm sands near distributary mouths. River discharge typically slows upon entering estuarine zones—often declining from 1000 to 20,000 m³/s to near zero—facilitating deposition rates of several cms per year. The Ganges-Brahmaputra-Meghna (GBM) estuarine delta exemplifies this dynamic. It receives over 1 billion tons of sediment annually, with peak monsoonal discharges exceeding 30,000 m³/s, driving rapid landscape reshaping and sediment redistribution. Physical features such as barrier islands can reduce wave energy by over 50%, enhancing shoreline stability and buffering against erosion. While estuarine deltas are prone to salinity intrusion, nutrient imbalances, and tidal amplification, fluvial deltas face increasing threats from sediment deficits, subsidence, and land loss due to upstream damming and sea-level rise. Recognizing the morphodynamic and ecological distinctions between delta types is

essential for sustainable management. Long-term resilience requires an integrative approach encompassing both marine and fluvial processes over decadal to centennial timescales.

9. Sea level and climate

River deltas are particularly vulnerable to sea-level rise (SLR) due to their low elevations—typically less than 2 m above mean sea level—and high population densities, with over 340 million people residing in deltaic regions globally. Since 1900, global mean sea level has risen by approximately 170 mm, with the current rate averaging 3.6 mm yr⁻¹ [12]. Under high-emission scenarios such as RCP8.5, projections indicate that mean sea level could rise by 0.75 to 1.1 m by 2100, while more moderate pathways (e.g., RCP4.5) predict increases of 0.5–0.65 m. Consequently, between 42,750 and 100,000 km² of deltaic land—representing up to 12% of the global delta area—could be permanently inundated and lost by 2100. This risk is exacerbated in deltas experiencing rapid subsidence, such as the Mississippi Delta, where land subsides at rates of up to 10 mm yr⁻¹, compounding relative sea-level rise to as much as 13–15 mm yr⁻¹ locally. In Southeast Asia, the Mekong and Red River Deltas face similar threats, with projected land losses of 38–70% under high SLR and sediment reduction scenarios. Such land submersion threatens agricultural zones, urban settlements, and critical ecosystems in deltas worldwide.

Saltwater intrusion poses an equally severe challenge. For example, in the Mississippi River Delta, salinity has advanced 20–40-km inland during low-flow periods and is projected to move an additional 10–20% farther upstream under 1 m of SLR. In the Ganges-Brahmaputra-Meghna Delta, groundwater salinity has increased by over 300% in coastal aquifers since the 1980s, reducing arable land by 15–20% in affected areas. Meanwhile, the frequency of 1-in-100-year flood events is expected to increase tenfold in many low-lying deltas by 2100 due to elevated base sea levels. Wetland ecosystems, which store up to 200 Mg C/ha in biomass and soil, are rapidly degrading; in Louisiana alone, over 4800 km² of coastal wetland has been lost since 1932, with current loss rates exceeding 40 km² annually. Sediment deprivation, largely caused by upstream damming (e.g., >50% reduction in sediment load in the Nile and Indus Rivers), further impairs natural delta accretion. Without substantial intervention—including sediment diversion, elevation enhancement, and global emissions reductions—many of the world's major deltas face the prospect of irreversible ecological and socioeconomic decline.

10. Population density and regional demographics

River deltas represent some of the most densely populated and socioeconomically significant landscapes on Earth. Although deltas cover less than 1% of the planet's terrestrial surface, they support an estimated 5–7% of the global population—amounting to around 560 million people as of 2023 [13]. Asia dominates this demographic, with an estimated 262 million people—around 77% of the global delta population—living in Asian deltas (as of 2017). Population densities frequently exceed 1000 to 2000 people per km², vastly surpassing the global average of about 59 people per km². The Ganges-Brahmaputra Delta alone is home to over 140 million people within roughly 100,000 km², while the Pearl River Delta has grown into a

megaregion of over 60 million people in just 50 years, now reaching densities as high as 10,000 people per km² in urban centers. The Asia-Pacific region contains more than 70% of global delta populations, with other significant concentrations in African and American deltas, such as the Niger (31 million in 70,000 km²) and Mississippi (15 million in 41,000 km²), respectively.

11. Urbanization, economic usage, and infrastructure pressures

The economic vitality of river deltas underpins their attractiveness for human settlement. Fertile alluvial soils and year-round access to freshwater make deltas the major centers of food production, accounting for an estimated 13% of global rice output and supporting extensive aquaculture and livestock activities. For example, Egypt's Nile Delta produces nearly 80% of the nation's agricultural yield, supporting 40 million people and contributing substantially to GDP. Concurrently, urban expansion in deltaic areas is accelerating, with urban growth rates of 3–5% annually—significantly above the global average. Industrial zones, ports, and manufacturing clusters flourish in these lowlands due to favorable geography. However, this growth places heavy stress on infrastructure, water supply, sanitation, and energy systems, particularly in mega deltas like the Yangtze and Pearl, where industrial output constitutes a substantial share of national economic performance [14].

12. Vulnerability, migration, and socio-environmental implications

Despite their economic centrality, deltas are acutely vulnerable to environmental hazards. Most lie below 5-m elevation, exposing them to storm surges, salinization, and flooding. SLR—currently advancing at 3–4 mm yr⁻¹—would inundate up to 20–40% of low-lying deltaic terrain in regions like the Ganges-Brahmaputra and Mekong by 2100. In the Mississippi Delta, land loss due to a combination of subsidence and rising seas is already occurring at rates of up to 75 km² per year [15]. Environmental degradation is intensifying migration pressures, with up to 20 million people projected to be displaced from deltaic zones by 2050. Migration, often involuntary and poorly planned, destabilizes regional economies and burdens receiving areas. These trends underscore the urgent need for integrated management strategies that couple environmental resilience with inclusive urban planning and equitable development to ensure the long-term habitability and productivity of deltaic systems.

13. Conclusions and future

River deltas globally are under severe stress due to a convergence of climate change impacts, anthropogenic pressures, and natural geomorphic processes. Sea-level rise stands as one of the most urgent threats, with global mean sea level increasing by approximately 170 mm in the past century and accelerating at 3.6 mm annually. Under high-emission scenarios, relative sea-level rise could exceed 1 m in some deltas by 2100, placing low-lying regions at high risk of coastal flooding, shoreline retreat, and saltwater intrusion. This is exacerbated by land subsidence—accelerated by groundwater extraction and sediment compaction—with localized rates as high as 10–30 mm per year [16]. Combined, these processes sharply increase inundation vulnerability.

Climate projections also indicate that the frequency of extreme precipitation events may rise by 20–30% by mid-century, increasing flood hazards, especially when coupled with more frequent and intense tropical storms and storm surges.

Anthropogenic alterations to river systems—particularly dam and levee construction—have reduced sediment delivery to many major deltas by 50–80%, diminishing their natural ability to build land and counteract sea-level rise [4]. Saltwater intrusion, exacerbated by both sea-level rise and reduced freshwater discharge, is advancing inland—by over 5 km in parts of the Mississippi Delta—degrading agricultural soils and contaminating aquifers. At the same time, rapid population growth in delta regions, often exceeding 1000 people per km², intensifies demands on ecosystems and infrastructure. Adaptation strategies increasingly rely on hybrid approaches combining hard infrastructure (e.g., seawalls) with nature-based solutions like wetland restoration [17]. However, success hinges on integrative governance frameworks, participatory planning, and robust funding mechanisms. The future resilience of deltas depends on transdisciplinary collaboration and a balance between economic development, ecosystem protection, and climate adaptation.

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Chapter 2

Meander River in Urban Area

Siti Murniningsih

Abstract

Urban areas are usually located in the downstream zone, which has a meander pattern. Since the Meander belt has a curvilinear shape, erosion of the river cliff or bank erosion is one of the serious problems in urban areas. Another problem there is also landslide that sometimes occurs as a response to the natural or man-made disturbance of the fluvial system. According to land utilization in urban areas, it is subject to potentially serious impact caused by meander river transformation due to erosion and sedimentation, and floodplains will undergo modification with time. The Meander River channelized in the past, causing environmental problems, changing the ecology of the river, and requiring heavy maintenance. In the lower zone of the river, the soil classification is usually Clayey Silt and Sandy Silt, with material composition are clay, silt, and sand. The previous research findings concluded that soil composition with a high percentage of silt would change rapidly compared to soil composition with a low percentage of silt. The result of the experiment is its qualitative approach without quantifying sedimentation in the inner bend and erodible sand in the outer bank, and finding the relation between meander river transformation and soil classification. The result may be able to help resource managers evaluate the long-term effects of floodplain management and bank stabilization measures related to urban development. Case study of the Pesangrahan river normalization that is located in Jakarta city also reflects the impact of cutting off the meander river located in the upstream area, triggering the amount of sediment transport at the downstream area.

Keywords: meander river transformation, soil classification, urban area, erosion, sedimentation

1. Introduction

The word meander originates from the *Maeander River of South-West Turkey*, which clearly shows the winding course characteristic of a meandering river.¹ In general, rivers originate from volcanic mountains and have a distinctive bed slope, which are steep at the upper reach, moderate at the middle reach, and nearly flat at the lower reach. When the bed slope changes from moderate to flat, the pattern of the river channel also alters from straight to braided or meander due to varying velocity and geometry of the channel. Meander patterns usually encourage sediment transport problems, such as riverbed aggradation in the area surrounding the inside of the bank, which then decreases the river capacity in retaining flood, which has a very serious impact on the community.

¹ Principles of River Engineering, page 133.

In general, the profile of a longitudinal river flow can be divided into three zones [1], that is, Zone 1 is the headwater or upstream part of the river, which has a steeper slope. The stream's flow swiftly down steep slopes and cuts a deep V-shaped valley; rapid and waterfalls are common. Zone 2 is the transfer zone. This area receives deposits originating from erosion in the headwater zone. Low-elevation streams merge and flow down gentler slope, the valley broadens, and the river begins to form a meander. Zone 3 is depositional, the zone that has an even lower elevation. The river wanders and meanders slowly across a broad, nearly flat valley. The lowest slope so in the flow velocity being slower, sediment occurs more frequently, and a river section tends to be shallower and wider. At its mouth or estuary, it may divide into many separate channels as it flows across a delta built up of river-borne sediments and into the sea (**Figure 1**).

In this transfer area, the grains transported in the stream will also shrink from the original large rocks, which will split into large gravel, small gravel, and further downstream will become clay and mud. This is because, along the way, the flow from upstream to downstream works deep forces or inner energy, which will break down the size of sediment transport from large rocks into smaller and finer grains. If the course of the river flow from upstream to downstream along the river channel is reviewed, there are erosion or degradation areas in the upstream and accumulation or aggradation areas, namely, downstream.

The problem caused by the degradation and aggradation is the tendency to decrease the slope of the river toward the elongated that is caused by the process of stabilizing the river channel against erosion and the accumulation of sediment transport. Thus, changes in river cross-sectional geometry and flow geometry and changes in riverbed soil classification can result in changes in sediment transport along the river channel. Rosgen [2] proposed type of river channel as state in **Figure 2**: straight river flow (type A, B) is in the headwaters zone with a slope greater than 4%; a braided and meander river channel (type C, D, DA) is in the transfer zone with a slope 2–4%; a meander river channel (type F) is in the transfer zone with a slope less than 4%; and a flat river channel (type F, G) is in the depositional zone with a slope less than 0.5%.

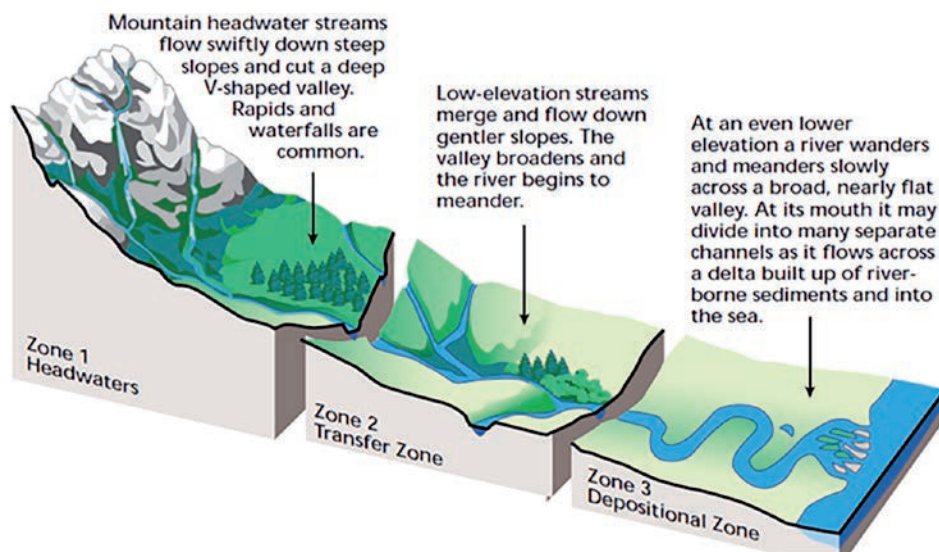


Figure 1.
Longitudinal profile of the river [1].

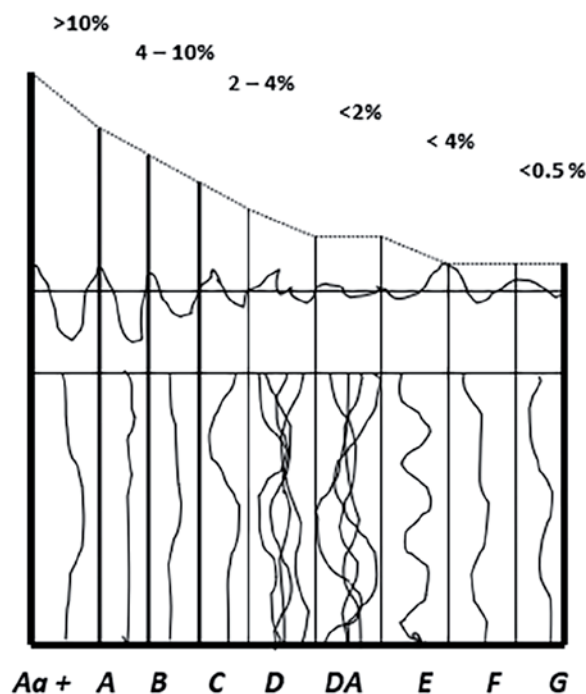


Figure 2.
 Type of river channel [2].

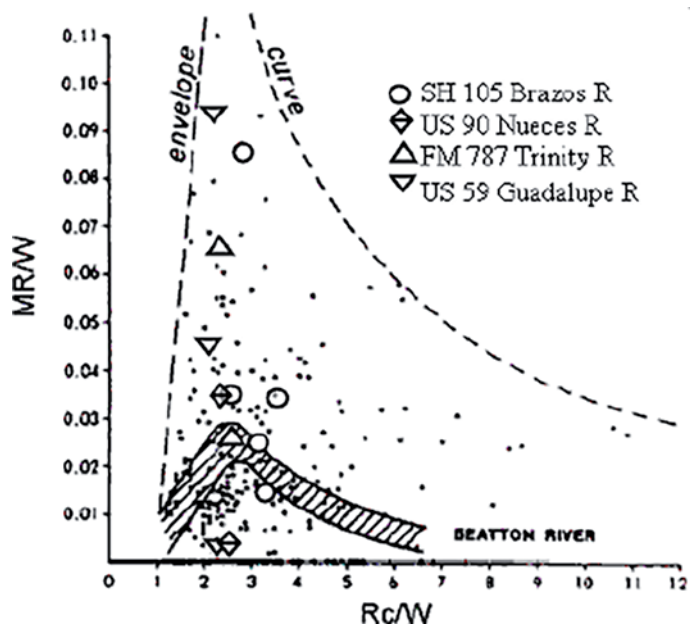


Figure 3.
 Relationship between migration rate and geometry [3, 4].

Part of the Meander Rivers that were channelized in the past, causing environmental problems, altered the ecology of the river and require heavy maintenance. The river channel has become much wider and deeper as the channel has been eroded, and many tributaries upstream have fed the river. Consequently, despite the gentler gradient, the velocity of flow may be as fast as in the uplands. One of the most distinctive features of the river in the lower reach is its increased sinuosity or channel migration. Unlike the relatively straight channel of the upper reach, in the middle and lower reaches, there are many meanders bends in the river (**Figure 3**).

Previously, river adjustments within the meander area were continually being made. The primary considerations are slope steepness and slope length. Therefore, eventually, the gradient of a stream is altered to accommodate the volume of water and the velocity necessary to transport the sediment load. However, this infrastructure to control the flow direction, such as the embankment, retaining wall, concrete sheet pile, cribs, and groyne, needs heavy maintenance and subsequently cannot avoid environmental problems due to an imbalance within the ecosystem.

For example, the Bengawan Solo River located on the Java Island has been developed, and part of the development along 24.2 km from Tawang Sari to Karanganyar was normalized in the year 1994. As a result, channel geometry was changed and the longitudinal slope became higher; consequently, the sedimentation at the downstream growth rapidly causes serious environmental damage such as flood disasters, habitat loss, structural damage, and pollution.

At the end of the year 2007 up to early year 2008, Bojonegoro, which is located at the downstream of the Bengawan Solo River, flooded, and 80 villages in 14 districts were submerged. This situation is probably the impact of the Tawang Sari – Karanganyar normalization, which results in an imbalance of the whole river, thus increasing the burden of flooding in the downstream zone.

According to land utilization in urban areas, it is subject to potentially serious impact caused by meander river transformation due to erosion and sedimentation, and floodplains will undergo modification with time.

2. Meander river in urban area

Urban areas are usually located in the downstream zone, which has a meander pattern. Since the meander belt has a curvilinear shape, erosion of the river cliff or bank erosion is one of the serious problems in the urban area. Another problem is there are also landslides that sometimes occur as a response to the natural or man-made disturbances of the fluvial system. Meander movements in urban areas are often triggered by the activities of human life that change the river corridor system by utilizing riverbanks for the purposes of human life. According to land utilization in urban areas, it is subject to potentially serious impact caused by meander river transformation due to erosion and sedimentation, and floodplains will undergo modification with time. To prevent these impacts, solving the meander problem needs to be approached in ways that are more environmentally sound, such as floodplain management or developing barrier plants to reduce flow energy that occurs especially at high discharge times, rather than channel protection. The floodplain is the area next to a riverbed that is more or less frequently covered with water in times of high-water discharges from adjacent rivers (**Figure 4**). By retaining water, floodplains can buffer the effects of heavy rainfall and, in this way, protect economic activities and communities further downstream from flood damage.



Figure 4.
Meander bend at Kalibata, South Jakarta (Ciliwung River, Downstream Zone).

2.1 Characteristics of meandering river

Generally, instability of channel pattern occurs as a response to natural or man-made disturbances in the fluvial system. In most cases, it causes the occurrence of imbalanced river morphology; therefore, it is important to understand the relative stability of a channel, which is revealed by its patterns. Meander migration is a process in which the water flow erodes the soil on one bank and deposits it on the opposite bank. Consequently, a gradual shift of the bank line occurs over time. For instance, its related processes of meander migration cause problems such as landslides or slope failures, floods, scour of infrastructure foundations, and ecological problems. In accordance with the process of river morphology, the channel movements are the cumulative result of a combination of climatic, geological, topographic, hydrologic, and human disturbance factors, as stated in **Figure 5**.

The conditions of the flow and the properties of the soil are the major factors affecting meander migration; thus, soil properties, meander geometry, channel relocation, and human activities on the floodplain of the river are the most important factors affecting meander. From several previous studies, a relationship has been obtained between the meander and properties of the river such as free surface slope of the river, catchment area, channel width, and channel geometry.

Keady and Priest [5] consider the prediction of meander migration to be a function of the free surface slope of the river, the meander amplitude, and the specific weight of water. They express the relation with the graph presented in **Figure 6** is based on data from the Red River in Arkansas and Louisiana, the Red Deer River in Alberta, Canada, and other rivers, as shown in **Table 1**. The points

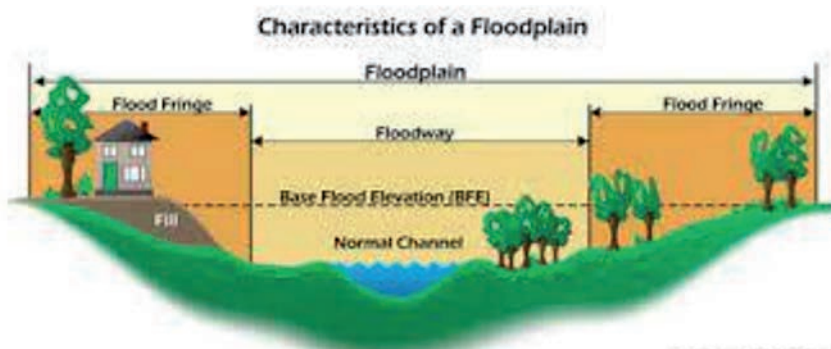


Figure 5.
Characteristics of a floodplain (Source: Scottish Floodplain Management).

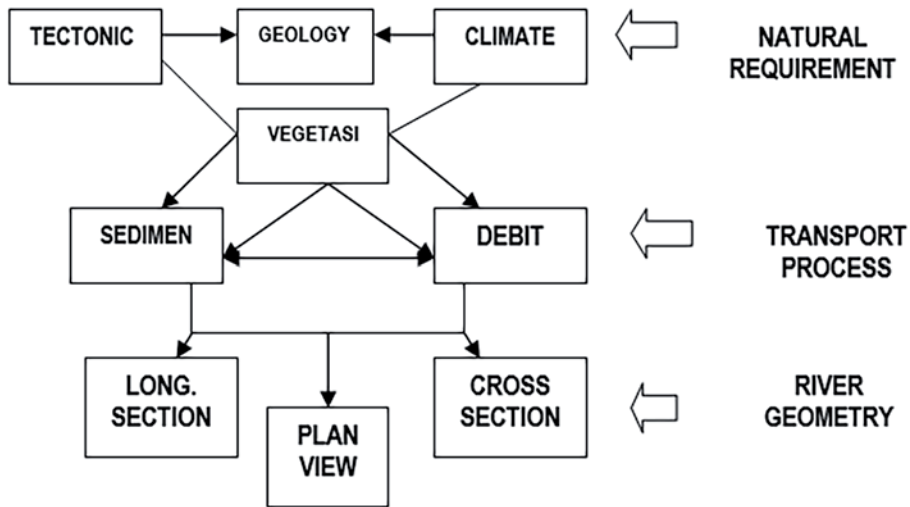


Figure 6.
River morphology process [6].

Identification	Velocity of migration (ft/year)	Meander amplitude (ft)	Slope
Mississippi R (LA)	60	13,000	0.0000436
Mississippi R (MS)	111	11,000	0.0000588
Mississippi R (TN)	225	13,200	0.0000777
Red R (ARK)	350	2900	0.000132
Pearl R (LA)	20	1050	0.000200
Red Deer R (Canada)	20	1200	0.000275
Tombigdee R (MS)	13	800	0.000421
Buffalo R (MS)	17	1560	0.000689

Table 1.
Data used by Keady and Priest [5].

corresponding to the case histories in a previous study [3] are also plotted on the graph. Hooke [7] proposed that the erosion rate is most closely related to the catchment area. He determined rates of bank erosion from field measurements and historical maps for 11 streams in Devon, England then compared the rates of bank erosion with worldwide published rates in 43 streams. **Figure 5** shows the data and regression for Hooke's equation. The data points from Briaud et al. [3] are added to this figure.

Brice [8] proposed that the rate of bank migration increases with increasing channel width. Brice's data consisted of 43 data points from four different stream types (equiwidth, wide bend, braided point bar, braided) as shown in **Figure 6**. The data points from Briaud et al. [3] were added to **Figures 7 and 8**.

Nanson and Hickin [4] showed that the ratio of radius of curvature of a bend (R_c) to the channel width (W) influences the lateral migration rate of a meandering river. The relationship between the channel migration rate (MR) and the ratio of radius of curvature to channel width for the Beaton River, Canada, and other rivers is shown in **Figure 9**. Data points from a previous study [3] were added to figure. This

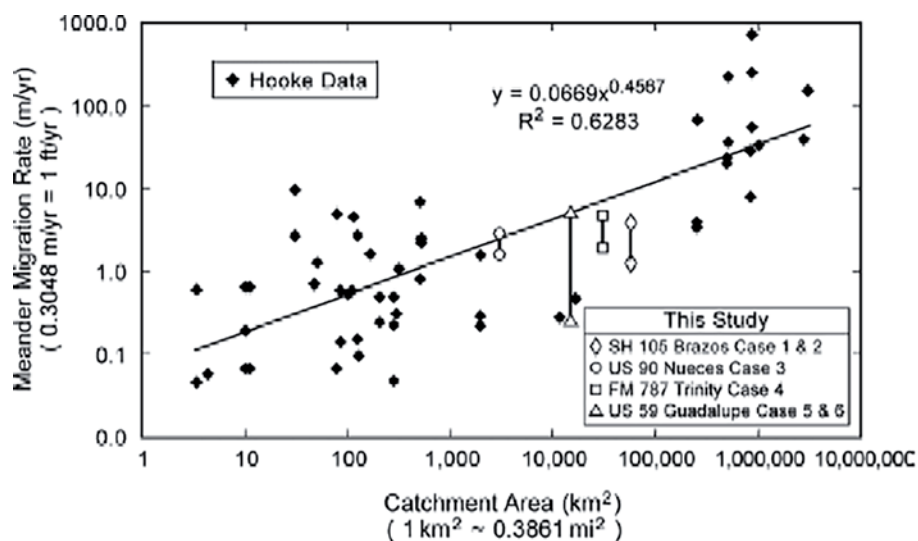


Figure 7.
Relationship between migration rate and catchment area [3, 7].

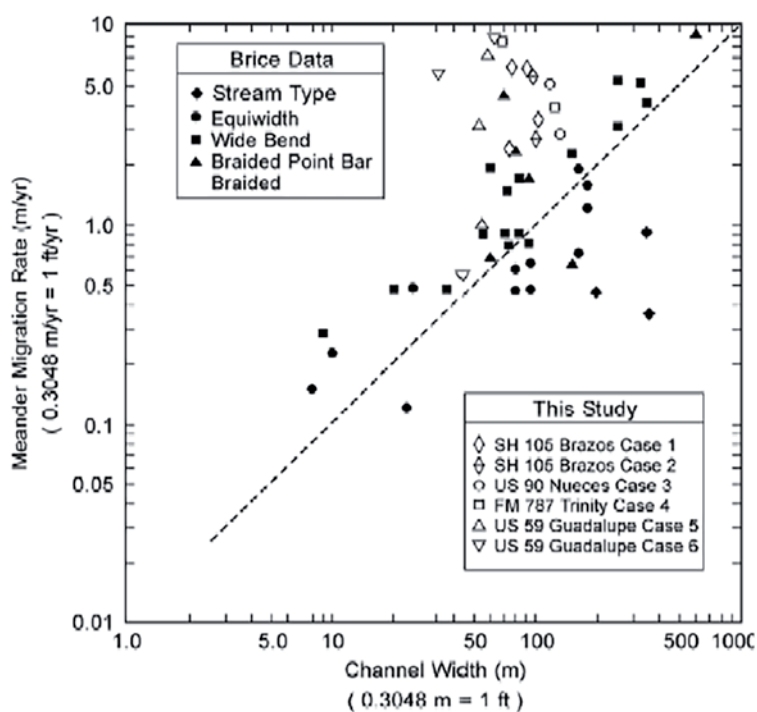


Figure 8.
Relationship between migration rate and channel width [3, 8].

relationship between migration rate and geometry is widely cited, but the data points are widely scattered, and the best-fit line is not obvious. Geometry is only one factor affecting meander transformation.

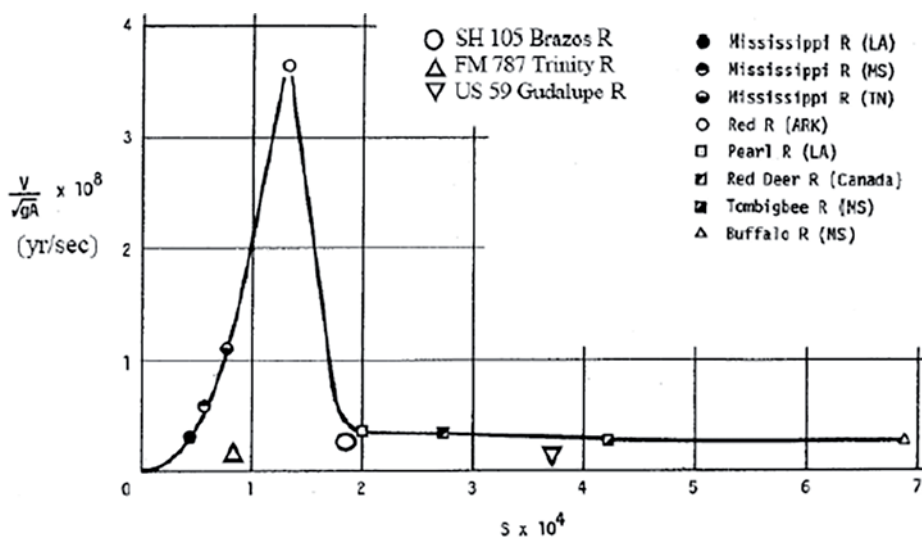


Figure 9.
Graph for determining rate of meander migration [3, 5].

2.2 Physical processes of erosion and sedimentation in a curved channel

Generally, riverbank erosion consists of two interactive physical processes: basal erosion and bank failure. Basal erosion refers to the fluvial entrainment of bank material by flow-induced forces that act on the bank surface, for instance, drag force, resistance force, and lift force; however, river cliff or bank failure occurs due to alluvial processes or geotechnical instability, such as planar failure, rotational failure, sapping, or piping. This process does not guarantee the retreat of the bank line because the eroded bank material may be deposited close to the banks. **Figures 3 and 10** shows cross profile along the curve channel in the various positions and orientations, in the large-scale strata geometries of channel belts [9].

The fundamental elements of meandering are the curvature of the channel axis; therefore, the parameter defining meander geometry is often used in the study as shown in **Figure 11**. Whereas: A is meander amplitude, W is channel width, M is channel migration distribution, R is radius of curvature, Φ is bend angle, Θ is relative angle within each bend, and t is time.

The basic elements of meandering are the curvature of the channel axis and the erosivity of the bed and banks. These two major processes, erosion on the outside of the meander and deposition on the inside, cause meandering loops to migrate laterally (**Figure 12**), and the velocity distribution at the meander bend is shown in **Figure 13a and b**.

Meandering rivers are characterized by bank materials that are mainly composed of fine-grained cohesive sediments, the mechanisms responsible for bank erosion are the direct removal of bank material due to fluvial entrainment and bank failure due to geomechanically instability. The distinction between cohesive and non-cohesive banks is shown in **Table 2** as follows:

Based on the characteristics of this type of riverbank, surface erosion and landslide will occur due to fluvial entrainment and bank failure, with temporary storage of the eroded material at the toe of the riverbank. It can be assumed that erosion of cohesive sediment particles will occur if the flow resistance, τ_w , is greater than the

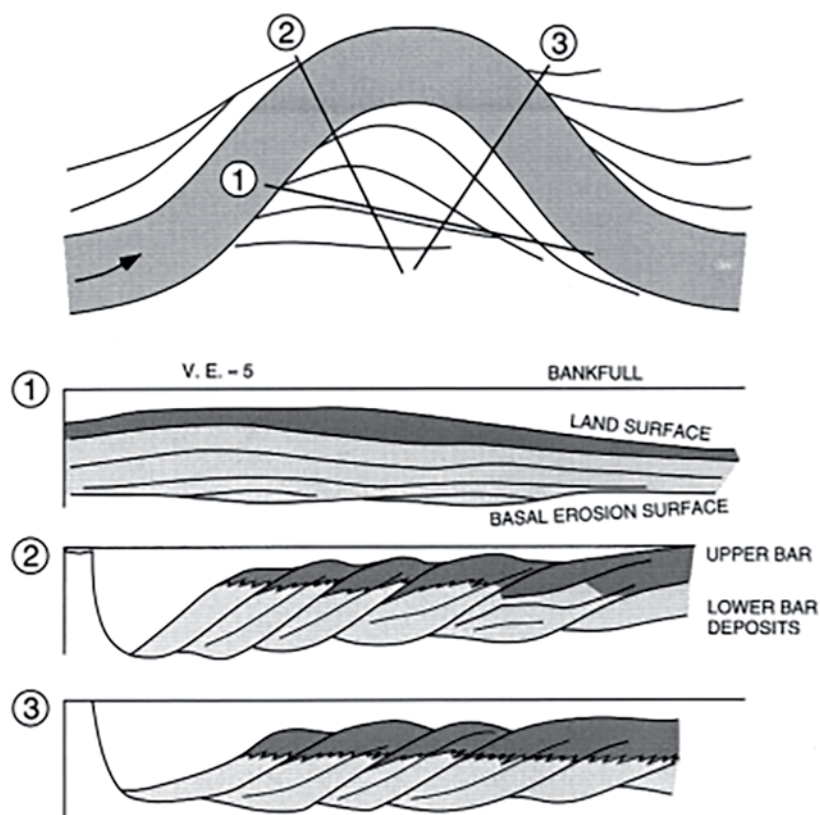


Figure 10.
 Simplified plan forms, cross profiles in various positions and orientations, and large-scale stratal geometries of channel belts.

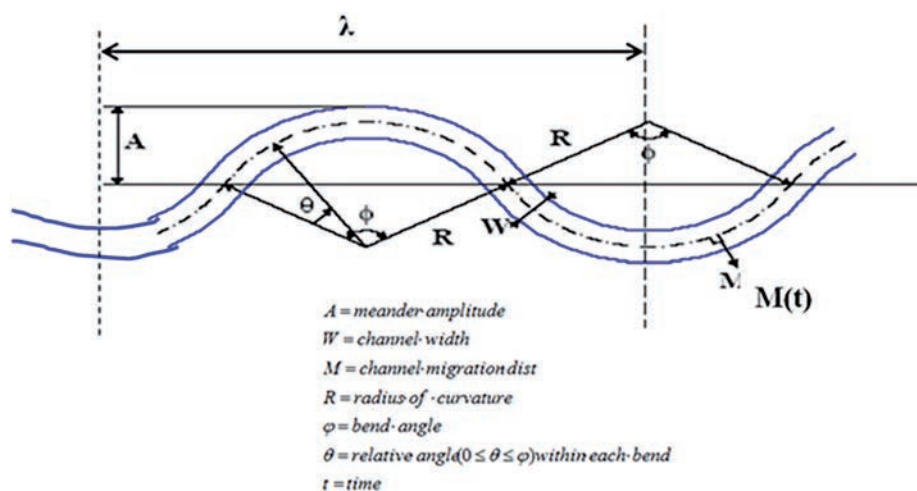


Figure 11.
 Parameters defining meander geometry.

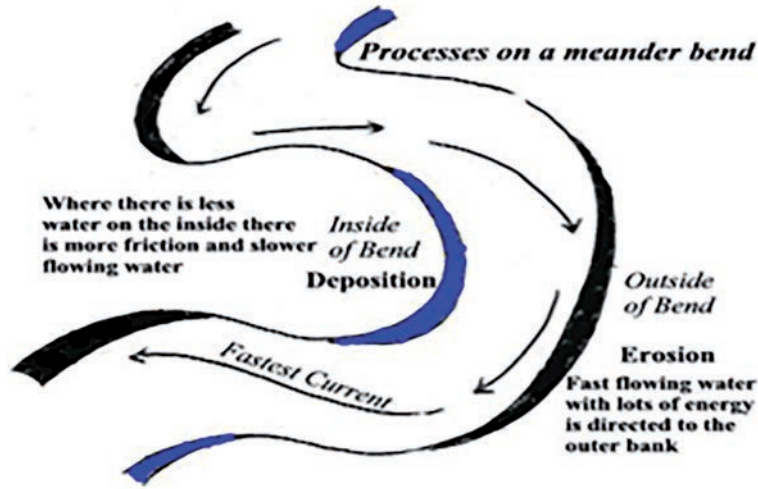


Figure 12.
Flow path at the meander bend.

soil resistance, τ_{cr} . Thus, the resulting erosion rate is proportional to $\tau_w - \tau_{cr}$, and the results of the propagation of flow resistance (τ_w) reflect the possibility of channel migration. The relation between grain size (D) versus critical shear stress (τ_{cr}) and critical velocity (u_{cr}^*) is shown in Shields graphic, as follows (Figure 14).

According to the flow direction, the flow resistance or friction shear stress in the x and y directions is stated below, in which $\bar{u}$ is velocity in x direction and $\bar{v}$ velocity in the y direction, and U is the depth-averaged total velocity, and n is Manning's roughness coefficient [12] :

$$\tau_{bx} = \frac{n^2 g}{h^{1/3}} \bar{u} U \quad (1)$$

$$\tau_{by} = \frac{n^2 g}{h^{1/3}} \bar{v} U \quad (2)$$

$$sf = \frac{n^2 U^2}{R^{4/3}} \quad (3)$$

For the one-dimensional computation, the velocity in the y direction is neglected and the computation is only done in the x direction; thus, the flow resistance τ_w is:

$$\tau_w = \frac{n^2 g}{h^{1/3}} U^2 \quad (4)$$

where τ_w is flow resistance (N/m^2), n is Manning roughness coefficient, h is averaged depth (m), g is gravity (m/det^2), and U is the depth-averaged total velocity (m/det).

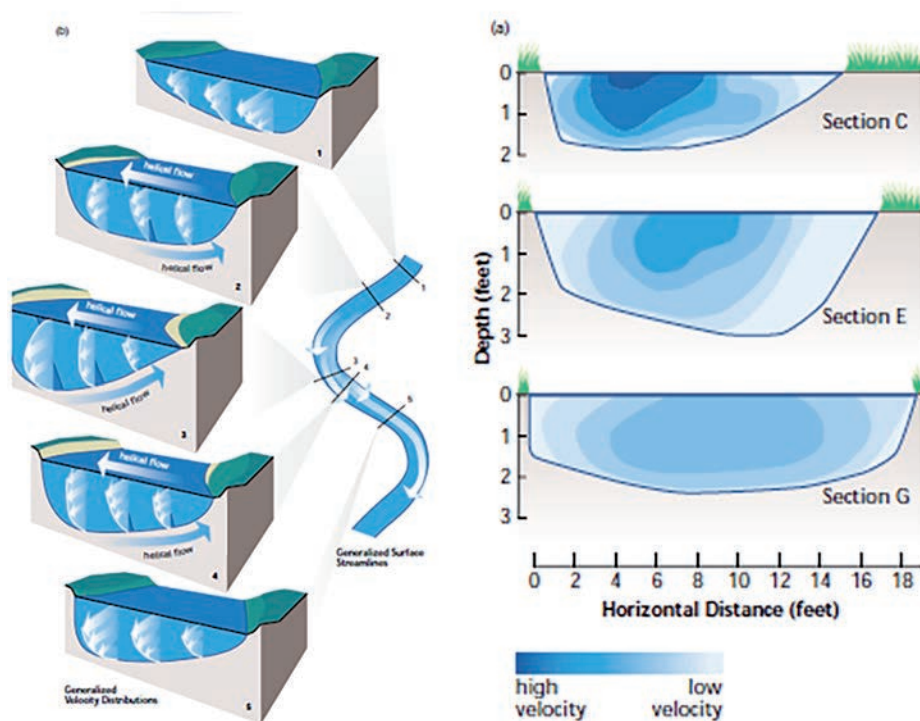


Figure 13.
Velocity distribution at the meander bend (Source: [1]).

Bank material	Type of bank erosion	
	Fluvial entrainment	Bank failure
Non-cohesive	Entrainment of an individual particle	Avalanching
Cohesive	Entrainment of individual particle: surface erosion	Sliding, slumping
	Entrainment of large aggregates of silt or clay particles: bulk or mass erosion	Temporary storage of erosion products at the bank to be followed by basal clean-out

Table 2.
Mechanism of bank erosion (Source: [10]).

2.3 The relation of soil classification and meander transformation

According to land utilization in urban areas, it is subject to potentially serious impact caused by meander river transformation due to erosion and sedimentation, and floodplains will undergo modification with time. The meander river was channelized in the past, causing environmental problems, changing the ecology of the river, and requiring heavy maintenance. Based on the longitudinal profile of the river (**Figure 1**), the urban area is located at the transfer zone and depositional zone. Thus, the soil classification is usually clayey silt and sandy silt, with material compositions are clay, silt, and sand. Hence, the simulation of the relation between flow and

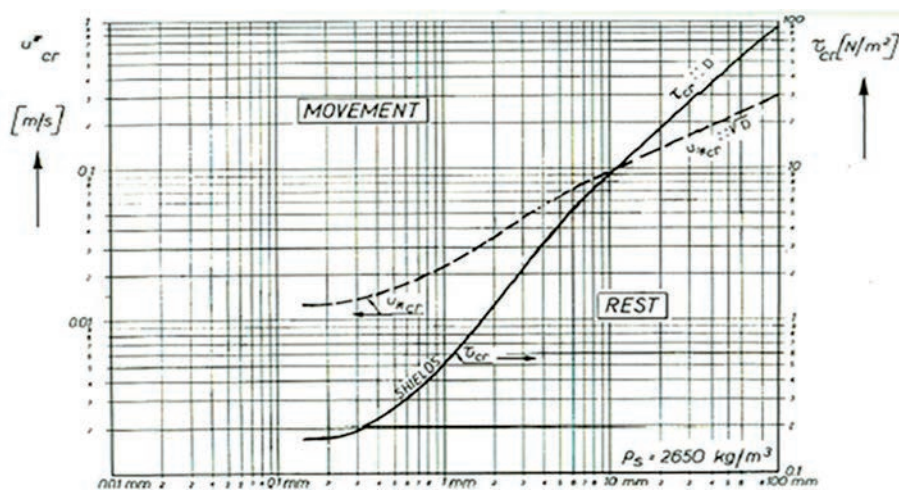


Figure 14.
Shields graph [11].

channel migration as part of the meander can be approached by building a physical model of a curved channel in a hydraulics indoor laboratory.

2.3.1 Physical modeling of single curve channel

A simulation of river cliff erosion on a single-curve channel was constructed on a mobile bed table apparatus, whereas the table was covered by clayey silt material and sandy silt material with an 80 mm thickness. The experiments were conducted in the laboratory by using a mobile bed and a visualization table, which is 200 cm long, 60 cm wide, and 12 cm deep (**Figure 15**). Channel beds had a non-erodible rigid acrylic material, while the banks consisted of non-cohesive material, as shown in the grain size distribution for each material classification and composition (**Figure 16**). Flow discharge is specified as constant at the inlet; however, the water surface elevation decreases gradually along the channel.

In the first experiment, a curved channel with a bend angle (φ) of 60° molded from relatively uniform sand with a mean size diameter of 0.425 mm. The cross section was rectangular, with a channel width of 50 mm, a channel depth of 80 mm, and the elevation of the surface water level was 50 mm above the channel bed. A constant discharge of 0.34 L/s was introduced at the inlet, and the initial velocity was 10 cm/s. There are five control points in this model, and observations were made every 30 minutes. After 3 minutes, channel cliff erosion began at the curvilinear area. Widening channel occurred after 13 minutes, meander formation after 24 minutes, and straight channel changes to meander after 2 hours and 4 minutes (**Figures 16 and 17**)

The process of the meander groove is affected by the degree of erosion in the outer bend and sedimentation in the inner bend. It can be observed that the process of forming meanders begins when the curve begins to be eroded and the straight channel at the downstream of the curve begins to change to the meander form, and it is triggered by a curvilinear shape at the beginning of the groove.

The second experiment, a curve channel with bend angle (φ) of 90° (**Figure 18**) with clayey silt material and material composition as sand 2%, silt 67%, and clay 31%. The experiment was stopped when equilibrium conditions were obtained, which

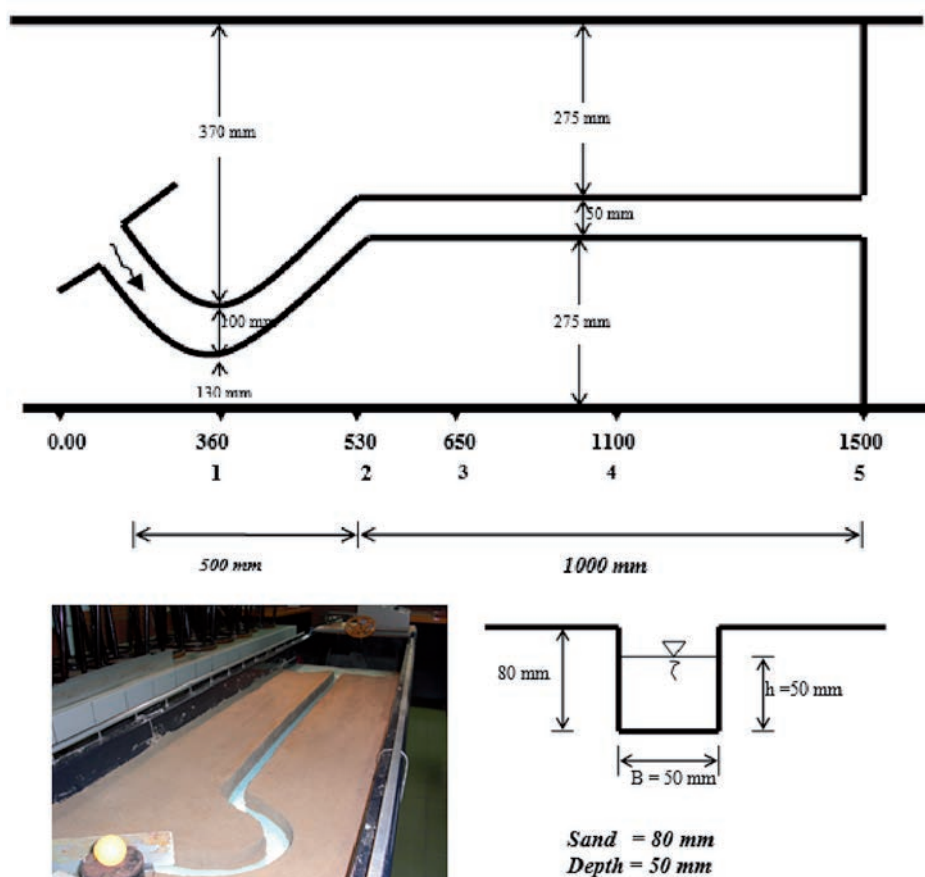


Figure 15.
 Plan form of physical model (first experiment).

reflected no material migration along the channel. The duration of the experiment is 210 minutes.

Experiment with clayey silt material and a material composition of sand 2%; silt 67%; and clay 31% shows that around 30 minutes after starting the laboratory testing, the initial channel cliff erosion began at the curvilinear area, as shown in **Figure 19**.

The laboratory testing findings concluded that soil composition with a high percentage of silt would change rapidly compared to soil composition with a low percentage of silt. The result of the experiment is its qualitative approach without quantifying sedimentation in the inner bend and erodible sand in the outer bank.

2.4 Case study Pesanggrahan River

Jakarta is the capital of Indonesia, with a high population density of around 10 million people and an area of around 661.5 km². Most of the north city of Jakarta is located below sea level and is crossed by 13 rivers, including the Pesanggrahan River, which is in the western part of the Jakarta City area, with a length of 66.7 km. The upstream of the Pesanggrahan River is in the Bogor area south of Jakarta, and ends at

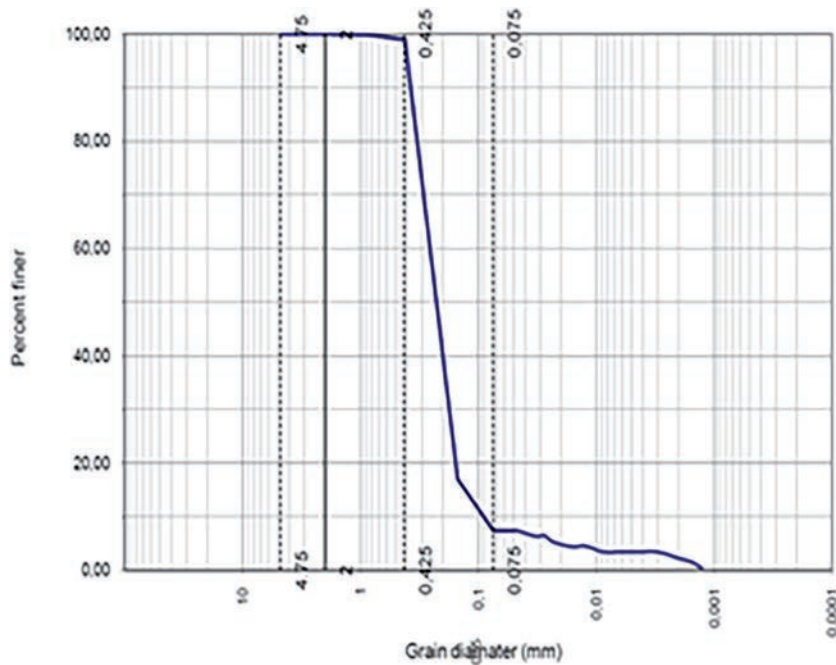


Figure 16.
Grain size distribution uniform material ($D_m = 0.425 \text{ mm}$).

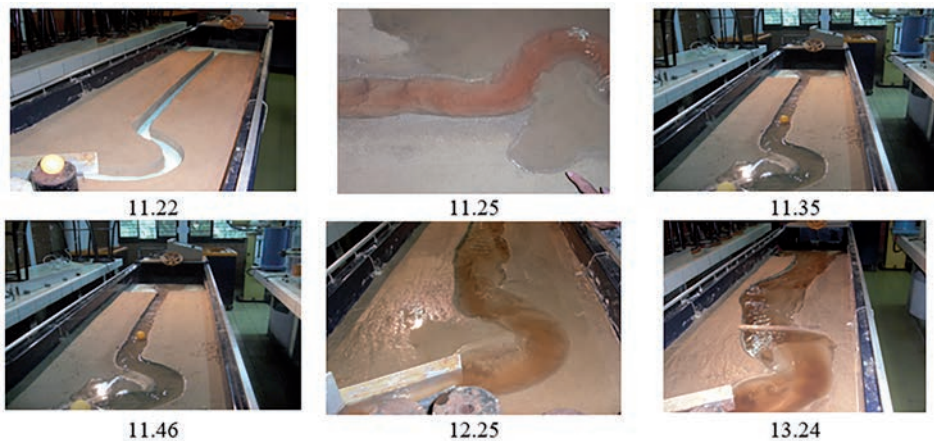


Figure 17.
Laboratory experiment (uniform material; $D_m = 0.425 \text{ mm}$).

Cengkareng Drain and then flows into the Java Sea. Regarding the longitudinal profile of the river (**Figure 1**), Jakarta City is located in the transfer area and depositional zone. Thus, based on Rosgen's [2] proposal, the type of Pesanggrahan River passes in Jakarta City is braided for the channel slope 2–4%, a meander for the channel slope less than 4% and a flat river channel if the longitudinal channel slope is less than 0.5% (see **Figure 2**).

The Pesanggrahan watershed, over the last 30 years, has experienced very significant land use changes that have resulted in a continuous flow stabilization

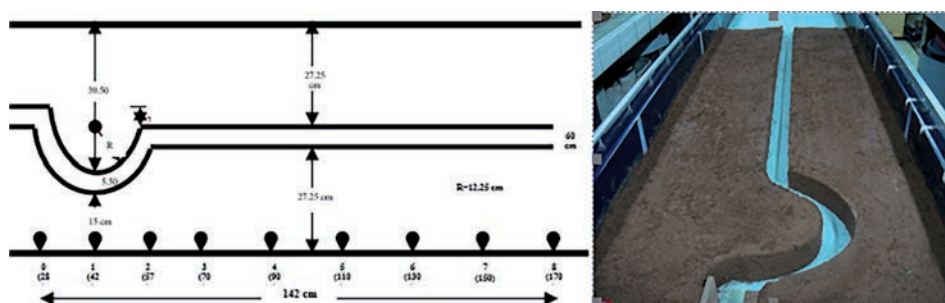


Figure 18.
Plan form of physical model (second experiment).

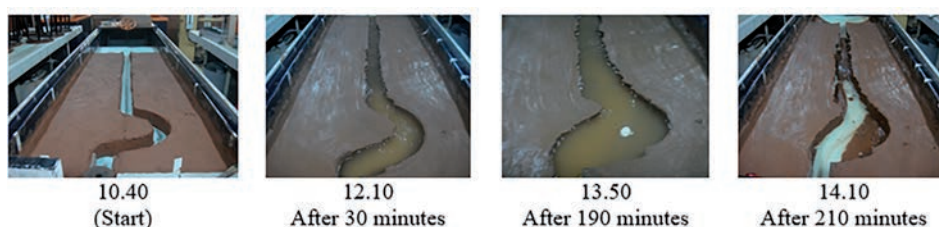


Figure 19.
Laboratory experiment; material composition sand 2%, silt 67%, and clay 31% (clayey silt).

process, which has changed the shape of the transverse and longitudinal channel. Due to the energy flow that will break down the riverbed grains from upstream to downstream, from large rocks into gravel and eventually become sand and mud, the geometrical shape of the elongated channel is related to the composition of the soil. The Pesanggrahan River in the middle and downstream pass-through areas have been built so that the change in flow geometry will cause inundation or flooding when the river discharge exceeds the normal discharge (**Figure 20**).

The location of this research is in a depositional zone, with a meandering river channel pattern in the upstream and toward into a widening and shallow channel in the middle and downstream area. To obtain a relationship between meander geometry and soil classification, riverbed material samples are taken from the upstream, middle, and downstream sections (**Figure 21**). Data from the results of grading of riverbed material from the three locations will be used to determine the soil classification and material composition, which will be used to make a physical model test with a single curve.

Based on geometry data obtained from the Central Office of River Region Ciliwung-Cisadane, there are differences between the rivers before and after normalization. The differences can be seen from the elongated profile and cross section of the river section studied. Normalization causes changes in the river length, where the length of the river before normalization was 10,127 m, and after normalization became 9029 m. It happened because there was a straightening and a cut-off of work on several river sections. **Figure 22** shows the differences between the longitudinal channel river before and after normalization.

From **Figure 22**, it can be seen that there are some sections of the river which had been cut-off. The slope of the river after normalization increases along with the shortening of the river. Furthermore, to change the river in an elongated direction,



Figure 20.
Pesanggrahan River middle area.

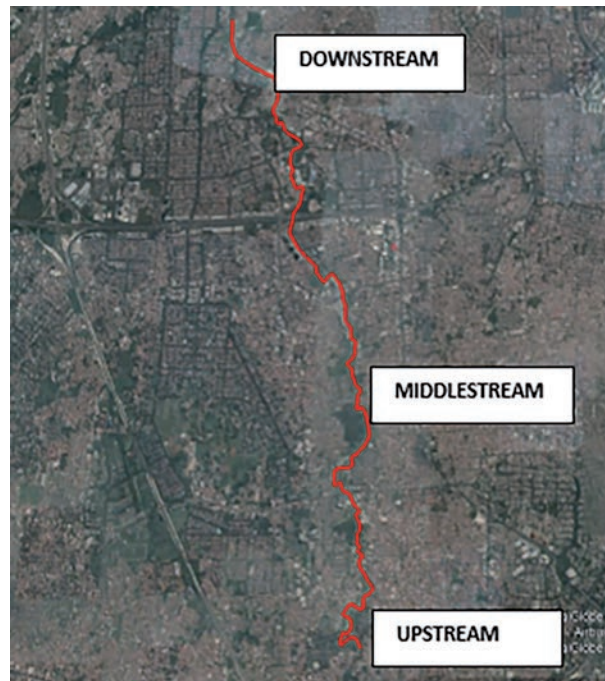
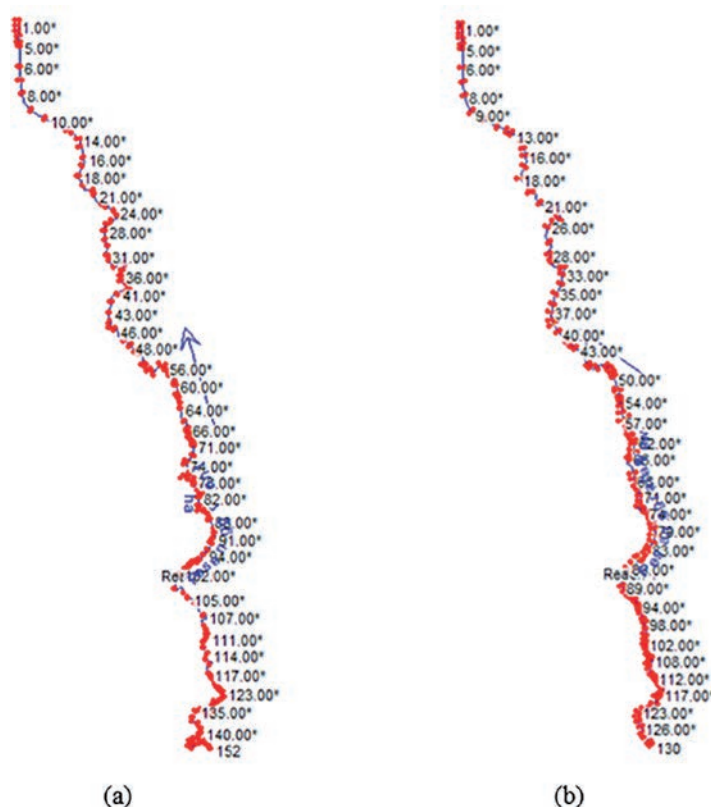


Figure 21.
Location of material sampling.

normalization also changes the shape of the cross section, such as widening, deepening, and bank protection.

In the upstream area of sharp-arched meander geometry with a bend angle (φ) smaller than 90° (ninety degrees), and the results of the gradation test of material sampling at upstream, soil classification is sandy silt, with a sand composition of 65%; silt 27%; and clay 8%. Google Maps shows from the year 2002 to the year 2012, the meander conditions in the upstream area Pesanggrahan River were relatively stable (**Figure 23**). Thus, it can be concluded that the area with sandy silt soil classification and the curvature meander radius with bend angle (φ) smaller than 90° (ninety degrees) is also relatively stable; hence, the meander does not undergo either transversal or longitudinal transformation. This condition is in accordance with the results of research on the relationship between soil classification and meander transformation [13].

**Figure 22.**

The differences in the longitudinal channel river (a) before normalization (b) after normalization.

Then, in the middle stream, soil classification is silty clay with 37% sand composition, silt 49%; and clay 14% has a meander arch with bend angle greater than 90° , while at the downstream, soil classification is clayey silt, with a sand composition of 2%; silt 67%; and clay 31%. The shape of the channel tends to approach a straight channel because the river cross-sectional conditions, with soil classification silty clay and clayey silt, are easily eroded; hence, the widening of the cross section occurs, the radius of curvature is getting larger, resulting in meander transformation in the longitudinal direction, and the channel path becomes straight. In addition to changes in the cross section and the slope of the longitudinal cross section due to normalization, sediment transport at the downstream of the normalized channel will increase due to changes in velocity at the upstream, resulting in changes in flow shear stress (τ_w) that will be greater than the critical shear stress (τ_{cr}) of the grains.

The empirical formula used in calculating sediment transport was developed by Ackers-White [14], where the sediment transport equation was developed from research data for fine-grained sediments ranging from 0.02 to 4.94 mm [15].

$$Q_s = Q \cdot X \quad (5)$$

$$X = \frac{S \cdot D}{H} \left(\frac{V}{U_*} \right)^n G_{gr} \quad (6)$$



Figure 23.
Meander area at the upstream Pesangarahan River since year 2002 to 2012.

$$G_{gr} = C \left(\frac{F_{gr}}{A} - 1 \right)^m \quad (7)$$

$$D_{gr} = D \left[\frac{g(s-1)}{v^2} \right]^{\frac{1}{3}} \quad (8)$$

$$F_{gr} = \left[\frac{v_0}{\sqrt{g \cdot D \cdot (s-1)}} \cdot \sqrt{32 \cdot \log \frac{\alpha H}{D}} \right] \left[\frac{U^*}{V} \sqrt{32 \log \frac{\alpha H}{D}} \right]^n \quad (9)$$

The relation of constant values is as follows:

$$n = \begin{cases} 1.0 & \text{for } D_{gr} \leq 1 \\ 1 - 0.56 \log(D_{gr}) & \text{for } 1 < D_{gr} \leq 60 \\ 0 & \text{for } D_{gr} > 60 \end{cases} \quad (10)$$

$$m = \begin{cases} \frac{9.66}{D_{gr}} + 1.34 & \text{for } D_{gr} \leq 60 \\ 0.17 & \text{for } D_{gr} > 60 \end{cases} \quad (11)$$

$$A = \begin{cases} \frac{0.23}{\sqrt{D_{gr}}} + 0.14 & \text{for } D_{gr} \leq 60 \\ 1.5 & \text{for } D_{gr} > 60 \end{cases} \quad (12)$$

Normalization		H (m)	A (m ²)	P (m)	R (m)	U ⁺ (m/s)	Q (m ³ /s)	V (m/s)	F _{gr}	G _{gr}	X (kg/m ²)	q _s (kg/s)	Q _s (ton/month)
Upstream	Before	3.53	30.6	24.98	1.12	0.09	81.1	2.42	2.79	17.00	2.05E-05	1.8E-03	56.76
	After	1.85	37.0	57.49	0.64	0.075	92.77	2.62	3.12	21.89	7.64E-05	6.0E-03	214.402
Middle	Before	3.18	35.76	32.22	1.11	0.09	88.09	2.48	2.03	2.52	4.43-06	3.90E-04	12.18
	After	2.07	27.41	51.57	0.52	0.07	92.77	3.82	3.19	7.79	3.74E-05	3.28E-03	101.83
Downstream	Before	4.38	65.98	49.55	1.33	0.10	88.09	1.33	0.73	0.21	2.69E-07	2.35E-05	0.739
	After	3.87	101.2	85.98	1.18	0.10	92.77	0.94	0.52	0.10	1.69E-07	1.48E-05	0.464

Table 3.
 Calculation of sediment transport before and after normalization.

$$\log C = \begin{cases} 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53 & \text{for } D_{gr} \leq 60 \\ 0.25 & \text{for } D_{gr} > 60 \end{cases} \quad (13)$$

where D is the sediment diameter (mm); ν is viscosity; D_{gr} is dimensionless grain diameter; H is water depth (m); S is sediment grain density to water density ratio; G_{gr} is mobility function; V is mean water velocity (m/s); α is constant value; U is shear velocity; and A , C , n , m are constant value depending on D_{gr} .

Sediment transport simulation is carried out using HEC-RAS [16] to obtain results in the form of water level, and then the calculation of sediment transport is carried out using the Ackers-White equation to calculate sediment transport that occurs in the upstream, middle, and downstream areas.

It can be seen from **Table 3** that the amount of sediment transport tends to decrease as it approaches closer to the downstream. This happens because the flow velocity of the river tends to decrease due to the widening of the cross-section, both before and after normalization. Consequently, the amount of sediment transport after normalization tends to be greater than before normalization.

Against the conditions at the upstream and middle, at the downstream, the amount of sediment transport tends to be smaller after normalization. This is due to the cross section of the river widening downstream, so that it reduces flow velocity and affects the amount of sediment transport calculated using the Ackers-White equation.

3. Conclusions

The fundamental elements of the meandering river are the curvature of the channel axis and the erodibility of the bed and riverbanks. Therefore, channel migration is strongly influenced by the geometry of the initial curvature, soil classification, and composition [17]. As a rule, rivers consist of three zones: upper, middle, and downstream, and there is a continuum of river patterns between straight, meandering, and braided, depending on the geomorphological condition and bed roughness. Since the meander river flows through urban areas, and the river plains and delta consist of alluvial soils, the meander river in urban areas usually encourages sediment transport problems.

The Pesanggrahan River, which passes Jakarta City, also has a meander pattern in the upstream zone and a straight pattern in the downstream zone. The soil classification in the upstream zone is sandy silt, with a sand composition of 65%, silt 27%, and clay 8%. The result of the physical model composed of sandy silt and meander geometry with a bend angle (ϕ) smaller than 90° (ninety degrees), it can be concluded that the area is relatively stable; hence, the meander does not undergo both transversal and longitudinal transformation.

Besides that, in the middle zone, soil classification is silty clay, and the bend angle of the meander arch is greater than 90° , while at the downstream, soil classification is clayey silt. The shape of the channel tends to approach the straight channel because the river cross-sectional conditions with soil classification silty clay and clayey silt are easily eroded; hence, the widening of the cross section occurs, the radius of curvature

is getting larger resulting in meander transformation in the longitudinal direction, and the channel path becomes straight. In addition to changes in cross section and slope of the longitudinal cross section due to normalization, sediment transport at the downstream of the normalized channel will increase due to changes in velocity at the upstream, resulting in changes in flow shear stress (τ_w) that will be greater than the critical shear stress (τ_{cr}) of the grains.

4. Recommendation

In accordance with the type of river channel in **Figure 2**, straight river flow (type A) is in the upstream with a slope greater than 4%, a branched channel (type D) is in the middle with a slope of 2–4%, river channel in the form of meander is in the upstream to the middle and middle to downstream (type C, E, and F) regions with slopes of less than 2%.

The shape of the channel in accordance with this classification is close to natural conditions; hence, if there is a change in the channel made outside the shape of the basic channel, it will produce an unstable shape and, within a certain period of time, will return to the original type of channel. For example, in a river channel in the form or pattern of a meander, if there is an alignment or river normalization to accelerate the flow of water toward the estuary, intermittent sedimentation will occur along the straightened river channel; consequently, within a certain period of time, it will form a channel with a meander pattern like the shape of the original channel.

From observations of meander patterns that are located upstream, with a geometry of grooves that have curved angles (φ) smaller than 90° , no river engineering needs to be done, as well as widening the channel by making new cross sections and straightening the meanders, but it is advisable to maintain the profile area of the river corridor as shown in **Figures 20 and 24**.

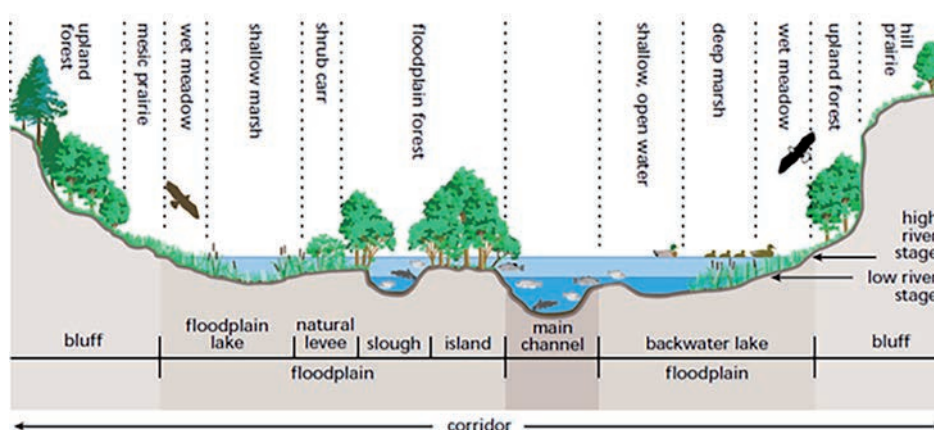


Figure 24.
 River corridor (Source: [18]).

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Simulation of the Phenomenon of Hydrodynamic Erosion in Riverbeds

Mihail Luca and Petru-Daniel Branianu

Abstract

A current field of research in the context of climate change is the morphological modification of the riverbeds where the undercrossing constructions of large-diameter pipelines are located. An excessive phenomenon of hydrodynamic erosion was studied for 18 years in a river bed with two arms, where the undercrossing of three pipes with diameters of 800–1000 mm is located. A hydraulic-mathematical model was created to simulate the phenomenon, especially the erosion depths on the watered perimeter. The research was carried out on a river section with a length of 420 m, width of 270 m, slope of 0.0876% slope, and water depth according to flow of 3.00–4.50 m. The model calculates parameters of the erosion phenomenon at the characteristic points on the watered perimeter of the river (tangential stress on the wetted perimeter, velocity at the wall, erosion depth, maximum diameter of the displaced particle, and others).

Keywords: non-cohesive rock, river, erosion depth, tangential stress, wall speed

1. Introduction

The climate changes of the last period of time produced in the European geographical space and implicitly in Romania have modified the annual distribution of precipitation, determining their seasonal concentration and the appearance of torrential rains of maximum intensity. Torrential rains have generated catastrophic floods in some watersheds. If 60–70 years ago, on the territory of Romania, natural factors of hydroclimatic risk (torrential precipitation, floods with high flows) dominated those of anthropogenic risk, at the current stage, the situation has reversed [1].

The anthropogenic risk factors have begun to manifest themselves significantly in the watersheds in Romania in the last 30 years. Among the main anthropogenic risk factors can be listed the intense deforestation of the forest fund, the irrational extraction of ballast from the river bed, the absence of maintenance works for the regularization of rivers, and the non-execution of rehabilitation operations of old works [1–3].

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extraction of ballast from the river bed, the absence of maintenance works for the regularization of rivers, and the non-execution of rehabilitation operations of old works [1–3]. In certain situations, there is a correlation between climatic risk factors and anthropogenic risk factors (e.g., a torrential rain on a deforested slope and a flood with a very high flow in a riverbed with degraded regularization works), a situation in which there is an amplification of the destructive effects on the natural and human environment [1, 4].

The research on the phenomenon of erosion in the river bed is differentiated according to the geometric characteristics of the constructions located in the flow section. The size of the constructions can be reduced and with a local location in the bed (e.g., piles and bridge abutments, isolated foundations), or large and with spatial location (e.g. spillways, breakwater, and bottom threshold). Each constructive type located in the riverbed requires a certain type of research on the parameters of the erosion phenomenon.

Transiting flash floods and particularly high flows produced important morphological changes in the cross-section and longitudinal profile of the watercourses. These changes affected the operational safety of constructions and installations located in the river bed and in the riparian area. Research in this field is carried out for various existing situations in natural [1, 5–9] or engineered [1, 3, 10] riverbeds.

The morphological transformations are much more obvious in the beds formed by weakly cohesive rocks of the type of alternating layers of gravel-sand-clayey sands, ballast, gravel, and others. The research carried out in such beds revealed intense phenomena of hydrodynamic erosion on the depth and width of the flow section (at the beginning of the flood) followed by deposition (in the final phase of the flood), situations that substantially transformed the geometry of the bed [3, 5, 8, 9, 11]. Also, in such riverbeds, there is a more intense degradation of regularization works and especially of bank defense [1, 3, 10, 12].

The design of constructions in riverbeds also requires the calculation of the erosion depth, in order to estimate the operational safety of the achieved objective. Empirical formulas are used for estimated values considering the large number of parameters that characterize the cooperation between the hydraulic phenomenon and the construction located in the river bed. Empirical calculation relationships are presented in the specialized technical literature, and each country has design norms for the erosion phenomenon of the river bed. Erosion depth calculation relationships are customized for special design situations existing in the river bed: bridges, bottom sills, spillways, weirs, etc. Empirical relationships determine the depth in a single section and for a single depth of water, which is a drawback in the design process [1, 3, 5].

The research on the morphological modification process of the beds under the action of the hydrodynamic erosion force is carried out in nature and on physical and numerical models [1, 13–15]. The forecast of the hydrodynamic erosion phenomena of the beds is elaborated with the data obtained by hydraulic modeling and numerically solved hydraulic-mathematical models [1, 14–16].

A current field of research in the context of climate change is the morphological modification of the riverbeds in which the undercrossing constructions of large-diameter pipelines are located [3]. Pipelines placed in water can be installed under the bottom of riverbeds [3], and on the bottom of lakes, seas, and oceans [17]. In each case of installation, it is necessary to know the depth of erosion determined by the action of water, as well as the stability of the pipe in the location. The research is complex due to the volume of primary data required (topographic, hydraulic, hydrological, resistance studies, and others) [18, 19].

2. Hydrodynamic erosion of river section with pipeline undercrossing

2.1 Geographical characteristics of the research area

The research was carried out on a section of the Moldova River located in the area of Soci locality in Iasi County, Romania (**Figure 1a**). On the river section considered in the research, the undercrossing construction of three pipes with large diameters ($D = 800\text{--}1000\text{ mm}$) is located [17].

The Moldova River is a right tributary of the Siret River and is located in the eastern part of Romania. The Siret River has the largest watershed in Romania, with an area of $44,835\text{ km}^2$, a length of 647 km (559 km in Romania), and contains 1013 coded watercourses. The Moldova River has a watershed area of 4315 km^2 (12.2% of that of the Siret watershed), length 216 km and average flow $35.5\text{ m}^3/\text{s}$. The watershed of the Moldova River has an elongated shape (**Figure 1b**). Most of the tributaries are on the right side, being fed from the mountain area on the upper course, respectively, from the hill area on the middle and lower course. From the source to the research area, the Moldova River has a length of 160 km , a watershed area of 3567 km^2 , and the average slope on the study sector is 0.130% . The orientation of the research section is NW–SE.

The Moldova River presents in the research area two arms of different length ($380\text{--}400\text{ m}$), of which the left arm is more developed in cross-section and longitudinal profile (**Figures 2 and 3**) [19].

The basement of the research area consists of geological formations originating from the Sarmatian and Quaternary. The surface layer, originating from the Quaternary, is formed by the alluvial deposits of the Moldova River. The alluvial deposits consist of alternating layers of dusty silty sands with intercalations of gravel, followed by layers of gravel and rolled boulders with underlying sand. The thickness of these layers is $7.0\text{--}12.0\text{ m}$ and varies according to the relief. In these filtering layers, the water from the piedmont and hill areas is accumulated, and the major bed and the riparian area have become an underground water reservoir with very good portability. The underground water tank is based on an impermeable layer formed by a marl of Sarmatian origin.

The research area has a temperate continental climate with cold winters, hot summers and frequent winds. Atmospheric precipitation has values of $501\text{--}600\text{ mm/year}$. The highest amounts of precipitation are in summer, between 38% and 46% of the

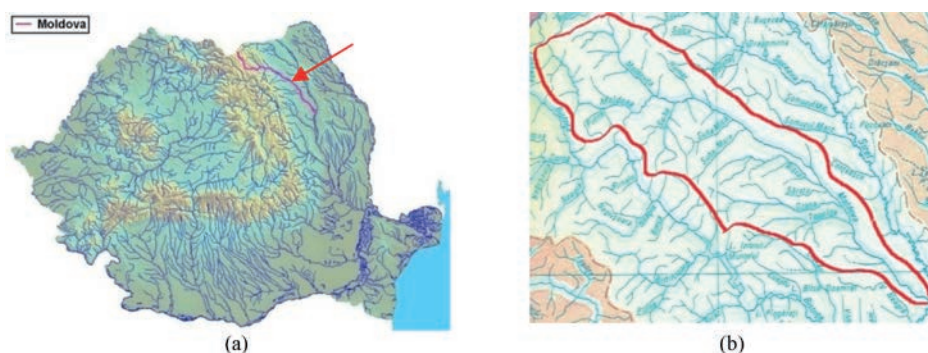


Figure 1.
Location of the research area: a – location of the Moldova River on the map of Romania; b – the watershed of the Moldova River [19].

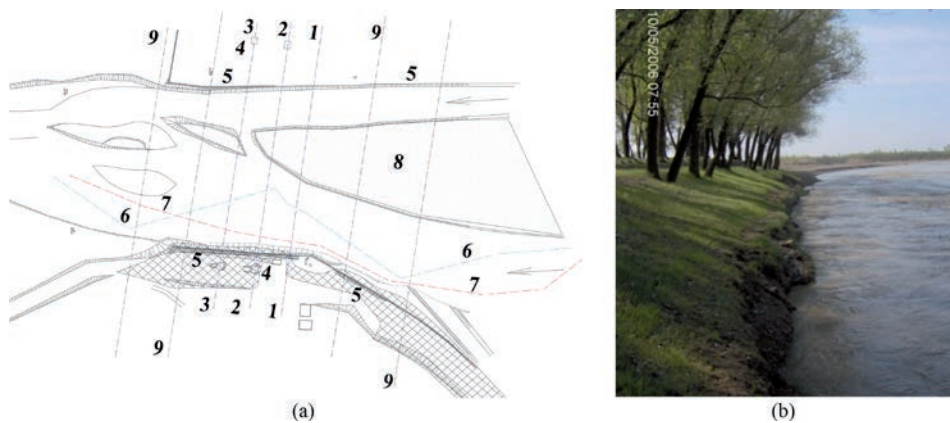


Figure 2.

The research area on the Moldova River: a – topographical plan made in 2006, 1, 2, 3 – adduction pipelines Ad1, Ad2a, and Ad2b (transverse profiles), 4 – pipeline visit homes, 5 – bank defense, 6 – stream centerline in 2006, 7 – stream centerline in 2012, 8 – island, 9 – transverse profiles; b – general upstream view of the left bank in 2004 [19].

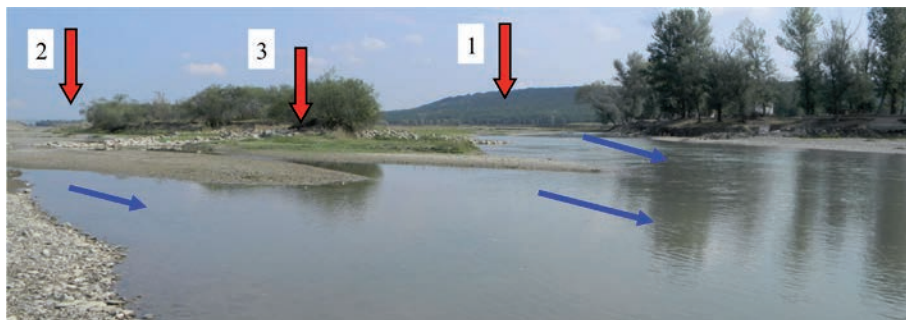


Figure 3.

Downstream view of the Moldova River in the undercrossing construction area: 1 – left arm; 2 – right arm; 3 – island.

annual total, and the lowest in winter. Climatic features have been disrupted over the past 50 years by global changes [1, 19].

In the study area, the Moldova River presents a winding route with multiple morphological changes in the longitudinal and transverse planes. In the research area in detail, where the undercrossing construction of the adduction pipelines is located, and the river presents a rectilinear and calibrated route made through regularization works. The frequent floods recorded in the last period of time produced changes in the longitudinal profile through erosion and clogging phenomena, an aspect also confirmed by the topographic studies carried out in 2006 and 2012 [19].

The flow regime in the river basin of the Moldavian River presents particularly great variations in time and space, with a high degree of torrentiality. The high degree of torrentiality is highlighted by the extreme multiannual values of the flow on Moldova. The ratio between the maximum historical and historical flows is about 1000. High values of the torrential coefficient are also present for the average monthly flows (about 170–175) and even the annual ones (about 5–6). Extreme values of rainfall occurred in different periods of the year: May 1972, June and July 1969, July and August 1991, September 2001, April 2005, July 2008, 2010, 2018, etc. The

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Q_s (Kg/s)	11.7	42.0	35.3	26.0	47.7	17.8	97.8	4.97	3.95	21.8	22.48

Table 1.
Annual maximum solid flows at HH Tupilati on the Moldova River [7].

concentration of precipitation over short periods of time determined the formation of floods with high flows at intervals of 2-3 years on the Moldova River [19].

The hydrological data for the research area were taken from the Tupilati Hydrometric Station (HS) located 12.80 Km downstream of the undercrossing construction, as well as from the Siret Water Basin Administration (WBA Siret) [7]. The maximum flow rate was measured in 1991 with a value of 1402 m³/s; the multiannual average flow was 32.46 m³/s; the minimum flow with the value of 11.90 m³/s was measured in 1990.

Solid flows measured at HS Tupilati show a large variation over time (**Table 1**). Their value was influenced in the last 30 years by the intensive extraction of ballast on the lower course of the Moldova River.

2.2 The technical characteristics of the undercrossing construction for pipelines

The behavior over time of pipelines located in riverbeds presents a complex case study through the dimensional and structural characteristics of the undercrossing construction, site geotechnics, watercourse hydrology and hydraulics, and others.

Pipelines can be placed in the river bed in various positions:

- transverse position when the bed is undercrossed at a certain depth below the level of the bottom (**Figure 4**); this position has the advantage of a minimum execution length;
- longitudinal position, which can be achieved in two variants: a – pipes located below the level of the bottom of the bed near the bank (**Figure 5a**); b – pipelines located on the river bank, where the bank defense offers them a high degree of protection (**Figure 5b**);
- oblique position with respect to the longitudinal axis of the bed; this position is imposed by the systematization conditions of the riparian zone that the pipeline crosses.

The undercrossing construction, in general, and the one on the Moldova River, is structured in two components (**Figure 2a**) [19]:

- the pipeline section mounted in the undercrossing and the attached constructions (houses with hydraulic installations, massive anchorages, monitoring equipment, and others) to ensure the normal operation of the adduction;
- works to regularize the river and protect the banks along a length that ensures the safety in operation of the pipelines.

The construction of the undercrossing was carried out in two stages. The first stage was completed in 1911 for the undercrossing of the Ad1 adduction pipeline



Figure 4. Pipes located in the undercrossing of a river bed uncovered by the action of a series of floods with high flows: *a – the supply pipe with $D = 1000$ mm on the Moldova River [19]; b – the supply pipe with $D = 800$ mm on the Tazlaul Sarat River [20].*

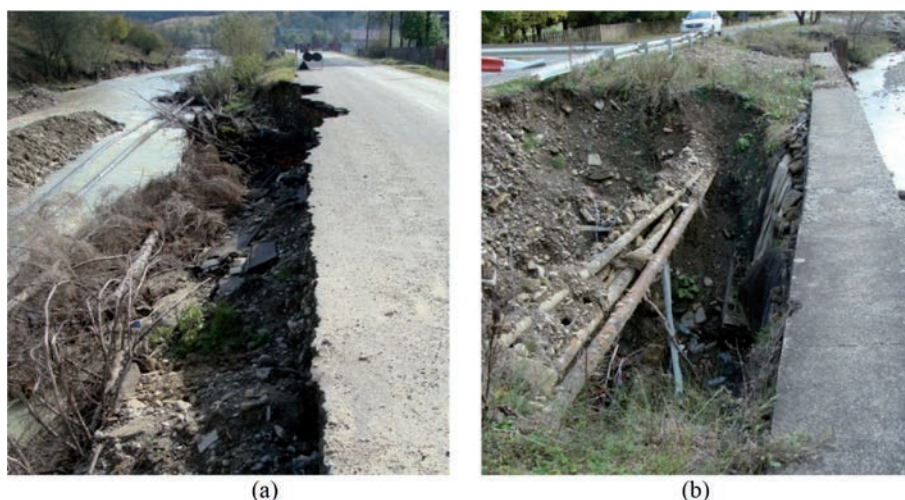


Figure 5. Pipelines located longitudinally in the bed of the Tazlaul Sarat River (upper course): *a – location in the bed; b – location on the shore [20].*

(**Figure 6**). The undercrossing of the minor bed of the Moldova River was carried out by using a pipe progressively descending from the riparian area of the right bank under the bottom of the bed and then progressively ascending in the riparian area of the left bank. The technological solution was specific to the years 1908–1911 and imposed by the use of 800 mm diameter cast iron socket tubes.

In the second stage, the Ad2 adduction pipe was built, with completion in 1973 [19]. The undercrossing of the minor river bed was carried out by using a pipe in the form of a descending siphon. According to the current design rules, the undercrossing was executed through two pipes (Ad2a and Ad2b) interconnected through the end chambers with hydraulic installations CV1 and CV2 on the right bank, respectively, CV3 and Cv4 on the left bank (**Figures 2a** and **6b**). Pipes Ad2a and Ad2b were made of steel with an outer diameter of 1020 mm. The distance between the three pipes in



Figure 6.
 The characteristics of the undercrossing construction on the Moldova River: a – scheme for the location of the pipelines on the left arm of the river, 1 – Ad1, 2 – Ad2a, 3 – Ad2b; b – the CV2 chamber with the hydraulic installation on Ad2b [19].

the undercrossing is 25 m (**Figure 6a**). The execution technology of the undercrossing determined the branching of the river into two arms by creating an island.

The bed regularization works in the undercrossing area aimed at linearizing them over a length of about 400 m and calibrating the flow section. The left bank and the right bank were protected with a rigid structure consisting of simple concrete slabs jointed with cement mortar.

2.3 Hydrodynamic erosion analysis of bank defense works on the research section

The process of structural degradation of the shore defense through hydrodynamic erosion was researched on a 420 m long section of the Moldova River (**Figure 2a**). The research took place between 2004 and 2015. The first shore defense was built in 1911 using wooden boxes filled with large stones.

The second coastal defense was built between 1970 and 1972 using a modern solution. The structure is formed vertically, in general, from the following components (**Figure 7**): a mattress of fascines, a prism of boulders, a concrete beam, a layer of concrete tiles jointed with cement mortar, and a row of special tiles on the ridge of a bank. The shore defenses from 1911 was incorporated into the new structure. For the

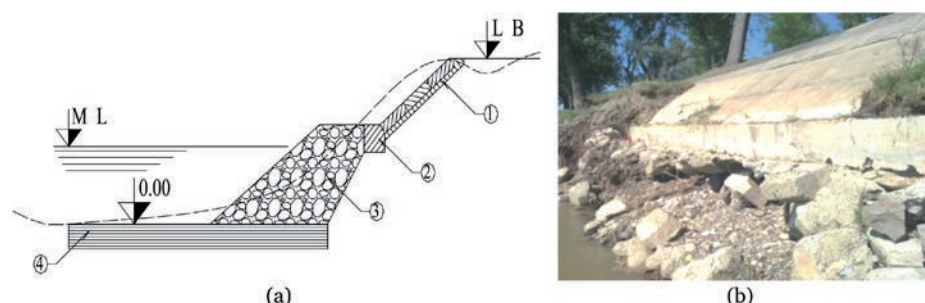


Figure 7.
 Images of the coastal defense on the research sector: a – execution model for type A1, 1 – concrete slabs, 2 – beam of reinforced concrete, 3 – broken stone prism, 4 – the fascinating mattress, ML – medium level, LB – level bank; b – detail regarding the state of degradation of the left bank defense in 2010 [19].

protection of the bank in the area of the undercrossing, four constructive variants (A1... A4) were designed and executed [10, 19].

The results of the research highlighted the corroboration of natural risk factors with anthropogenic risk factors present in the current period. In the period from 1973 to 2005, natural risk factors were prevalent, represented in particular by floods with maximum flows produced at relatively long time intervals.

After 2005, the anthropogenic risk factors stand out, two of which become extremely aggressive, respectively [10, 18, 19]:

- irrational extraction of ballast at distances of 50–300 m from the shore defense (**Figure 8a**); through this action, the morphology of the bed upstream of the undercrossing was substantially changed (change of the flow path, partial blocking of the right bank); also, the ratio of flows on the two branches of the river has changed (the left branch, which initially took 70% of the flow, reached 80-90%) (**Figure 3**);
- the ballast was extracted on the right arm of the river at the limit of the shore defense, a situation in which its stability was disturbed (**Figure 8b**);
- the absence of maintenance and repair works for the coastal defense in the period 1990–2015; also, no regularization works were executed to avoid the erosion of the left bank.

Floods with high flows were recorded annually in the Moldova River between 2004 and 2010 (with the exception of 2009) (**Figure 9**). The flood of 2005 had the highest flow rate, 1168 m³/s. In 2010 there were two floods: summer with flow rate 660 m³/s and autumn with 965 m³/s [18]. Flood discharges were below the calculation probability of the bank defense works (**Table 2**), but their effect led to the degradation of the protection works. The flow on the research section decreased in 2009 and 2011-2015, but the degradation of the shore defenses increased due to anthropogenic risk factors (especially ballast mining).

The monitoring of the erosion phenomenon of the river bank in the area of the pipelines undercrossing was carried out at different time intervals, depending on the structural condition of the defense works. The flood wave produced in 2005 on the Moldova River initiated the process of detailed monitoring of the bank defense works.



Figure 8.

Changing the morphology of the bed in the upstream area of the research section by extracting the ballast: a – blocking the flow to the right arm of the river through ballast deposits; b – disturbing the stability of the right bank by extracting ballast from the area of the foundation of the shore defenses [19].

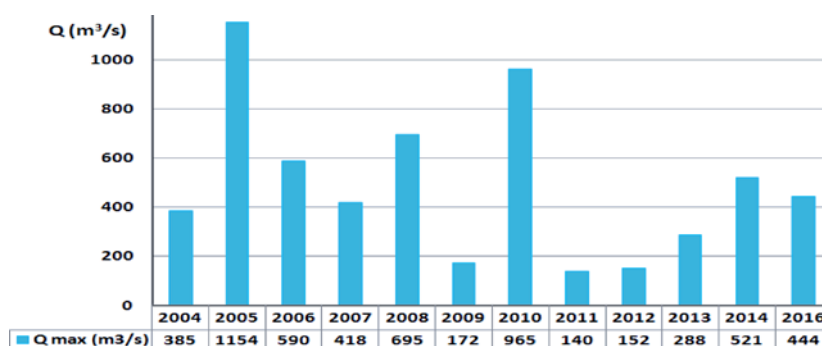


Figure 9.
 The frequency of annual maximum flows during the analyzed period ($Q = f(t)$ in the years 2004 – 2016) [10].

p (%)	1%	2%	5%	10%	50%
$Qp_{\%}$ (m³/s)	1810	1555	1200	940	28,80
H (mLBS)	257.15	256.95	256.50	255.90	253.10

H (mLBS) – the water level with the Black Sea reference elevation.

Table 2.
 Flows and levels with calculation probabilities ($p\%$) on the research section on the Moldova River [19].

In the research sector, three complete topographic plans were made in 2006, 2012, and 2015, and one only of the left bank in 2008. The topographic plans included transversal profiles through the bed (3 in 2006 and 14 in 2012) and additionally through the left banks (5 in 2012). Longitudinal profiles were also made on the two arms of the bed.

The rapid degradation of the bank defense works, especially on the left bank, was achieved through destructive processes between 2006 and 2015 (**Figures 10** and **11**).

The degradation process took place in several stages: 1 – washing away the layer of alluvium deposited on the bank defense (**Figure 10b**); 2 – driving the stone from the supporting massif (**Figure 10c, d**); 3 – removing the cement mortar from the joints and washing the ballast layer from under the concrete slabs (**Figure 10d**); 4 – cracking and breaking of concrete slabs; 4 – removing the stone from the supporting massif and losing the stability of the protective work; 5 – the breaking of the support beam and the collapse of the concrete slabs (**Figure 10e**); 6 – entrainment of concrete pieces and stone in the river bed (**Figure 10f**); 7 – the hydrodynamic erosion of the bank and the advance of the bed in the riparian zone (**Figure 11**) [10, 19].

The morphological changes of the Moldova River bed upstream of the island, especially the extraction of ballast, led to a lower flow on the right arm of the river. Thus, the phenomenon of erosion was reduced (**Figure 12b**). The degradations that occurred in the years 2008–2015 were determined by the exploitation of ballast right inside the right arm (**Figure 12d**).

The analysis of data obtained through research in the time interval 2004–2015 highlighted the rapid degradation of the left bank defense construction. The protection works (**Figures 10** and **11**) were degraded by 90–100%, while those on the right bank only by 20–35% (**Figure 12**). If in 2004–2005, the shore defense on the left and right banks was clogged for lengths of 6.0–14.0 m in the bed (**Figure 10a**), in 2015, about 90% of the protection surface of the left bank disappeared (**Figure 11c**). The natural risk factors (fast and high-frequency floods) have combined with the

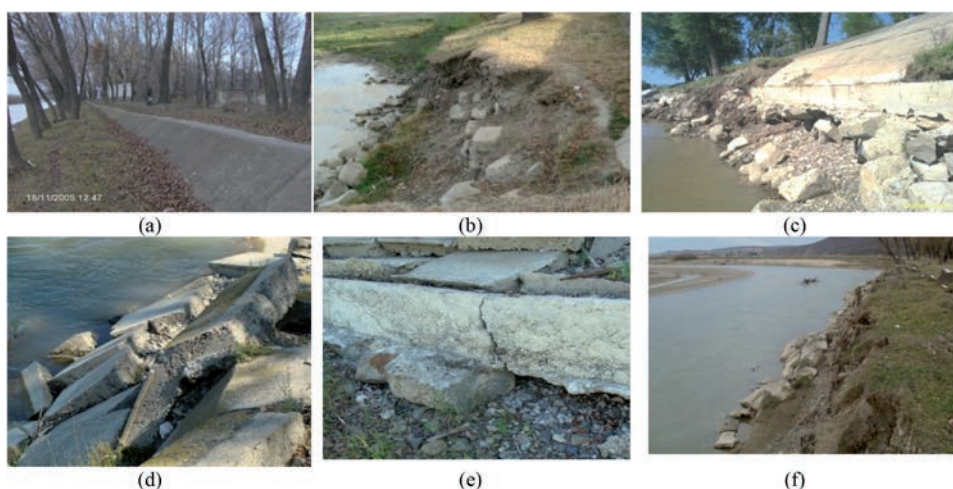


Figure 10.

Degradation stages at the left bank protection work: a – the initial state of the bank (alluvial deposits above the bank defense, in the 2005 year; b – washing of alluvial deposits, 2006–2007; c – driving the stone from the supporting massif, 2008; d – breaking of the concrete beam supporting the concrete slabs 2008 - 2009; e – sliding of the concrete slabs on the slope; f – training the components of the protection work in the river bed, 2010.

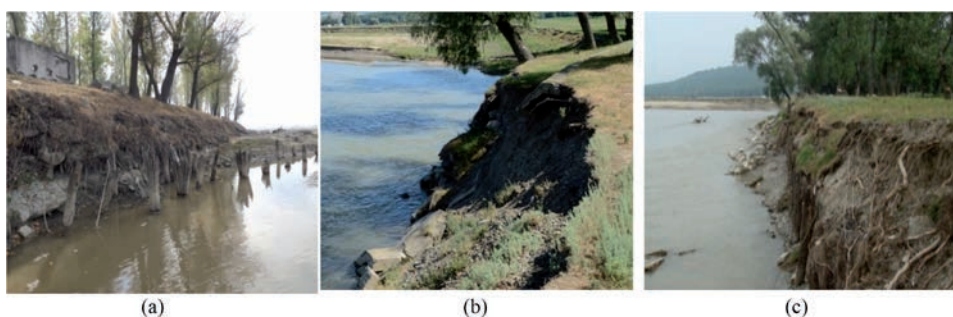


Figure 11.

The erosion process of the left bank and the riparian zone: a – erosion of the bank defense work carried out in 1911; b – local erosion of the bank entering the riparian area, 2010; c – the generalized erosion of the bank entering the riparian zone, 2015.



Figure 12.

The state of degradation over time of the protection of the right bank on the Moldova River: a – the initial state of the bank; b – subsidence of the shore defenses; c – loss of stability of the protective work by extracting the ballast [19].

anthropogenic factors (irrational extraction of ballast and the absence of coastal defense repair works) and have determined the advanced state of degradation of the undercrossing construction of the three pipelines adduction.

The results of the topographic monitoring for the research section TP10.lf (left), located on the left bank, are shown in **Figure 13**. The figure highlights three topographic measurements made in 2006, 2008, and 2012 and supplemented with local measurements in the other years. The processing of the experimental data for the Pt10lf transverse profile is shown in **Table 3**.

From the analysis of the data in **Table 3** and **Figure 13**, the processing of the data taken from the measurements made over time, the lengths and depths of erosion in the bank defense in the cross-sectional profile TP10.lf and further in the left bank of the Moldova River result. The shoreline in 2006 (line 2, **Figure 13**) resulted from the clogging over time of the shore defense work carried out in 1970.

The alluvium deposit was eroded by the action of the floods produced on the Moldova River in 2006, 2008, 2010, and 2012, determining the situations presented by lines 3 and 4 (**Figure 6**, **Table 2**). In 2008, the degradation of the shore defense began, highlighted by the position of line 3. The shore defense in TP10lf was progressively degraded starting in 2008, and in 2010 it was completely destroyed. From 2010 to 2012, the river bank was eroded for lengths of 1.50–3.25 m, a situation highlighted by the position of line 4. The erosion process advanced until 2015 in the riparian area for a length of 1.50 m from the crown of the work of defense (**Figure 12c**).

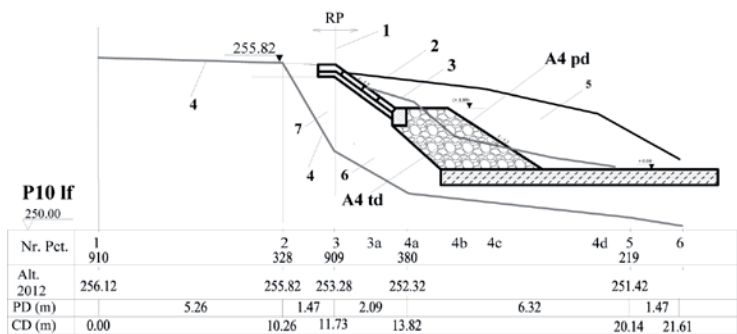


Figure 13. Scheme of the erosion phenomenon for the TP10.lf transverse profile on the left bank of the Moldova River: 1 – reference point 2; 2 – the shoreline, year 2006; 3 – the shoreline, year 2008; 4 – the shoreline, year 2012; 5 – layer of alluvium; 6 – bank erosion zone; 7 – erosion in the riparian area/major river bed; A4pd – shore defense type A4 partially degraded; A4dt – shore defense type A4 totally degraded.

Date	2004	2005	2006	2008	2010	2012	2014
L (m)	18.24	17.21	16.11	13.91	12.88	- 1.74	- 1.92
H _{er} (m)	—	—	0.42-0.69	1.76-1.93	2.27-3.05	2.88-4.12	3.28-4.80
D.T	—	—	—	PD	PD	TD	BE

PD – partial degradation; TD – total degradation; BE – bank erosion; D.T. – Degradation type.

Table 3. Monitoring of shore defense erosion parameters in transverse profile TP10.lf.

In a similar way, the data were processed for the seven cross-sectional profiles considered in the research in the area of the left bank through which the three adduction pipelines pass.

2.4 Safety in operation of pipelines undercrossing on the research section

The phenomenon of hydrodynamic erosion of the bed in the research area is three-dimensional. The bed of the Moldova River, which developed in a granular layer, is very responsive to the temporal variation of the liquid flow and also to the action of anthropogenic factors. The axis of the water current changed its position on the left arm between 2006 and 2012, according to the longitudinal profiles made (**Figure 2a**). The maximum erosion depths moved in the transverse profile and increased in value over time (about 0.40–1.10 m in 2006 and 0.60–1.30 in 2012). The longitudinal profile of the left arm (stream centerline) was located toward the middle of the bed in 2006. In 2012, the profile was positioned in the vicinity of the left bank, a situation that confirms the intensification of lateral erosion.

Lateral erosion is extremely active in the cross-section, as previously mentioned in Section 2.3. This aspect intensified the process of stripping the pipes over a relatively long length in the bed. This situation was also confirmed by research [20] carried out on the undercrossing of a cast iron pipe with $D = 800$ mm, where the erosion process took place near the bank and then in the bank and the riparian area (**Figure 4b**).

Erosion along the flow direction is exemplified by the vertical evolution of the longitudinal profile along the research section. The differences between the minimum and maximum areas recorded on a length of 362 m are 40–130 cm [19]. The uncovered pipelines turned into bottom sills, a situation that intensified the phenomenon of erosion downstream of them (**Figure 4a**).

The morphological modification of the bed, represented by the lowering of the level of the watered perimeter on the left arm of the Moldova River, caused the stripping of the Ad1 and Ad2a pipelines under the crossing. Pipeline Ad1 was ruptured in 2008 after an uninterrupted operation of 97 years [19]. The Ad2a pipeline was stripped in 2012, (**Figure 4a**). On the route in the bed of the Ad2b pipeline, a large stone prism was made for erosion protection (**Figure 6a**). The sharp degradation of the undercrossing construction required the design of its rehabilitation and modernization works. The project was carried out in 2012, and its application was made in 2015 [21].

3. Simulation of the phenomenon of hydrodynamic erosion on the watered perimeter of the riverbeds

3.1 The hydraulic-mathematical simulation model

The general state of hydrodynamic entrainment of alluvium in riverbeds is a particularly complex physical process, being determined by a large number of parameters of a hydraulic, hydrological, and geotechnical nature and mode of exploitation of the water course. The phenomenon of hydrodynamic erosion and deposition is a function of a series of parameters that characterize the contact of the water current with the granular layer on the surface of the bed. They are mainly represented by wall friction velocity (v_*), wall tangential stress (τ_0), particle diameter (d), Re and Fr numbers, average velocity and water depth, and others. The movement of alluvium in the bed occurs when the critical state of their entrainment is achieved, characterized

by the critical entrainment tangential effort (τ_{cr} or τ_b) and the critical entrainment speed (v_{cr}) [7].

The critical tangential driving stress in natural beds has a non-uniform distribution on the perimeter due to local variation in the shape of the flow section, water depth and mean velocity. This situation did not allow obtaining semi-empirical calculation relations for the tangential stress distribution. In this context and from technical considerations required by the stability of the pipelines located transversely in the river bed, a hydraulic model was developed to obtain hydrodynamic erosion parameters on the granular perimeter of the bed.

The movement of water in natural beds is non-permanent, as mathematically described by the Saint-Venant equations. On a river section of limited length and over a longer time interval, a gradually varied non-uniform permanent movement can be admitted at the initial moment. To obtain the hydraulic parameters in natural beds, the finite difference form of the equation of the varied gradual non-uniform motion (VGNM) is used. The state of motion in rivers with small bed slopes is generally subcritical (the Froude number is subunit, $Fr < 1$), a situation in which the control section and the command elevation are located at the downstream end of the calculation section [22]. The following boundary condition results:

$$x = x^0; Z = Z^0, \quad (1)$$

where x^0 and Z^0 are known values for the spatial coordinate x and the water level elevation Z .

In the downstream section of the calculation section, $x^0 = x_0 = 0$ is considered, and for the upstream section, $x^0 = x_0 + L$, where L is the length of the section of river for analysis.

Thus, in the control section located in the downstream section of the calculation section, $x^0 = x_0 = 0$ is considered, and for the upstream section, $x^0 = x_0 + L$, where L is the length of the river section considered in the calculation. In this analysis case, the equation of motion has the form [22]:

$$Z_{up} = Z_{dw} + \frac{1}{2g} \left(\alpha_{dw} \frac{Q_{dw}^2}{A_{dw}^2} - \alpha_{up} \frac{Q_{up}^2}{A_{up}^2} \right) + \frac{(Q_{dw} + Q_{up})^2}{(K_{dw} + K_{up})^2} \Delta x = 0 \quad (2)$$

where Z is the elevation of the water level; Q – volume flow; K – flow module; A – watered area of the bed; Δx – the length of the calculation sector; α – Coriolis coefficient; indices: up – upstream, dw – downstream.

For the wall tangential stress (τ_0) at the riverbed bottom was considered the expression [7]:

$$\tau_0 = g\rho \frac{n^2 v^2}{h^{1/3}}, \quad (3)$$

where v is the average speed; n – roughness coefficient according to Manning; h – water depth; ρ – water density.

The average speed of the water, according to Chézy's relation, in which the coefficient C is expressed by Manning's formula and the hydraulic radius, is approximated by the depth h , results in the expression:

$$v = \frac{1}{n} h^{2/3} \sqrt{I_h}, \quad (4)$$

where I_h is the hydraulic slope. From the equations (Eqs. (3) and (4)) it follows:

$$\frac{n^2 v^2}{h^{1/3}} = h I_h. \quad (5)$$

Since $g \cdot \rho \approx \text{const.}$ and the product “ $h I_h$ ” is an increasing flow function, from the equations (Eqs. (3) and (5)), it follows that the training stress at the bed bottom τ_b is also an increasing flow function. The state of morphological stability of the bed depends on the distribution on the watered perimeter of the hydraulic parameters v , h , and n for the difference of the considered flows.

The hydraulic-mathematical model for simulating hydrodynamic erosion is based on a two-dimensional model that takes into account the geomorphological characteristics of the analyzed cross-sections in a consistent manner. The cross-sections of the bed are diagrammed on current tubes, where the velocities are averaged according to the average depth of the tube (**Figure 14**).

The river bed is of a natural type, with a random geometric evolution in longitudinal profile and cross section. In the simulation, the geometric characteristics must be defined for the longitudinal profile, as well as for each cross section considered in the analysis. The following geometric characteristics are defined in the investigated river section:

- the longitudinal profile made on the waterline at the bottom of the river bed through the pairs of coordinates (x_j, Z_{tvj}) collected in N points (**Figure 14b**), respectively:

$$(x_j, Z_{tvj}), j = 1, 2, \dots, N, \quad (6)$$

where Z_{tvj} is the elevation of the bottom of the bed at point j ;

- the cross sections j , at the points of the longitudinal profile (Eq. (6)) are represented by an open broken line, on which there are M coordinate nodes (y_i, Z_i) (**Figure 14c**),

$$(y_i, Z_{i,j}), i = 1, 2, \dots, M, \quad (7)$$

where $Z_{i,j}$ is the water level at point i ;

The slope of the bed, $I_{j,j+1}$ on the analysis section delimited by the consecutive cross sections j and $j + 1$, is obtained by processing the coordinates (Eq. (6)) and with the relation,

$$I_{j,j+1} = -\frac{Z_{tvj+1} - Z_{tvj}}{x_{j+1} - x_j} \text{ with } j = 1, 2, \dots, N - 1 \quad (8)$$

The characteristics and hydraulic parameters in the cross-sections j positioned in the longitudinal profile of the investigated river section are:

- water level elevation, Z , $Z \in (Z_{tvj}, Z_{nInd,j})$, where $Z_{nInd,j}$ is the elevation of non-flooding in cross-section j ;
- the watered section of the river bed, A ; the watered perimeter of the cross-section j , P ; hydraulic radius of the watered section of the riverbed, $R_h = A/P$; the width at the water mirror of the watered section j , B ; the average water depth

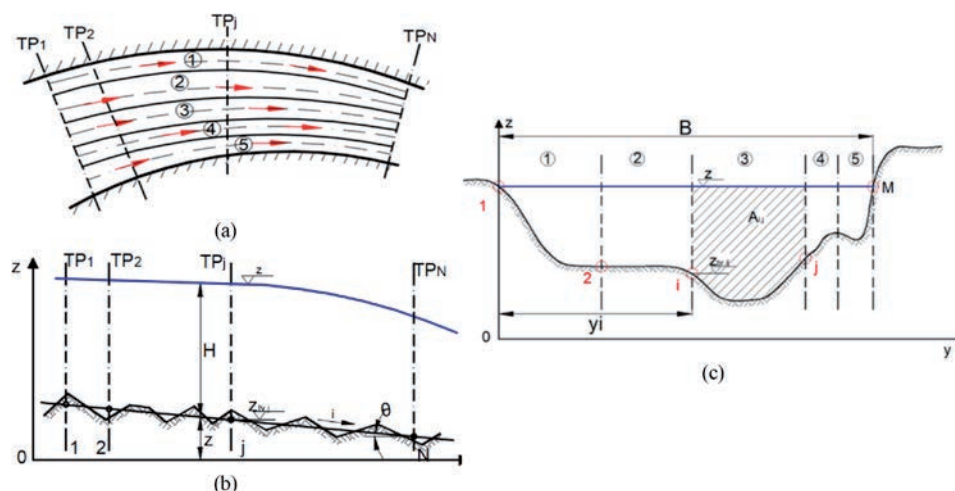


Figure 14.
 Analysis scheme of the simulation model: a – plan view of the bed; the longitudinal profile of the research section;
 c – transverse profile with the calculation sections highlighted.

in the watered transversal section j , $h_m = A/P$, the relative width of the watered cross-section j at the water mirror, B_r , where $B_r = B / \bar{h} = B^2 / A$;

- the roughness coefficient n of the wetted perimeter (according to the calculation relations of the Chézy coefficient used); when the roughness is uneven on the perimeter, the values of the coefficient n must be specified in all nodes (Eq. (7)) through the set of values n_i , with $i = 1, 2, \dots, M$;
- volume flow on the considered river section, Q ; average velocity in wetted cross-section j , $V = Q/A$; velocity modulus of the watered cross-section j , W ; flow modulus of the watered cross-section j , K .

The detailed processing of the hydraulic parameters included in the simulation model is presented in detail in the article [23].

3.2 Numerical model for simulating perimeter erosion in riverbeds

To determine the parameters of hydrodynamic erosion on the perimeter of the river beds, a set of programs was developed in MATLAB, which implements the hydraulic-mathematical model. The program set consists of the main program `MPGV_River_Bed.m`, to which a number of user functions are added according to the research objectives. The main program for the current research problem has nine user functions, namely [23]:

- The user function `F1 myfun_Albie.m` determines according to the elevation of the water level Z in a cross-section hydraulic parameters of the bed: A , P , B , h_m , V , R_h , C (Chézy coefficient), n_{ech} , and K .
- The user function `F2 myfun_Tet_Delt_BetR.m` reassess according to the relative width Br the parameters: K , I_h , $\bar{V}_i$, and V_b , including a series of coefficients specific to the movement.

The user function *F3 myfun_hU.m* evaluates according to the flow rate Q and the slope I_h the normal water depth h_u and the water level elevation Z_u in the uniform movement.

The user function *F4 myfun_hCR.m* evaluates as a function of the flow rate Q , the critical water depth h_{cr} , and the water level elevation Z_{cr} in the critical motion regime.

The user function *F5 myfun_Z_Am.m* generates the equation of stepwise variation motion in finite differences.

The user function *F6 myfun_Tip_Remuu.m* determines, according to I_h , Z_u , Z_{cr} , and Z_{GV} , the type of the curve of the free surface of the water.

The user function *F7 myfun_Efort_Forfecare.m* determines the bottom shear stress τ_{bi} , related to each of the nodes (y_i, Z_i) , according to V_i , h_i , and n_i (considered in the calculation variants and with processed values from the geotechnical study). It should be noted that only in the case of areas with forest vegetation (the island and the floodable portions of the shore) were values adopted from the specialized literature. In this case, the related τ_{bi} values were greatly reduced because the sediments are fixed and can no longer be entrained in motion.

The user function *F8 myfun_Tau_D.m* determines the wall friction velocity U_{*i} , and the maximum diameter of the displaced grain $D_{max,i}$. The user function *F9 myfun_Curba_Granulom_p_ProcD_Shd.m* determines the percentage of the sediment sample, p_{Di} , related to the granulometric diagram of the diameter $D_{max,i}$ as well as the equivalent thickness of the bed perimeter layer that is in motion, $s_{ech,i}$.

3.3 Results regarding the simulation of hydrodynamic erosion perimeter depths

The simulation of the phenomenon of perimeter erosion was carried out on a length of 287.36 m, respectively, on the last part of the research section located on the Moldova River. On this length, seven transversal profiles (TP1 – TP7) were selected, which also include the three adduction pipelines located in the undercrossing of the river (**Figure 15**).

The erosion simulation program was used for two scenarios (Sc1, Sc2) differentiated by the value of the maximum flow. Each scenario had two analysis variants differentiated by the roughness coefficient estimation method. In the first scenario, the flow rate $Q_{max,1} = 493 \text{ m}^3/\text{s}$, was used, obtained by averaging the flow rates from the period 2004 to 2014 (**Figure 9**), during which the adduction pipelines were emptied, and the shore defense was destroyed. In the second scenario, $Q_{max,2} = 630 \text{ m}^3/\text{s}$ was used, where two flows with very low values were excluded from the average. In 2015, the morphology of the river bed was changed by rehabilitating the undercrossing construction of the adduction pipelines.

A synthesis of the results obtained in the Sc1 scenario and the V1 variant is presented below. The input data to the simulation program were as follows:

- general data: water density ρ (1000 kg/m^3); gravitational acceleration g (9.81 m/s^2);
- topographical data for the simulated river section: $L = 287.36 \text{ m}$, longitudinal profiles with coordinates (y_j, z_{tvj}) , seven transverse profiles TPci calculation (TPc1 – TPc7) with coordinates (y_i, z_i) and with characteristic nodes n_i (**Figure 15a**); the width of the minor bed varies from upstream to downstream with values of 260 m before the island and 127.0 m on the left arm, respectively, 74.0 m on the right arm; downstream of the island is 145.0 m; the maximum depth of the bed varies between 4.74 and 4.32 m;

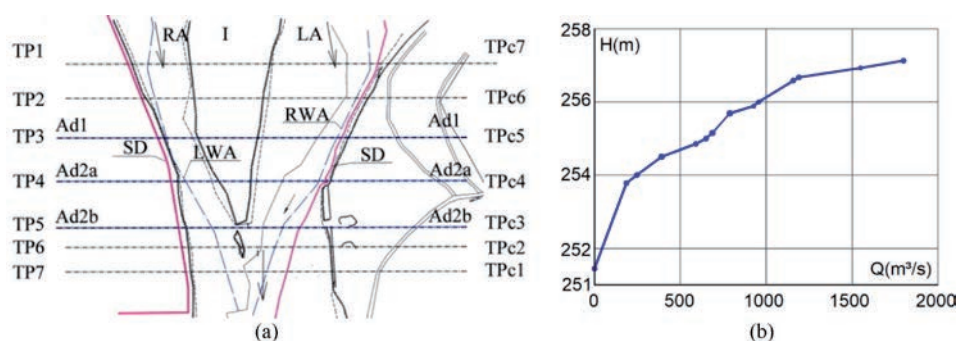


Figure 15. Input data to the simulation program: a – situation plan with the river section for simulating the perimeter erosion phenomenon, TP1... TP7 – transverse profiles, TPc1... TPc7 – transverse calculation profile, LA and RA – left and right arm of the river, I – island, LWA, RWA – left and right water axis, Ad1, Ad2a and Ad2b – location of supply pipes, SD – shore defense; b – correlation $Q = f(H)$ in the downstream simulation section.

- hydraulic and hydrological data: flow rate $Q = 493.00 \text{ m}^3/\text{s}$, water share in the downstream section, $Z_{\text{dw}} = 255.29 \text{ mLBS}$ (the share is the Black Sea level), according to the correlation $Q = f(H)$ from (Figure 15b) [19]; variable roughness coefficient on the wetted perimeter, $n = 0.023\text{--}0.045$, according to Chang's relation (the diameter of the gravel grains obtained by processing the samples taken from the bed was the difference $d = 1.50\text{--}45.00 \text{ mm}$, and $d_{50} = 25 \text{ mm}$ [19, 23, 24]); for the island area covered with vegetation (shrubs + trees), $n = 0.081$;

The output data from the simulation program is represented in the form of tables, diagrams, and graphs. In the first step, a hydraulically continuous and positive slope was processed on the simulated river section (Figure 16a) as a way to solve the equation (Eq. (2)). It resulted in a total approximation function of the type of a second degree polynomial of the form:

$$Z_{\text{tv,cll}} = 0.000164423 x^2 - 0.003031636 x + 251.182, x \in [0; 287, 36], \quad (9)$$

with the graphic presentation of the function $Z_{\text{tv,cll}} = f(x)$ in (Figure 16b). This function allows the determination of the bed bottom elevation in each considered transverse profile (TPci).

The geometric and hydraulic parameters considered and processed in VGNM were (Table 4): I_{tv} , K_{neq} , Z_{w} , h_{w} , n_{ech} , B_{cr} , A_{cr} , Z_{cr} , h_{cr} , and others. These define uniform motion, varied gradual motion, and the type of free surface curve formed on the simulation sector. Processed parameters highlight a gradually varied non-uniform movement, represented by a rising curve in a state of subcritical movement ($h_{\text{u}} > h_{\text{cr}}$, where the characteristic depths vary in the gap, $h_{\text{cr}} = 2.14\text{--}2.71 \text{ m}$ and $h_{\text{u}} = 2.58\text{--}5.41 \text{ m}$).

For each TPci profile, the following geometric and hydraulic parameters were processed and evaluated in GVPM: B , A , P , R_{b} , C , B_{v} , K , V , Z_{GV} , h_{GV} , and a series of coefficients involved in the analysis (Table 5). With the data from columns 2 and 10, the curve of the free surface ($Z_{\text{GV}} = f(x)$) was drawn on the river sector delimited by the TPc7-TPc1 profiles (Figure 16a). Columns 10 and 11 show the depth and elevation of the water level (h_{GV} and Z_{GV}) in the GVPM, in each TPci profile.

The geometric and hydraulic parameters, y_{b} , z_{b} , h_{b} , and V_{b} , for the evaluation of the shear stress on the wetted perimeter, τ_{bi} , were determined in each calculation profile

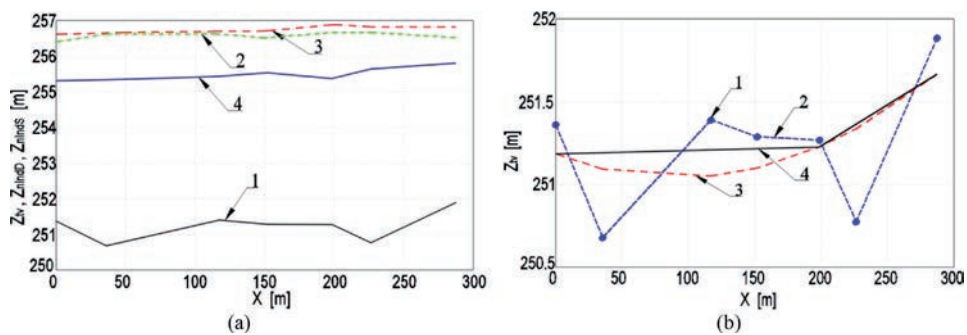


Figure 16.

Geodetic slope on the research section: a – natural slope (year 2012), 1 – bed bottom line of coordinates $(x, Z_{iv}(x))$, 2 – left bank line, 3 – right bank line, 4 – the curve of the free surface ($Z_{GV} = f(x)$); b – simulated slope, 1 – coordinate points (x, Z_{iv}) ; 2 – natural longitudinal profiles; 3, 4 – simulated longitudinal profile with degree II polynomial, respectively, degree I; notice: the coordinate $x = 0$ is applied in the downstream section according to the calculation model.

TPc1, TPc2, and TPc7. It should be noted that each calculation profile has a different number of n_i nodes where all parameters are processed (Table 6). For example, the data processed in the TPc4 cross-section, where the second adduction pipe located in the undercrossing is located (Figure 4a and 15a), are presented (Table 7). The field investigation of the Ad2a adduction pipeline revealed the removal of the covering ballast layer but also of the special protective layer, although the pipeline was buried at a depth of about 1.50–2.00 m below the bottom of the river bed [19].

Parameters of the perimeter erosion phenomenon for the TPc4 transversal profile are presented tabular (Table 7). The original data table contains 25 lines with processed values, where only 10 lines will be selectively presented in this paper. Columns 2 and 3 show the coordinates (y_i, z_i) of nodes n_i , on the watered perimeter. The fourth column shows the water depth, h_i , in the n_i nodes, and the fifth column shows the average water velocity V_i over the depth, h_i , in each n_i node. In the sixth column, the shear stress at the bottom in each of the nodes n_i is presented, and in the seventh column, the wall friction velocity U^* is presented.

j_i	x (m)	$Z_{iv,c}$ (m)	I_{iv} (‰)	nec_h	Z_u (m)	h_u (m)	K_u (m ³ /s)	h_{cr} (m)	Z_{nfl} (m)	Z_{nflr} (m)
1	2	3	4	5	6	7	8	9	10	11
TPc1	0.00	251.18	0.226	0.04036	256.38	5.20	32774.3	2.41	256.38	256.59
TPc2	35.83	251.19	0.226	0.04052	256.60	5.41	32774.3	2.45	256.60	256.63
TPc3	117.19	251.21	0.226	0.04029	256.60	5.39	32774.3	2.51	256.60	256.67
TPc4	151.92	251.22	0.226	0.04037	256.48	5.26	32774.3	2.49	256.48	256.69
TPc5	198.75	251.23	1.407	0.04029	256.27	4.04	13140.9	2.71	256.64	256.86
TPc6	226.70	251.37	3.769	0.04186	254.52	3.15	8029.3	2.57	256.65	256.80
TPc7	287.36	251.67	4.951	0.04029	254.25	2.58	7006.40	2.14	256.51	256.80

Table 4.

Processed geometric and hydraulic parameters for GVPM on the simulation section (selective display).

j_i	x (m)	A (m ²)	P (m)	R_h (m)	C (m ^{1/2} /s)	B_r (-)	K (m ³ /s)	V (m/s)	Z_{GV} (m)	h_{GV} (m)
1	2	3	4	5	6	7	8	9	10	11
TPc1	0.00	378.93	146.35	2.589	31.44	55.492	17774.3	1.301	255.29	4.11
TPc2	35.83	360.50	135.41	2.662	31.50	48.672	16841.1	1.368	255.31	4.12
TPc3	117.19	367.36	143.51	2.560	31.43	54.569	17262.7	1.342	255.41	4.20
TPc4	151.92	343.75	139.84	2.458	31.11	54.053	16434.4	1.434	255.52	4.31
TPc5	198.75	315.31	142.38	2.215	30.50	61.529	13905.3	1.564	255.35	4.13
TPc6	226.70	432.74	208.54	2.075	29.06	97.307	18950.3	1.139	255.62	4.26
TPc7	287.36	540.82	239.36	2.260	30.63	254.25	102.43	0.912	255.80	4.13

Table 5.
Geometric and hydraulic parameters processed in GVPM for TPci calculation profiles (selective presentation).

From the analysis of the data obtained in the TPc4 profile, a variation of the average speeds results in the gap of 0.81–2.86 m/s on the partial calculation areas; the unit tangential drive effort has values 3.56–27.10 N/m²; the diameter of the gravel particles that can be moved have values 2.21–3.64 cm on the left arm of the river, and on the right arm of 1.73–2.57 cm (the granulometry of the ballast and gravel layer in the bed shows $d_{50} = 2.50$ cm). It follows that a large part of the gravel layer on the perimeter of the bed, especially on the left arm of the river, is entrained in the flood movement with $Q = 493$ m³/s. In 2010, when the erosion of the Ad2a adduction pipe site increased, there were two floods in the research area with flows of 660 and 965 m³/s.

The variations of the wall shear stress (γ , τ_{bi}) and the wall velocity (γ , U_*) in each node n_i on the wetted perimeter in the transverse profile TPc4 are shown graphically in (**Figure 17a**) for simulation scenario 1 and option 1 (Sc1-O1). The variations of the maximum diameter (D_{max}) of the displaced particle, as well as of the equivalent thickness of the displaced alluvium layer (s_{ech}), in each node n_i on the watered perimeter in the TPc4 transverse profile, are graphically presented in (**Figure 17b**).

The graphical variation of the parameters of the perimeter erosion phenomenon in the TPc5 transversal profile, where the undercrossing of the Ad1 adduction pipeline is located, is presented in (**Figure 18**). For the transverse profile TPc3, where the undercrossing of the Ad2b adduction pipe is located, the variation of the parameters is presented in (**Figure 19**).

The variation of the main parameters of the perimeter erosion phenomenon on the investigated river section was graphically represented for the seven transversal profiles and three longitudinal profiles. The magnitude of the shear stress at the bottom (τ_{bi})

TPci	TPc1	TPc2	TPc3	TPc4	TPc5	TPc6	TPc7
n_i	22	23	23	20	20	22	24
Z_{GV} (m)	254.55	254.57	254.55	254.67	254.77	254.61	255.14
I_h (‰)	0.7261	0.8739	0.7677	0.0829	1.20	0.6735	0.3829

Table 6.
The number of computing nodes for each cross-sectional profile TPci.

Node n_i	y_i (m)	z (m ²)	h_i (m)	V_i (m/s)	τ_{bi} (N/m ²)	U^* (cm/s)	D_{max} (cm)	p_D (%)	s_{ech} (mm)
1	2	3	4	5	6	7	8	9	10
1	56.98	254.47	0.30	0.98	7.00	8.37	1.03	78.84	8.12
5	63.96	251.49	3.28	2.86	27.09	16.46	3.64	100.0	36.42
6	66.62	251.50	3.27	2.79	25.99	16.12	3.50	100.0	35.02
7	69.34	251.73	3.04	2.73	25.26	15.89	3.41	100.0	34.08
9	75.78	251.83	2.94	2.65	24.12	15.53	3.26	100.0	32.63
10	79.54	251.90	2.87	2.59	23.30	15.27	3.16	100.0	31.58
14	118.91	252.77	2.00	1.04	5.29	7.27	0.80	73.52	5.86
16	160.78	252.56	2.21	2.23	18.76	13.70	2.57	100.0	25.74
20	185.63	253.09	1.68	0.81	3.56	5.97	0.56	49.02	2.73

Table 7.
Geometric and hydraulic parameters processed in GVPM for TPC4 calculation profiles (selective presentation).

was represented to scale ($1 \text{ m} = 10 \text{ N/m}^2$) in nodes n_i through vertical segments in each of the transverse profiles TPC1 – TPC7. The analysis of the obtained data highlights an uneven distribution of the tangential effort, with minimum values (zero values) at the banks and maximums in the nodes with a high water depth. The other parameters of the erosion phenomenon were also represented with vertical segments: velocity at the wall, U^* , the equivalent layer of displaced sediments, s_{ech} , and the maximum diameter of the displaced particle, D_{max} , each with representation scales.

The way of geometric development of the river bed in the research section, especially of the right arm, greatly influenced the size of the hydraulic parameters and, implicitly, of the hydrodynamic erosion parameters in each transverse profile. The right arm of the river at the entrance to the research section (profiles TP1, TP2, and TP3) has the shape of a confusor, and the minimum width is in the area of the Ad1 pipeline (Figure 15a). In this context, high speeds occurred between profiles TP1 – TP4, and

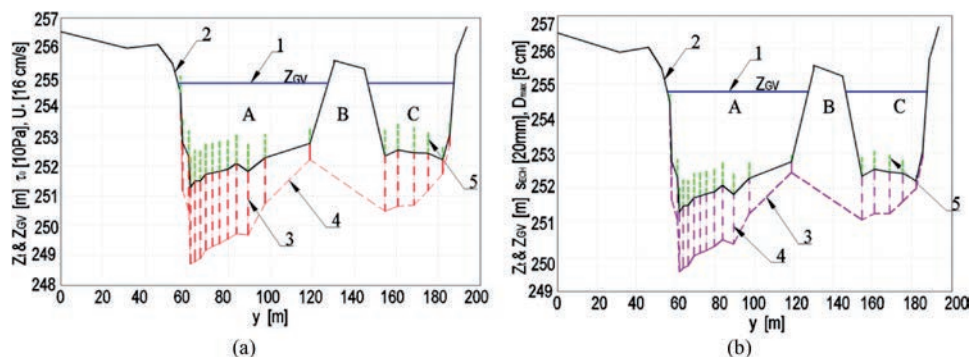


Figure 17.
The variation of perimeter erosion parameters in GVPM at the transverse profile TPC4, Sc1-O1; a – graphic representation of correlations (y, τ_{bi}) and (y, U^*): 1 – $Z_{GV} = f(y)$, water gloss in GVPM, 2 – $z_i = f(y)$, cross-section through to river bed, 3 – (y, τ_{bi}), size of the wall shear stress at the bottom, 4 – $\tau_{bi} = f(y)$, shear effort variation at the bottom, 5 – (y, U^*) magnitude of speed friction, A, C – the left and right arm of the river, B – island; b – graphic representation of correlations (y, D_{max}) and (y, s_{ech}): 3 – $s_{ech} = f(y)$, the line of erosion; 4 – (y, s_{ech}), the thickness of the eroded layer; 5 – (y, D_{max}), the maximum diameter of the dragged particle.

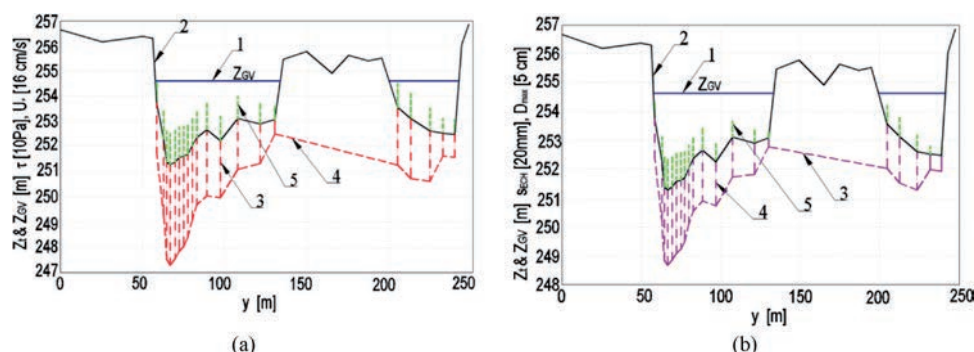


Figure 18.
 The variation of perimeter erosion parameters in GVPM at the transverse profile TPc5, Sc1-O1; a – graphic representation of correlations (y , τ_{bi}) and (y , U); b – graphic representation of correlations (y , D_{max}) and (y , s_{ech}). Note: the notations correspond to those in (Figure 17).

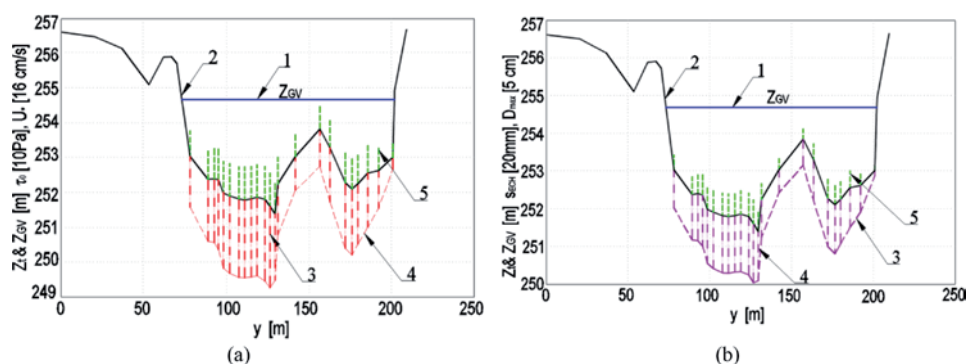


Figure 19.
 The variation of perimeter erosion parameters in GVPM at the transverse profile TPc3, Sc1-O1; a – graphic representation of correlations (y , τ_{bi}) and (y , U); b – graphic representation of correlations (y , D_{max}) and (y , s_{ech}). Note: the notations correspond to those in (Figure 17).

the strongest erosions were recorded in profiles TP3 and TP4 (representative of this situation are the longitudinal profile (Figures 4 and 16) and (Table 5 and Figures 8 and 17). After the Ad2b pipe (TP4 profile), the right arm has the shape of a diffuser, a situation that reduced the water speed and favored the formation of alluvium deposits (Figure 3).

4. Discussion

The methodology and calculation program developed is being improved to consider some aspects that intervene in the process of perimeter erosion of riverbeds. An aspect taken into account is that of the “paving phenomenon” of the bottom of the bed, which can modify some simulation results. The frequent and high-flow floods produced in the research area revealed the rapid dislocation of the pavement and the local appearance of erosion pits alternating with sediment deposits.

Research on the erosion of riverbeds in the presence of constructions located in the flow section is many and diverse in subject matter. The most frequent refer to bed erosion in the area of bridge piles [24, 25] or in the downstream section at river spillways.

But, the bibliographic references about the erosion of riverbeds in which pipelines that undercross the flow section are placed are relatively few. In the case of a bed formed by a rock with high mechanical resistances, the pipelines positioned in the sub-crossing are protected against erosion by the rock layer and protective constructive elements. In this context, making a comparison with other similar research was difficult at the time.

Beds formed in weakly cohesive rocks are excessively affected by the phenomenon of hydrodynamic erosion, a situation in which the pipes mounted in sub-crossing at a certain depth will also be more accessible to erosion [19–21]. This erosion phenomenon is similar to that formed at the pipelines located on the bottom of the sea [17].

From the research carried out by Chiew [17], it follows that the piping parameters are the dominant cause of the initiation of vertical erosion in a pipeline placed on non-cohesive sediments. Erosion occurs downstream of the pipeline, and the phenomenon is similar to that produced after a bottom sill located in a riverbed.

A hydraulic model research of hydrodynamic erosion in the river bed is presented in the paper [15] but for the purpose of predicting the roughness coefficient for different forms of the sediment layer. Research of this type was used to process the roughness coefficient on the perimeter of the bed used in the research.

In the transverse profiles Tpc1, Tpc3, Tpc4, and Tpc5, topographic measurements were carried out in 2015. The measurements indicated an erosion depth of the bed bottom of about 0.47–0.62 m in the profiles Tpc3, Tpc4, and Tpc5. The formed erosion depths exceeded the value of those predicted by the design calculations [21]. This aspect indicates the importance of creating a program for modeling the phenomenon of perimeter erosion on a short length of the river. Monitoring of the phenomenon of hydrodynamic erosion in the area of pipelines under the river beds can be achieved much more efficiently by combining hydraulic and numerical modeling.

5. Conclusions

The design of pipeline undercrossing constructions through riverbeds, as well as the monitoring over time of their safety in operation, requires the most accurate knowledge of the erosion depths on the watered perimeter of the bed in the site area.

The hydraulic-mathematical model developed aims to determine the unitary shear stresses and the pulling speeds on the perimeter of the riverbed and compare them with the admissible limit values in order to evaluate the erosion depth. The simulation model also determines the thickness of the eroded sediment layer and the maximum diameter of the solid particle entrained in the river bed.

The modeling program has the advantage of a comprehensive analysis of the erosion phenomenon on a river section with a variable width and a large number of cross-sections, taking into account the variable geometry of the river bed. The computational software has the advantage of processing geometric, hydraulic, and hydrological parameters along the length of the river sector and in no nodes of the cross section.

The model for simulating the phenomenon of hydrodynamic erosion on the perimeter of the riverbeds involves conducting in-depth topographical, hydrological, hydraulic, and geotechnical studies in order to obtain viable data for analysis, as well as for the design of undercrossing constructions.

Appendixes and nomenclature

h , [m]	water depth
Z , [m]	the absolute level of water
A , [m ²]	cross-sectional area of flow
P , [m]	wetted perimeter
R_h , [m]	hydraulic radius
B , [m]	width of water surface
C , [m ^{0.5} s ⁻¹]	Chézy coefficient
Q , [m ³ s ⁻¹]	discharge
V , [m s ⁻¹]	average speed of water
n , [s/m ^{1/3}]	roughness coefficient (Manning)
W , [m s ⁻¹]	speed module
K , [m ³ s ⁻¹]	flow module
Z_{tv} , [m]	the elevation of the bottom of the bed
$Z_{nIn\Phi}$, [m]	the elevation of non-flooding
h_{GV} , [m]	water depth in GVPM
Zh_{GV} , [m]	absolute level of water in GVPM
τ [Nm ⁻²]	the training stress at the bed bottom
p_D , [%]	the percentage of the sediment sample
s_{ech} , [m]	thickness of the sediment layer
g , [m s ⁻²]	gravitational acceleration
ρ [m s ⁻³]	water density
L , [m]	length
I_h , [–]	hydraulic slope
D_{max} , [m]	maximum diameter of the dragged particle
x, y, z	axial coordinates

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u	uniform movement
cr	critical state of motion
GVPM	varied gradual non-uniform motion

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Chapter 4

Social Constructs of the Living Environment through Nature Sports Practice's Locations and Attitude of Public Authorities towards Peri-Urban Natures

Damien Féménias, Barbara Evrard and Olivier Sirost

Abstract

The aim of this research is to understand how the living environment is both constructed through nature sports practice's locations and attitude of public authorities towards peri-urban natures. The scale's observation is the Seine's estuary (1.5 million inhabitants), considered both as an ecosystem and as a system of cities. Results show that the logics of use refers to contrasting social roots, marks ecological inequalities and generates strong territorial appropriations and several typical experiences (secretly deviant, protester, submitted, established). Playgrounds or spots, far from always being consensual, are sometimes tolerated, sometimes obtained with great struggle, when they are not purely and simply poached. These experiences are social constructs as territorial mediations and can be explained by the relationships they maintain with the continuous process of development of the Seine estuary. Territories and the mediations they organize are both and just as much the product of uses as of public development policies. It is therefore necessary to examine both the points of view of the inhabitants and those of the technical or political personnel who represent and lead them. The synthetic re-presentation and discussion of results in the two stages of the discussion are formalized by two typologies that re-inscribe nature sports leisure in the territorial dynamics that shape them and that they structure in return.

Keywords: estuary of the Seine, nature, anthropization, nature sports, territorial mediations, public policies, sustainable development, ecosystem resources

1. Introduction

Deltas and estuaries are dynamic ecosystems, fluctuating and pressurized environments, which are home to a particular and varied biodiversity, in which the aquatic

element plays a central role. The context of the Seine's estuary illustrates the interactions between hydrological processes—the river flows generally come from the chalk aquifer—and human activities: (i) the quality of water resources is conditioned by human activities and (ii) land management requires knowledge of hydrological processes and the associated potential risks to property and people [1]. Inland water systems have long been used for fishing, water supply, agriculture, transport, energy production, industrial production, etc. The strategic importance of waterways has not escaped the attention of political leaders, who have placed them under the control (ownership, management, development) of the State [2, 3]. The developments have accumulated over the centuries and have strongly modified the morphology of the rivers, and therefore their functioning [4].

But waterways are also necessary for our mental and social balance. The modern condition develops a romantic vision of waterways, as well as a number of recreational activities (creative and playful) on and at the water's edge. Leisure activities have taken over the aquatic areas. People like to swim there and relax in front of the flowing water or the passing landscapes. Mills and dams became heritage objects that were restored and enhanced, and the towpaths were used for walking, running or cycling [5]. Nowadays, the entertainment of free time in metropolises owes a lot to the practice of sporting leisure activities. Anyone seeking to localize activities immediately notices the extent to which “green” spaces and bodies of water, whether urban or peri-urban, are taken into account, particularly on sunny days. The cultural revolution of free time [6] is thus part of a reinvention and an extension of the city: metropolitan residents, through their sporting leisure activities, bring out different sites, places and territories [7]. Having become mobile, they move the boundaries of the city [8].

The crowds that flock to the shores during the holiday periods testify to this attraction and encourage us to reflect on the need to take into account the role of social regulation played by waterways. However, the study and development of watercourses has mainly been the work of engineers concerned with managing physical water resources, including their excesses and shortages. Scientifically speaking, geologists and geographers were among the first to study waterways as morphologically structuring their valleys. Ecologists came late, because lakes were easier to study than rivers [4]. Sociologists are still few in number and have recently been looking into the social relations mediated by the “non-human” [9], even though the concerns inherent in sustainable development (as a horizon of meaning and as a form of governance) should make it one of the strong components of planning and reconquest policies.

Focused on the social and spatial distribution of sports leisure on the scale of a system of cities—the Seine's estuary, which is considered one of the most anthropized (developed, urbanized and industrialized) in Europe, this contribution studies the sporting uses of urban and peri-urban natural spaces, and seeks to understand how these activities contribute to the establishment of the living environment of urban populations. What are the territorial mediations at work, whose sports leisure are the crucible and which build the framework of contemporary urban life? This chapter re-inscribes sports leisure in the territorial dynamics that shape them and that they structure in return. This writing distinguishes spaces (spatial properties of practices and objects) and sites (delimited spaces) from territories, which “relate to a collective reading and meaning. [The territory] is at the same time more experienced, more extended and more extensive, less circumscribed, less limited and less closed, therefore more uncertain, but ultimately less imposed by institutions or by language than the place” [10]; the “indigenous” and historically recent terminology of “spot”

designates a delimited territory of practice(s) recognized as such by practitioners (each practice thus has not only its reference “spots” or “high places” but also its “secret spots”); the spot is part of a larger territory of practice, which is also called a playground. These notions involve games of scale. But if the site is only a piece of space, the question arises as to whether and in what forms the spot gives access (or not) to a more global awareness of the territory(ies) in which it is located.

The first part of this chapter establishes the scale of observation and analysis, and presents the aim of the empirical investigations (methods and first results) on which the research is based. The Seine estuary is one of the most anthropized, that is to say, one of the most developed, the most urbanized, the most industrialized and the most polluted in Europe because it constitutes, between Paris and the sea, a coherent strategic axis on an economic level. The surveys [11–13] were sought to understand the experiences of the estuary that produce nature sports leisure activities, so as to provide an original and armed look at its social functions. The first part shows what activities the populations use in this space and how they deploy there. The first and main observation on the ground is that the estuary gives rise to a wide variety of activities, which generate authentic pleasures and strong territorial appropriations. It also quickly became apparent (second observation) that the estuary was a very vast space, very unevenly used and very discontinuous. Observations, interviews and documents reveal (third observation) several typical experiences (secretly deviant, protester, submitted, established) resulting from the development of the Seine estuary and which contribute to urban management. Finally, it appears that these experiences have to be questioned as territorialized and territorializing social constructions, that is to say, as territorial mediations.

Our hypothesis is that these experiences can be explained by the relationships they maintain with the continuous process of development of the Seine estuary. The second part of this chapter is a discussion, in order to understand how do these experiences contribute to the territorial dynamics, and how the scales of the inhabitants-practitioners and those of scientists and managers interfere. Territories and the mediations they organize are both and just as much the product of uses as of public development policies. To understand these products or “social constructs”, it is therefore necessary to examine both the points of view of the inhabitants and those of the technical or political personnel who represent and lead them. The synthetic re-presentation of results in the two stages of the discussion is formalized by two typologies (which distinguish “social worlds”, relationships to different realities and not identities “in themselves” [14]).

Using typologies in comprehensive sociology is already a way of interpreting scattered results, of giving them meaning by re-inscribing them in a meaningful totality (a social world) [15–19]. The production of a typology aims to describe a phenomenon analytically by putting the materials in order. In the context of the research presented here, the two typologies are placed in a perspective of discovery rather than verification, because the surveys were not built on prior territorial hypotheses [20–28]. The territorial issues dealt with here have emerged gradually, according to empirical discoveries and with scientific experience (openness to new research questions) built up in contact with geographer colleagues, with whom comparable research work has been carried out in other fields during the same time (coastline and urban forests). The hypothetico-deductive typologies are usually placed in a perspective of verification and, most of the time, generally based on quantitative formalizations (clusters) that are obtained with the assistance of computer tools [29, 30]. The data collected could be reworked in order to arrive at cluster formalizations: the necessary human

resources are currently not available, and the result is not guaranteed because neither the interviews nor the questionnaires have been standardized around such hypotheses from the outset. The main concerns of the research revolved more around the perceptions of the environments than territorial appropriations. The typological approach presented here analytically describes a previously defined phenomenon by arranging materials in such a way as to make the phenomenon intelligible. It proceeds empirically to identify, by trial and error, the categorization criteria. The basic operations correspond to the principles of plausibility and resemblance, since it is first of all a question of condensing each interview, each observation or each document into a comprehensible memo and then proceeding to comparisons. This operation of comparison/confrontation leads to the constitution of “types” and is structured by constraints, both logical and practical, which impose limiting the number of types and differentiating them “radically” (differentiating between “pure” logics [14–30]).

The discussion proceeds in two stages. The first stage presents the territorial mediations in which the leisure experiences are part and that they generate. The territorial mediations at work can be better understood by using a first typology, which crosses two variables. The spots (**Table 1**: territorial mediations) can be distinguished by (i) the level of consensus, which defines them in their recreational function and, second, based on (ii) their location, depending on whether or not they encroach on spaces considered strategic for the economic development. Four constructs of the living environment through sports leisure activities emerge, which integrate all the cases observed and offer an interpretation of territorial mediations on the scale of a system

Sports leisure	Nb. cit.	Fréq.
Bathing, swimming	900	74,30%
Beach games	504	41,60%
Hiking	279	23,00%
Bike	199	16,40%
Running	162	13,40%
None	114	9,40%
Fishing	100	8,30%
Sailing	67	5,50%
Skate, BMX, roller	61	5,00%
Kite	57	4,70%
Horse riding	48	4,00%
Motorized water activities (jet-ski, motorboat, etc.)	42	3,50%
Scuba diving and freediving	34	2,80%
Rowing activities (canoeing, kayaking, stand up paddle, etc.)	26	2,20%
Gliding activities (surfing, body boarding, skim-boarding)	15	1,20%
13 other activities were reported (not shown here)	- de 15	- de 1%
TOTAL	1212	

Table 1.

Sports activities practiced by the respondents after recoding (n = 1212). The number of citations is higher than the number of respondents because of multiple possible answers.

of cities: spots or playgrounds, far from always being consensual (nature devices), are sometimes tolerated (diverted interstitial natures), sometimes obtained with great struggle (disputed natures), when they are not poached (poached natures—generally degraded and forbidden natures).

The second part of the discussion completes the previous one by reversing the perspective adopted on the territories and by questioning the attitude of the public authorities towards the natures previously described and characterized on the basis of the levels of consensus relating to their destinations and uses. The second typology complements the previous one and builds on it: it is content to turn the perspective on these mediations, by no longer examining these mediations from the point of view of practices (and practitioners), but from the point of view of the public authorities that administer these territories. These territories relate to levels of consensus on the one hand and levels of intervention by public authorities on the other hand, which allow them to be observed in a new light. A second typology presents four typical attitudes of public authorities (planner, liberal-tolerant, negotiator, looks the other way).

2. Observation scale and empirical investigation

2.1 The estuary as an urban network and as a territorial system

The Seine estuary is defined (for the scientific community, which is still working on, in the Seine-Aval Public Interest Group's (GIPSA's) programs) by zone of influence of the dynamic tide on a watercourse; for the Seine, it currently finds its upstream limit at the Poses dam. The Seine estuary corresponds to the last 160 kilometers of the river: in its meanders, it accommodates a 93% urban population of around 800,000 inhabitants, concentrated in two main towns, Rouen (Rouen-Elbeuf-Austreberthe Community: 495,000 inhabitants) and Le Havre (Agglomeration Community of Le Havre: 250,000 inhabitants), which are home to two seaports of international importance. The Seine estuary presents itself as a system of towns, which has seen its population multiply by 4 over the last two centuries [31]. The territory considered here corresponds to the meanders of the river and the coastline. The Territorial Development Directive for the Seine Estuary (DTAES, BO of July 12, 2006), which works based on data from the 1999 census and defines a larger territory, estimates for its part at 1,550,000 the number of residents, two-thirds of whom live in urban areas (840,000 in the three urban areas of Caen, Rouen and Le Havre; 150,000 in the numerous medium-sized urban areas) [32].

This urban network of course has a history and, as in most European estuaries (Clyde, Elbe, Scheldt, Gironde, Loire, Severn, Solent, Weser...), the historic port city at the bottom of the estuary (Rouen) has retained its role as a regional metropolis, even if the majority of port activities now fall under a more recent town, located downstream: Le Havre [33]. The estuary has undergone the same migratory phenomena—rural exodus/urbanization then reurbanization—as those which have been observed elsewhere in France: the two metropolises have developed by spreading out, Rouen downstream, Le Havre upstream, while medium-sized towns have emerged between these two urban centers, notably under the effect of new industries (Communauté de Communes Caux Vallée de Seine: 68,000 inhabitants). Initially peri-urban, the phenomenon of rurbanization [34] is increasingly expanding in space. With the rise of urban areas, urban space is moving out of the city. The scale for understanding this sprawl takes the enlarged port areas as a reference. If the Seine

estuary is today one of the most developed and one of the most polluted in Europe, we understand that the living environment plays a determining role there, which generates a divide within the urban areas between low-valued industrial and worker sectors and residential or tertiary areas that are increasingly sought-after by households in a situation of upward mobility (**Figure 1**) [35].

This urbanized system includes natural areas, some of which are precisely protected “from” the city (Boucles de la Seine Normande Regional Natural Park, Estuary Nature Reserve, etc.). The Boucles de la Seine Normande Regional Natural Park, formerly Brotonne Regional Natural Park, was created on May 17, 1974; it extends over 80,000 hectares and concerns 72 municipalities, including two port cities (Rouen, Le Havre).

The Seine estuary constitutes a territorial system whose complexity takes multiple forms and which is due to two main fault lines: the economic and political domination of the upstream (Île-de-France) over the downstream (two regions of Normandy subjected to Parisian interests) adds a social and cultural divide between the right bank (industrial and proletarian) and the left bank, agricultural and recreational, for Paris. What is at stake here is “the confrontation of local interests and Parisian influence, the large industrial conurbation and high-end tourist areas. It is the coexistence of the main French petrochemical platform and natural areas of ecological interest at European level” (**Figure 2**) [36].

2.2 The estuary of practices: Survey methodology, first results

The surveys [11–13] were sought to understand the experiences of the estuary that produce nature sports leisure activities, so as to provide an original and armed look

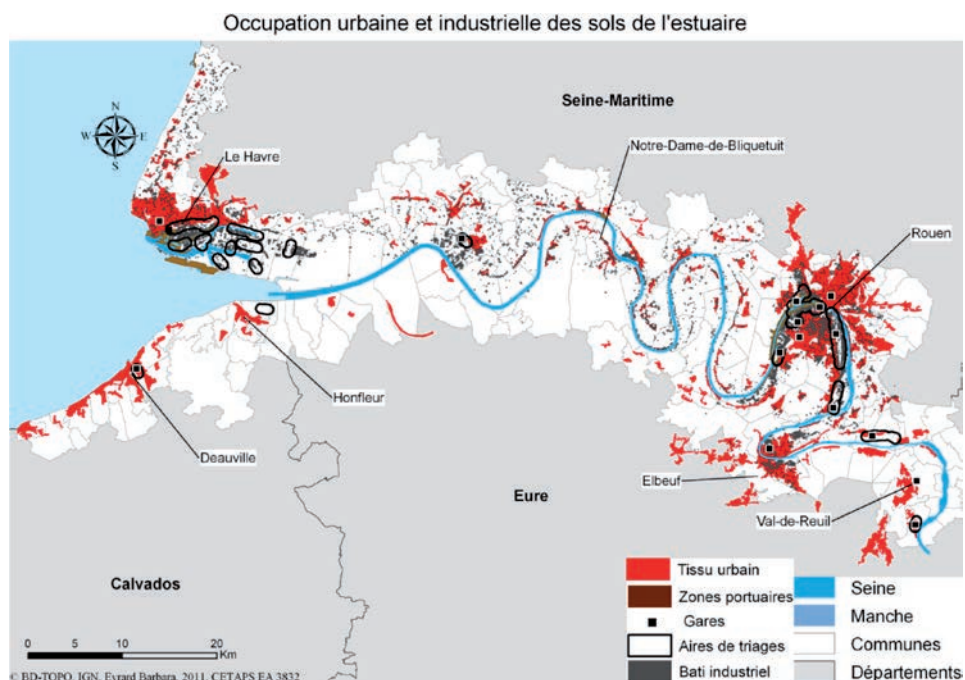


Figure 1.
Urban and industrial land use in the Seine's estuary.

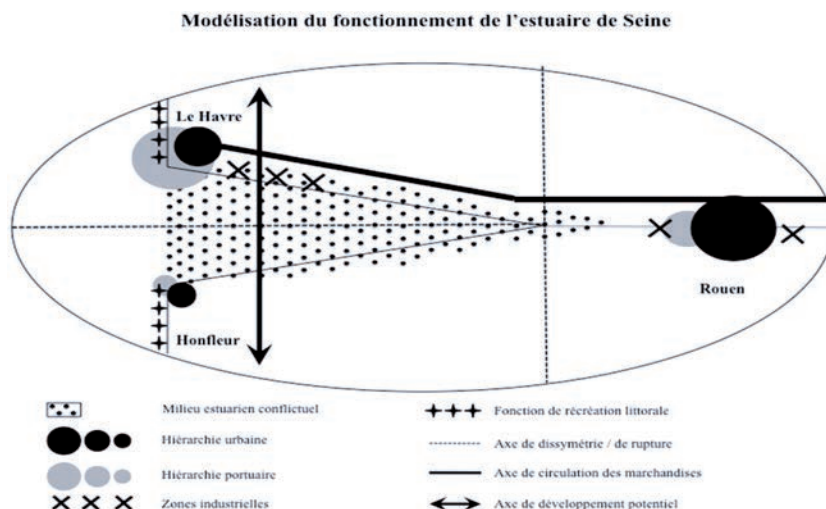


Figure 2.
 Model map of the Seine estuary adapted from the model developed by Brocard and Lecoquierre [36].

at its social functions. The aim of identifying social uses and perceptions through empirical surveys was to provide scientific knowledge (multidisciplinary, sometimes interdisciplinary and for the first time in the program from sociology) of the ecological state of the estuary and its evolutions. The two scientific questions “how is the estuary?” and “how is the estuary evolving?” were intended to enlighten the decision-makers-managers, the funders of the program [gathered in the Seine-Aval Public Interest Group (GIPSA)], responsible for answering the (political) question “what estuary do we want?”. The data were produced by surveys (4153 questionnaires, 80 interviews) that were carried out on nature sports and nature leisure in the Seine’s estuary. The purpose of each of the surveys was to question the perceptions generated by the uses of each fragment of the Seine’s estuary (riverbed, beaches at the mouth, banks, related bodies of water).

The approach adopted in these surveys multiplies the empirical insights into the subject, cross-references data that are different in nature (constructed by questionnaires, interviews, ethnographic observations, document analyses, etc.), multiplies the interlocutors (elected officials, public services, associations, users, companies), in order to put mediations (historical, social, cultural, spatial, “natural”) into perspective, and to multiply comparisons by using the typological approach [14, 30]. The results presented relate to the sporting practices that take place at the water’s edge, whether it be the river (the Seine) and its tributaries, its mouth and its coastal beaches (Côte Fleurie and Côte d’Albâtre) or its closed bodies of water, equipped with Outdoor and Leisure Bases (BPALs).

Each data collection campaign mobilized, in addition to the authors (two statutory teacher-researchers responsible for the projects), between four and six contractual survey managers, recruited over periods of two to three months. During the surveys on nautical practices (2007), on recreational sports on the banks (2009) and on the 24 hours of motorboating in Rouen (2011), the respondents were selected from the insights (This term, initially proposed by Maurice Halbwachs to characterize the forms of relationship to space, finds its extension in Augustin Berque, who sees in the oecumène a dynamic of reciprocal connections) that they developed, through

their practical experiences, on the river. The sampling technique consisted of searching, activity by activity, for practicing populations active on the Seine or on the banks of the Seine. For the riverbank survey (2009), we sought a compromise between two contradictory poles, since on the one hand, it was necessary to work on the entire length of the estuary (its two banks, its places and landscapes) and to understand how the managers and users of these spaces identified them (24 sites, located between Poses and Tancarville, were surveyed), and on the other hand to deal with resources that are by definition limited. We therefore identified the moments and places of gathering (the “events”) to have a substantial body of questionnaires, and we favored an ethnographic approach on “withdrawal” practices and on the most confidential sites. The last phase of the program (2010) focused on six sites located at the mouth of the estuary, between Le Havre and Houlgate, and the three main BPALs, located in Léry-Poses, Bedanne and Jumièges. On the bases as well as on the coastal beaches, we proceeded by coring (among all those present) and from a prior identification of the practice areas. A total of 4153 questionnaires were collected during these various surveys and made it possible to cover most of the recreational areas of the estuary. The questionnaires were used exclusively with active athletes. The choice of delivery areas is first subject to an identification and inventory of the sites, practices, audiences and events taking place there.

Nearly 40 sites were surveyed, spread across the entire downstream part of the estuary (between Poses upstream and Le Havre/Houlgate downstream). This mapping is already a way of thinking about the sample of athletes and its characteristics. It fairly faithfully accounts for the liveliness and very heterogeneous use of the river’s length, and reveals that a large part of its banks (which remains to be measured, but which is estimated at 50%) is inaccessible. It also shows that sports gatherings take place in the most densely populated areas, and that the least urbanized areas of the estuary (left bank of the Boucles de la Seine Normande Regional Natural Park (PNRBSN), Vernier marshes, Estuary Nature Reserve) have been studied exclusively qualitatively. Overall, the surveys were carried out in spring and summer during social times conducive to leisure (evenings, weekends, vacations and public holidays).

The 80 interviews collected, qualified by convention as “semi-directive”, constitute an additional source of information, essential for understanding the meaning that planners, managers, elected officials, athletes, etc., give to their estuary practices. An observation of the different sites was carried out and each spot was the subject of photography campaigns [37]. The questionnaire survey sessions were also an opportunity to take notes on the weather, the atmosphere felt, the individuals present and the activities in which they engaged as well as on the arrangement of the facilities (heavy or light) on the different spaces. Locations are systematically identified with a view not only to qualifying the organization and uses of the estuary, but also to better situate them in their interrelation with other sites and other practices. Each of the investigations was also the subject of a collection of documents produced by the actors (stakeholders’ information documents, number of members or those registered for an event, promotional documents, etc.). Working on documents produced by stakeholders first requires knowing the author. For some, like town planning documents, the source is easily identifiable (the municipality). Second, when it comes to producing a report on a project, it becomes important to know the data production methods used. The quality of the data collected may actually vary and interest us directly or not depending on whether the report is carried out at national, regional or

departmental level, for example. Finally, it may also be necessary to know the target audience in order to place the document produced in its context.

The questionnaire survey carried out in 2007 on nautical uses of the river surveyed 43.7% of licensed sportsmen. These uses are overwhelmingly (75.9%) the work of educated men (42.6% of higher education graduates), among whom executives are overrepresented and workers absent. Licensed athletes, more frequently and more regularly active on the Seine than others, provide access to the benchmarks that shape experiences of the river, which institutions transmit. The majority of nautical experiences on the river involve gentle, instrumented and slow gliding activities.

When we ask the respondents what water activities they practice in the Seine, we discover that they indulge in multiple leisure activities on the river, which appears to be an authentic playground.

A second survey, carried out specifically among the teams (pilots and mechanics) of the 24 hours of motorboating in Rouen, reveals a minority of enthusiasts, fans of motorized speed. These handymen are again overwhelmingly men, among whom employees and craftsmen/business leaders are overrepresented: their experiences of the river are both diverse and motorized.

For the population of athletes interviewed on the banks, the most declared sporting practices (as main activity) correspond fairly closely to the results presented by the national surveys. The banks of the river once again constitute a real and appreciated playground, which we explore in multiple ways, with multiple activities.

Let us also note that the declared activities are ambulatory or traveling and have a discreet presence of traditional activities driven by the land.

A total of 1212 respondents make up the coastal beach sample, including 60.2% women and almost a quarter of students. The respondents come from the middle and upper social classes, and 43.6% hold a diploma higher than baccalauréat (bac +2). As many as 90.6% of those questioned on the beaches said they practiced a sporting activity on the Normandy coast (0.3% no response and 9.4% "no sporting leisure" responses). **Table 1** gives an overview of the diversity of activities carried out on these sites.

The sample of those interviewed on the leisure centers presents very specific characteristics if we compare it to the populations of other surveys carried out in the estuary: if the bases seem to attract, like the coastal beaches, more women (57.5%) and the youngest, they also welcome more inactive people (40%), more employees (38.6% of active workers present) and workers (22.6% of active workers present), which clearly positions them like the popular practice territories of the estuary. If locally elected officials today tend to consider the bases as a product with tourist appeal, the survey shows that they provide a social function, in accordance with their original vocation, and are presented above all as local recreational spaces (87.7% of respondents come from neighboring towns).

However, when we cross-reference the socio-professional categories with the activities carried out on the different survey sites, we see that the two variables are not independent: the unemployed and the inactive are either under-represented on the practical spots, or over-represented in activities such as swimming and napping/tanning, on coastal or BPAL beaches. The working classes benefit from the development of the body of water when it is located nearby, but benefit, including in the BPAL, rather less than the others from the peri-urban nature available; the most athletic are also the most mobile, the most senior, from higher categories. Everything suggests that those who are active in the natural landscapes of the estuary, who travel and survey them, are culturally equipped to do so.

Finally, we note that the practitioners interviewed by questionnaires in the Seine estuary are city dwellers who live in the large towns of the watershed, a maximum of 250 kilometers away. **Figures 3 and 4** also show that the presence of Parisians is especially evident on the coast (mainly lower Normandy).

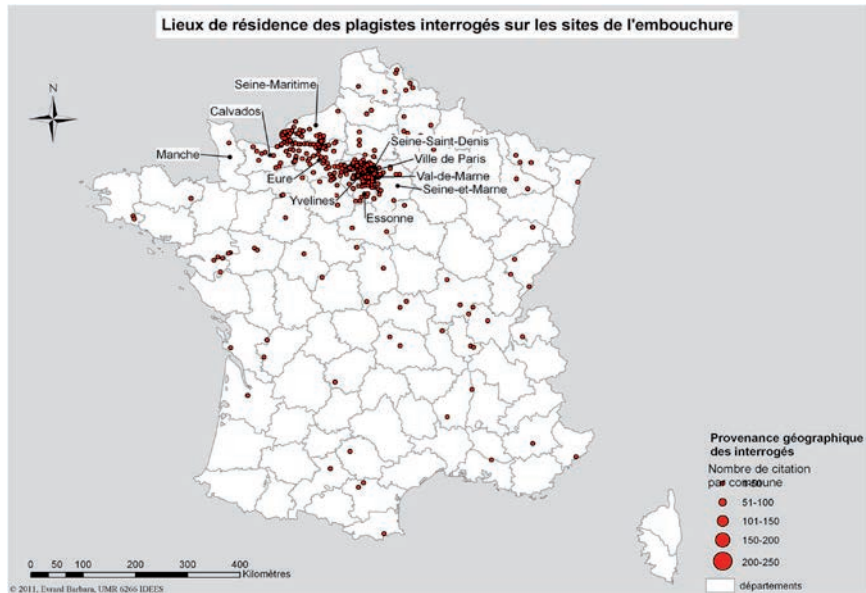


Figure 3.
Main residence of the respondents on the beaches of the mouth.

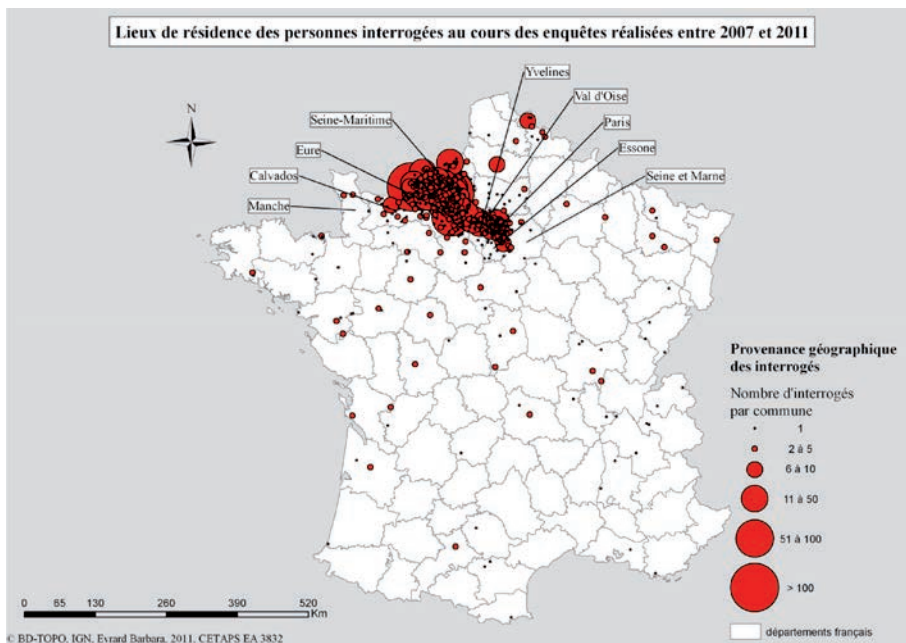


Figure 4.
Main residence of the practitioners throughout the program.

Questioning this map allows us to learn many lessons, which cannot be explained in detail here. Let us say that those who gather in the estuary for sporting events mainly live nearby, in the large towns of Rouen and Le Havre; the activities produce migrations that are essentially oriented and magnetized to the west: the Rouenners are more numerous to participate in the sporting events that take place along the river. Everything happens as if the sea keeps the sportsmen closer to the coastline, and as if the Parisians cross the estuary more than they travel along it. Basically, the data acquired by questionnaire mainly tell us about athletes who frequent nearby peri-urban areas but do not live there.

The first part shows what activities the populations use in this space and how they deploy there. The results reveal a wide variety of practices. The first and main observation on the ground is that the estuary gives rise to a wide variety of activities, which generate authentic pleasures and strong territorial appropriations (attachments to places). We have already shown in Ref. [38] that the driving logic specific to each practice generates specific perceptions and appropriations of the estuarine ecosystem, and that the activities gave access to fragmentary forms of social awareness of the estuarine environment (ecosystem and even anthroposystem). In order to account for these “lived worlds”, we speak of fragmentary perceptions of the ecosystem: the whole of the estuary is revealed in each of its parts, in each of the habitats. There is ordinary estuarine awareness on the part of the practitioners, who are sensitive to the changing conditions of the environment they frequent.

It also quickly became apparent (second observation) that the estuary was a space that was both very vast, very unevenly used and very discontinuous. The estuarine scale as such is only very rarely mobilized by practitioners and inhabitants (third observation), who speak instead of bodies of water, courses and loops (meanders), which are all functional landmarks on the scale of their specific practices. Although they perceive the estuary by its manifestations (tides, winds, precipitation, flora, fauna, etc.), inhabitants and practitioners do not use common sense reasoning on the estuarine scale.

Observations, interviews and documents reveal (fourth observation) several typical experiences (secretly deviant, protester, submitted, established), which will attract our attention here. Our hypothesis is that these experiences result from the development of the Seine estuary and contribute to urban management. People sometimes say they are satisfied with the areas of practice they frequent for walking, running, cycling, sailing, camping or fishing, which seem to them to be of good quality overall, and above all designed and adapted to the uses they make of them. We will qualify these experiences as established. This attitude is opposed to the protest behavior of those who make their voices heard and openly challenge the developments or development projects that the public authorities impose on them. Practitioners sometimes say they are hindered, embarrassed in their practices, which they develop legally and under the control of the authorities, with discretion, in territories that are devoted to other uses, priority over their own: we call this experience submitted. Long and careful observation, the most successful exploration, finally makes it possible to discover very discreet if not secret practices. Long and careful observation, the most accomplished exploration, finally makes it possible to discover very discreet if not secret practices, clandestine and secretly deviant practices, certainly rare but very real, which consist of acting outside the legal framework, or which openly (consciously) transgress the regulatory framework (**Table 2**).

In short, it appears that these experiences, in order to be explained, have to be questioned as territorialized and territorializing social constructions, that is to say, as

Leisure experiences	Secretly deviant	Protester	Submitted	Established
Swimming	All along the river	Saint Jouin Bruneval (Antifer)		Leisure quays, seaside resorts, open-air centres
Cycling	towpaths, wasteland and industrial-port wasteland			Leisure quays, seaside resorts, open-air centres
Walking and Running	towpaths, wasteland and industrial-port wasteland			Leisure quays, seaside resorts, open-air centres
Sailings and rowings			All along the river	On the river and on the sea, under pressure
Camping	industrial-port wasteland: Octeville cabins			Seaside or riverside resorts, open-air centres
Fishings, huntings or animal conservatories	Port's areas, Octeville, temporary dispositions	Saint Jouin Bruneval (Antifer) Natural Reserve of the Estuary Animal Parc of Roumare PNRBSN		Leisure quays, seaside resorts, open-air centres

Table 2.
Leisure experiences (territorial experiences) observed.

territorial mediations. The objective of the discussion to follow will be to relate these experiences to the relationship they have with the ongoing process of development of the Seine estuary and management of this large-scale development.

3. From practice frameworks to living environment: Leisure and territorial mediations

The leisure estuary brings together very diverse activities in an area that is both very vast, very unevenly used and very discontinuous. Is this fragmentation conducive to or does it shield an awareness of the estuarine anthroposystem? How do the practice spots interfere with the visions and developments of the estuary? Do they make these developments acceptable and do they participate in their design or in their contestation?

The survey shows a diversity of territorial mediations at work, which can be accounted for using a typology, by crossing two variables. We can first differentiate the practice spots based on the level of consensus, which defines them in their recreational function and, second, based on their location, depending on whether or not they encroach on spaces considered strategic for the economic development. Four forms of construction of the living environment through sports leisure activities emerge, which integrate all the cases observed and offer an interpretation of territorial mediations on the scale of a system of cities (**Table 3**).

Territorial mediations, building forms of living environment carried out by sports leisure activities		Location/position of practice spots	
		On the fringes of the economic corridor	Encroachment on the economic corridor
Attitudes towards developments	Consensus or consent of practicing populations	Resorts, Quays, Cycle routes 1. Natural devices equipped and promoted for the leisure of urban dwellers	Nautical uses, swimming in the Seine 2. Interstitial natures: sacrificed but diversions tolerated
	Resistances of practitioners to development projects and their consequences/impacts	Octeville cabins, fishing mountain biking on land waves 4. Degraded and poached nature, “secret” uses	Antifer; PNRBSN; Estuary Natural Reserve, Animal Parc of Roumare 3. Disputed natures, snatched away by compensatory measures

Table 3.
Territorial mediations, social constructs of living environment carried out by sports leisure activities.

3.1 Nature devices equipped and promoted for the leisure of urban dwellers

Beyond the historical, social and cultural heritages that differentiate them, there are playgrounds defined and delimited as such. Seaside resorts refer to the advent of leisure [39], which saw in the nineteenth century a “leisure class” 1. Nature devices equipped and promoted for the leisure of urban dwellers [40] appropriate spaces left vacant (the sea, “territory of the void”) [41] and reinvent, particularly through sports, ways of creating an elite and creating a society. From this point of view, Deauville offers, unlike Dieppe or Trouville that existed before their emergence as “stations”, the example of a city created ex nihilo in 1859, as an outlet from the marshes [42]. No prior popular establishment risks stopping worldly success: the conditions of self-confidence are met, allowing high society to consider extended stays in this homogeneous collective group [43]. Generally speaking, the resorts offer a natural setting to contemplate, and a new setting for socialites to deploy. Sea bathing also renews the benchmarks of attention to oneself—the hygiene of the origins becoming more esthetic with the rise of a playful imperative, such as those of the view of nature, which very early on must be protected in order to be exposed to it [44, 45]. The sea becomes a value and a setting, a perspective of oneself in nature, which architects arrange and developers make profitable.

The Outdoor and Leisure Bases have been part of development plans, which, close to towns, have been part of the circular of January 20, 1964, which provides recreational spaces open to all. These versatile and scalable sports complexes primarily benefit cities that have built up significant land reserves in peri-urban areas [46]. In the Seine estuary, this equipment is part of the plans carried out by the Basse Seine Development Mission, which in 1968 became the Basse Seine Public Establishment (EPBS). This pioneering establishment has succeeded in sustaining its action, despite an administrative history made up of fratricidal struggles [47]. At the time, the EPBS prepared the lower valley to “welcome Paris without suffering it”, developed a culture of land anticipation in communities and supported them in their projects. Located in counterpoint to new towns (Le Vaudreuil for that of Léry-Poses) and on the outskirts of dense housing areas (Rouen for that of Jumièges, Elbeuf for that of Bedanne), the

BPALs structure the leisure policy [48] and function as laboratories for equipment engineers, who recover and transform industrial exploitation sites (sand pits, quarries, landfills). These rehabilitations serve today as a model and concrete illustrations for the engineering of sustainable development in the production of public space [49].

Communities are currently seeking to enhance the surroundings of rivers and watercourses: the structures are aging, and the nature and cost of the interventions are questioned. In this context, municipalities pool their experiences (for example: www.seineenpartage.com) and the EPBS supports the economical management of land in large cities by allowing them to “rebuild the city within the city.” Described as “reconquest”, this recycling engineering reabsorbs industrial and port wastelands by producing public recreational spaces. The western districts of Rouen, the Caen peninsula and the southern districts of Le Havre are part of the same momentum, which seeks to reconcile these cities with their maritime environment [50]. The ports, by moving away from historic centers, free up space for town planning (reconversion of docks and quays) as well as entertainment (Voiles de la Liberté which became Armada, local variations of Paris Plage (Paris “on the beach”), departures of the Transat in place of transatlantic connections). Linear or “surface”, these urban interfaces offer joggers, skaters and others an adapted materiality (treatment of surfaces) and an original theatricality (near the port while being in the city), which suit them [51]. Beyond the largest towns, the entire length of the river is planned to be reconverted into a greenway, in order to better weave the network of cities.

Overall, we can clearly see that these leisure systems are all the more consensual as they do not or no longer encroach on territories considered strategic for the development of the economy. They fully participate in the reasoned ordering and sharing of the anthropized spaces of the estuary, present natural esthetic and hygienic to the inhabitants of cities, and in this sense create the city by “gardening nature”.

3.2 Diverted interstitial natures: Discreet uses, tolerated leisure activities

There are also practices that encroach on the economic corridor: the clubs offer nautical uses (rowing, canoeing, kayaking, dinghy sailing, motorboating, water skiing) of the estuary, which are only tolerated. The meanders shelter bodies of water that maritime and port authorities subject to the pressure of dense and imposing commercial traffic: the trajectories of barges and cargo ships are on those of sports associations with absolute priority. In fact, the associations fear repression and accept a domination, which marginalizes them: they submit and discreetly divert the flows of their commercial function. Three main nautical sites stand out, concentrated around the Rouen meander: Hénouville, in the heart of the Regional Natural Park (downstream), Rouen, from Lacroix Island, and finally Belbeuf and Elbeuf, upstream, which open onto the Seine of the islands. From the sea to Rouen, the dikes have transformed a winding river, made up of a multitude of islands and channels, into a “pipe”. Maritime Affairs discourages seeing it as a playground and limits access to the river to sail and motorboats. The descent and ascent of the Seine downstream of Rouen are “strongly discouraged” for boaters, the stops necessary for these journeys are very insufficiently equipped, and the creation of a winter port for pleasure boaters in Rouen, inaugurated in 2008, has been long delayed. The 250 “pranksters” who venture there despite everything in habitable conditions (count of passages in 2007) remain “annoying tourists” for the Seine pilots, who maneuver cargo ships in a channel that they consider narrow. From Rouen to Poses, although largely reworked, the Seine is still dotted with islands, forming numerous secondary or dead arms. Voies

Navigables de France (VNF), more welcoming, opens the river area to leisure activities, with the exception of windsurfing (prohibited), and relegates practices to the backwaters of the river or on its tributaries.

The difficulties encountered by the organizers of the 24 hours of motorboating in Rouen support this reading. Since 1964, the race has followed a circuit that circles Lacroix Island, making the river a speed ring and the city center quays into stands and stands (paddocks). But a fatal accident in 2009 highlights the limits of a voluntary organization, which, despite the local audience and the succession of editions, did not obtain from the authorities the suspension of commercial traffic during the event. On a material level, the event is still based on a diversion of port equipment and does not have any specific equipment. Responsible for the issue of risks and pollution caused by the event, the organizers are trying to mobilize public opinion (in the media, through petitions); this tension, not very threatening for the public authorities (no recourse to the courts, effective mobilization of opinion not very obvious), makes evident the asymmetry of positions: not being in a position to change the rules of the game, organizers and practitioners struggle to save what in their eyes constitutes the essential—the holding of the test and submit to the conditions imposed on them.

The investigation revealed that, against all expectations, informal bathing practices exist in the Seine. Even if the numbers concerned are in the minority, including among those who are regularly active on the river (less than 20% of the 523 surveyed in 2007), it appears that they depend on the complicity in the aquatic element that the practices seal.

Immersion, opportunistic and hedonistic, are the work of “sailors” and kayakers who, accustomed to falling into the “turbid” waters of the river (the quality of which they nevertheless judge severely: 90% of respondents declare the Seine “very polluted” [52]), are not very suspicious of them. Swimming is a diversion to the extent that, without being formally prohibited, it is ignored by public authorities (the sites are not secure, and the quality of the water is far from being certified). Estuarine flows open up, at the heart of a system of cities, multiple possibilities for diversion: nature, even interstitial, remains associated with retreat and alternatives [53]. There are other forms of tactical adjustments [54–56] to the influence of cities, which spring from leisure: protest on the one hand, and dissident reserve on the other hand, indifferent to the injunctions of power, outside of his game. Let us now examine the concrete forms they take in the Seine estuary. If those practicing the Seine “du Parc”, like those of the Seine “des Iles” also swim more than the others, it is because the spots bring into play other sensory landmarks than the city, and are similar to interstitial natures [57] gained from the city (Elbeuf, Belbeuf) or preserved from the city (Hénouville, Léry). The bases shelter elective affinities built on an elementary contact with nature [58]: we camp there, we eat there, we play there together. Each installation, even rudimentary, is valuable for its ability to function as a cabin, and welcomes their families around the sporting activity of members, offering everyone multiple possible recreation options. Interviews and observations show the attachment to places and what links the game and the playground(s).

3.3 Disputed natures, snatched away by compensatory measures

In what way and how is the industrial-port orientation of the estuary contested, negotiated or changed today through leisure activities? Tensions sometimes crystallize through acts of commitment, which, implementing credible threats [59], take the form of conflicts. The latter lend themselves easily to observation, to the extent that

“problems” and power relations are constituted as such in the public space [60]. This type of territorial mediation—conflictual and contestatory—has manifested itself in multiple zones of the estuary [wetlands, valley, coastal zone]: the history of the conflict around the Antifer site shows how sports leisure activities can be registered in such forms of resistance. An oil terminal and sports leisure spot, Antifer allows us to understand to what extent users of the estuary are attached to the fragments of nature that remain available and which they convert into playgrounds. The story of the site and the report of the public debate published online by the Special Commission for Public Debate (CPDP), as well as the actors’ notebooks, the written contributions of the participants, the testimonies published in the press and interviews have already been made subject of an in-depth study [61], which we will simply mention here in order to illustrate a general case.

Antifer beach is originally (photographs of the original site and its transformations are available on Source: www.saint-jouin-bruneval.fr) a narrow strip of pebbles located at the bottom of a valley, in the town of Saint-Jouin-Bruneval: you access it by a dirt road and with the help of a rope to descend a precarious staircase in the cliff. The fishing resource is abundant in the area.

Specialized since the 1930s in the reception of petroleum products [62], the Autonomous Port of Le Havre (PAH) had to find a new site after the war to accommodate ever-larger tankers: the decision to build a terminal at Antifer was taken in 1969. This equipment will require ten years of studies and work and an investment of one billion francs [63]. Deprived of access to the sea, users contest, and a compromise was found in 1976, which granted leisure activities the possibility of developing on this industrial project.

Antifer indeed has many advantages, which make it an exceptionally versatile spot. At low tide, it has become one of the rare sandy beaches on the Alabaster Coast. It is the only site outside the city easily accessible between Étretat and Le Havre, and the vast reservation located at the foot of the cliff offers parking with a capacity of around 900 vehicles. There we find the only launching slipway between Le Havre and Fécamp, with a dedicated parking lot that makes it very functional. Well exposed, the spot is ideal for many activities (motorboat, jet-ski, swimming, fishing, dinghy sailing, windsurfing, kite-surfing, diving, spearfishing, beach games, etc.). Isolated from the town, the site is secure (supervised beach) and welcoming: it has sanitary facilities, games for children, a chip shop and the beach turns its back on the sea wall and the tanks. On the parking side, the “free ride” descents (on rollers, skateboards, longboards, sleds, etc.) of the bends of the access road humanize—by diverting it—the monumental scale of the equipment.

This precarious balance was recently called into question by the PAH which, wishing to make the equipment profitable, wanted to add an liquefied natural gas (LNG) terminal to it: Poweo responded to the call for tenders, and the National Commission for Public Debate (CNDP) was contacted in 2007, in order to promote consultation and gain public support and consent [64]. The protests are numerous and public participation is strong: supporters and opponents of the project confront each other. The desire to preserve a living environment already tainted by what they consider to be a “wart” disrupts public debate. Here, it is not simply a question of NIMBY (Not In My Backyard), it is different visions of society and the coast which confront each other.

For the purposes of the presentation, we will only retain here in a very summary manner the arguments developed by the opponents of the project. The reasons presented introduce debates on the public scene on the appropriateness of the project, on the acceptability of nuisances and on the relationships between the different uses

of space [65]. Counterproposals have been constructed: all play the card of sustainable development, and for some also that of leisure and green tourism. The conflict clearly concerns the exercise of control over space. The reactions all go in the direction of a form of territorial appropriation, which is expressed by marking (graffiti, panels, mascot; on these productions see Ref. [66]) and by use. The mobilized protest collective literally occupies the land, the beach, and animates it (notably through fishing on foot [67]): its omnipresence symbolizes its attachment and its determination, and allows it to exist in the social space [68]. Tools for publicizing the protest, these symbols also produce a discourse and representations on space, the issue at stake in the conflict [69].

Antifer is only one case, which ended in 2010 with the temporary abandonment of the industrial project. Other disputes arise from leisure activities, in the Seine estuary, and are part of the general form of the conflict. The Estuary Nature Reserve (RNE) and the Boucles de la Seine Normande Regional Natural Park (PNRBSN) are two institutions resulting from similar protests, again relating to territories whose urban developments have strongly disrupted ecosystems: urban sprawl in the loops of the Seine—and threats to forests, construction of the Normandy bridge and extension of the port of Le Havre (Port 2000)—and threats to wetlands and mudflats. These struggles have each time been led by collectives who have been able to bring together actors who usually oppose each other (farmers, hunters, ornithologists, professional fishermen, for example, in the case of wetlands [67]). These struggles, which bring the environment into the political game, have often found at the European level (supranational level) the legal levers necessary to lead to (1) the obtaining of measures to protect part of the estuary, (2) on nature governance institutions (RNE, PNRBSN, global estuary management plan, etc.) and (3) on compensatory measures. Whether it is the forests and landscapes of the loops of the Seine (PNRBSN), wetlands (RNE) or the coast (Antifer), we see that these natures torn from the city, which we can call “natures compensation”, entered into politics for the role they play in the dynamics of biodiversity, are also each time defined as recreational and productive natures (reed beds, agriculture/fishing, forestry).

3.4 Degraded and poached nature: Secret uses

The land area of ports and industries is considerable in the Seine estuary. The displacement of production leaves vacant spaces and industrial wastelands which constitute, as long as their recycling is not envisaged or carried out, as much waste land, access to which is more or less explicitly prohibited, which is in any case abandoned and without supervision, without clearly established limits. Many of these areas are “despite everything” frequented and give rise to opportunistic leisure uses: hiking (hiking or mountain biking), fishing (angling, fishing, on foot, etc.), gardening, camping, DIY (do it yourself)... The strategic separation of social functions projected onto the estuary does not alone explain the closure of certain sites to leisure uses. This is particularly the case for a small number of sites at the outlet of the estuary, which are experiencing significant cliff erosion (Cap de la Hève, Octeville). In “closed” theory, these spaces also correspond to nature degraded by the externalities of the urban and economic corridor: the zone thus includes an industrial wasteland (former NATO (North Atlantic Treaty Organization) oil reserve), a boat cemetery, serves (in principle for large) discharge for contaminated sludge, dredged in ports or in the Seine channel.

Fishing on foot thus appears, at the exit of the estuary, as a popular and traditional activity of elderly people, which produces and stems from a strong attachment of users to their living environment. It constitutes for them a way of feeling “alive” as much as a way of feeling “from here”. For the most part, they ignore the prohibitions on practicing and only pay “oblique attention” to their meaning, characteristic of many popular uses [70]. When the fishermen are questioned, they openly declare their intention to continue their practice, even if it were to be banned. It is in this sense that they resist the urban conditions in which they live: the fishing zones, however contaminated they are, function as territories, their own.

A village of cabins is nestled near Le Havre, in the Octeville cliff. This environment shelters, as much as it exposes and destroys, concrete and wooden sheds, the materials of which were transported on the backs of men. These leisure shelters refer to ancient occupation forms of the coast, which today seem to be disappearing: a feeling of precariousness and a scent of prohibition unite the residents against all these “others” (prefecture, town hall, media, scientists, etc.) who would like them to dislodge. A multitude of seaside leisure activities have for several generations weaved original and marginal sociabilities at the heart of this peripheral nature, as contaminated as it is abundant in terms of fisheries.

We will not dwell here on all the uses of poaching, which would require significant developments, and many of which are still the subject of investigation. We will simply refer to works now published, having as their subject fishing on foot at the outlet of the estuary [71], and simply mention the practices of extension and fencing of residential gardens on the paths of river haulage (privatization of the banks), fishing practices on prohibited sites (by line, trap or on foot: in the river, in ports, as well as at the estuary outlet) or transgressive forms of hunting (numerous). All reveal uses and users who remain indifferent to the prohibitions and injunctions of the authorities. It is nevertheless important to mention them to highlight the operational nature of the constructed typology.

Generally speaking, the wastelands of sports and leisure reveal tactical adjustments to everyday conditions, “poached” forms [54–56] of appropriation of the living environment. The clandestine practices that take place there often escape observers, either because they are unaware of them or because they neglect them and forget to take them into account [71]. These leisure activities are not spoken about or displayed: their users form “secret” communities [72]. These wastelands are moving away from the centers of our cities today as the urban becomes more widespread: these peri-urban natures, “degraded” or “limited” for those who adopt the wilderness as their normative reference point, nevertheless bear witness to our landmarks, which have become vague, as to the limits of the city.

3.5 Reversing the perspective: What about the public authorities’ attitudes?

The Seine estuary constitutes a privileged terrain for observing contemporary redefinitions of nature, which are all markers of the generalization of our urban condition. The river’s flows cross and shape a system of cities, integrating into changing uses and definitions of the living environment that evolve with the expectations of populations that have become urban. Differentiated based on the level of consensus which defines them in their recreational function and, on the other hand, based on their location vis-à-vis the economic corridor, the territories of practices reveal four typical forms of territorial mediations on the scale of a system of cities.

The sporting leisure activities of urban dwellers must not only be considered based on the demands for escape into nature to which they respond, but also on the basis of the territorial mediations in which these practices participate. To put it another way, the sporting leisure activities of urban dwellers construct the natural environments that they invest in, and must be differentiated according to whether they contribute to the equipment of nature (sporty by destination, and therefore secure), to its diversion, its redefinition (dispute) or its poaching.

We see that leisure sports practices in fact recompose not only the sharing of nature, but also the horizon of their definition. What the public does in nature questions, by feedback effect, the way in which public policies, which today find in the regulatory idea of sustainable development a horizon of meaning and a form of governance, seize these territorial mediations. These territories relate to levels of consensus on the one hand, and levels of intervention by public authorities on the other hand, which allow them to be observed in a new light (**Table 4**).

There are currently active public policies that think and act strongly on peri-urban natural spaces in their recreational dimension. The State now has three major tools for action and management in this territory [73]. The Territorial Development Directive for the Seine Estuary shows by its existence (there are only 7 in France, and this one dates from 2006) the strategic importance of this area in the eyes of the State: this document of a new type of town planning allows the State to express its position and impose it on communities, while proposing support policies. The EPBS, which has allocated tax resources, constitutes the tool for land control and long-term planning. What we called “nature devices”, which recycle wasteland into recreational nature (BPAL, banks, quays and docks), in fact fully constitute gardenized environments, built and managed with communities, for the needs of city residents. These devices are part of an ideal of dynamic environmental management. Part of this philosophy, the Estuary Global Management Plan (3rd tool, new in 2002), appears both as one more compensatory measure, snatched by protesting groups, and as an alternative to simple protection measures, which tend to pile up without defining an overall vision, to sanctify (sanctuary) without being fully satisfactory and to no longer be able to be discussed. Both restored nature and protected nature respond to nature sacrificed

Attitude of public authorities towards the peri-urban leisure activities		Level of intervention	
		Strong “Managed” natures	Weak (definition of prohibitions) “Abandoned” natures
Type of construction	Consensual	Natural devices: recycling - requalification Resorts, Quays, Cycle roads Direct management and territorial reconversions	Interstitial natures: sacrificed but diversions tolerated Nautical uses, swimming in the Seine Liberal accountability of users
	Conflictual	Disputed natures, snatched away by compensatory measures Antifer, PNRBSN, Estuary Natural Reserve, Animal Parc of Roumare Governance of the nature, accountability of public authorities by activist associations	Degraded and poached nature, “secret” uses Octeville cabins, fishing mountain biking on land waves Ostrich policy / looks the other way: no assistance to people in danger?

Table 4.
Attitude of public authorities towards peri-urban nature.

for the needs of ports and industry, and largely explain the fragmentation of practice spots; in the long-term management of ecosystems, these restoration measures require actors to question not only the natures they wish to construct, the stakeholder interactions that these public problems mobilize, but also their symbolic dimensions, their economic cost, etc.

We also see that there are, by contrast, nature areas in which the public authorities still intervene very little, at least in their recreational dimension: we can qualify these peri-urban nature areas as abandoned, to the extent that users are left to their own devices. The priority given to maritime and river traffic costs nothing economically, at the same time as it subjects and makes nautical associations responsible by relegating them to the interstitial natures that continue to exist. However, there is potential for development, which would easily fit into the symbolic momentum and contemporary reinterpretation of local maritime heritage driven by communities. The degraded nature, and in particular the contaminated waters of the estuary, reveal real ecological inequalities and reflect a mutual incomprehension of public authorities and users. Managers simply prohibit access to sites or the practice itself, without implementing a prevention, information or education policy aimed at the general public. We can wonder if these territorial units and these marginal practices, which expose vulnerable populations, who tinker in a contingent way with the natures that they find in their immediate environment, do not contain the seeds of the protests to come, and perhaps call for new forms of governance.

4. Conclusion: Between fragmentary awareness to fragmented territory

Focused on the social and spatial distribution of sports leisure on the scale of a system of cities—the Seine’s estuary, which is considered one of the most anthropized (developed, urbanized and industrialized) in Europe, this contribution studies the sporting uses of urban and peri-urban natural spaces, and seeks to understand how these activities contribute to the establishment of the living environment of urban populations. What are the territorial mediations at work, whose sports leisure are the crucible and which build the framework of contemporary urban life?

This chapter re-inscribes sports leisure in the territorial dynamics that shape them and that they structure in return. The surveys were sought to understand the experiences of the estuary that produce nature sports leisure activities, so as to provide an original and armed look at its social functions. The aim of identifying social uses and perceptions through empirical surveys was to provide scientific knowledge (multi-disciplinary, sometimes interdisciplinary and for the first time in the program from sociology) of the ecological state of the estuary and its evolutions. The two scientific questions “how is the estuary?” and “how is the estuary evolving?” were intended to enlighten the decision-makers-managers, the funders of the program [gathered in the Seine-Aval Public Interest Group (GIPSA)], responsible for answering the (political) question “what estuary do we want?”. The data were produced by surveys (4153 questionnaires, 80 interviews) that were carried out on nature sports and nature leisure in the Seine’s estuary. The purpose of each of the surveys was to question the perceptions generated by the uses of each fragment of the Seine’s estuary (riverbed, beaches at the mouth, banks, related bodies of water).

The first and main observation on the ground is that the estuary gives rise to a wide variety of activities, which generate authentic pleasures and strong territorial appropriations. It also quickly became apparent (second observation) that the estuary

was a very vast space, very unevenly used and very discontinuous. Observations, interviews and documents reveal (third observation) several typical experiences (secretly deviant, protester, submitted, established) resulting from the development of the Seine estuary and which contribute to urban management. Finally, it appears that these experiences have to be questioned as territorialized and territorializing social constructions, that is to say, as territorial mediations.

Our hypothesis is that these experiences can be explained by the relationships they maintain with the continuous process of development of the Seine estuary. The second part of this chapter is a discussion, in order to understand how do these experiences contribute to the territorial dynamics, and how the scales of the inhabitants-practitioners and those of scientists and managers interfere. Territories and the mediations they organize are both and just as much the product of uses as of public development policies. To understand these products or “social constructs”, it is therefore necessary to examine both the points of view of the inhabitants and those of the technical or political personnel who represent and lead them. The synthetic re-presentation of results in the two stages of the discussion is formalized by two typologies (which distinguish “social worlds”, relationships to different realities and not identities “in themselves”).

The discussion proceeds in two stages. The first stage presents the territorial mediations in which the leisure experiences are part and that they generate. The territorial mediations at work can be better understood by using a first typology, which crosses two variables. The spots (**Table 1**: territorial mediations) can be distinguished by (i) the level of consensus which defines them in their recreational function and, second, based on (ii) their location, depending on whether or not they encroach on spaces considered strategic for the economic development. Four constructs of the living environment through sports leisure activities emerge, which integrate all the cases observed and offer an interpretation of territorial mediations on the scale of a system of cities: spots or playgrounds, far from always being consensual (nature devices), are sometimes tolerated (diverted interstitial natures), sometimes obtained with great struggle (disputed natures), when they are not poached (poached natures—generally degraded and forbidden natures).

The second part of the discussion completes the previous one by reversing the perspective adopted on the territories, and by questioning the attitude of the public authorities towards the natures previously described and characterized on the basis of the levels of consensus relating to their destinations and uses. The second typology complements the previous one and builds on it: it is content to turn the perspective on these mediations, by no longer examining these mediations from the point of view of practices (and practitioners), but from the point of view of the public authorities that administer these territories. These territories relate to levels of consensus on the one hand, and levels of intervention by public authorities on the other hand, which allow them to be observed in a new light. A second typology presents four typical attitudes of public authorities (planner, liberal-tolerant, negotiator, looks the other way).

The physical transformations of the estuary's territories are of course part of a symbolic reality: the horizon of generalized mobility, which makes the contemporary individual a nomad, caught up in multiple loyalties, which affiliate him with territories and groups via practices and esthetics. However, the surveys reveal contrasting social roots and marked ecological inequalities: the natures we use and within which we play have little connection with each other. In fact, this is a way to question these different forms of nature that our cities produce with regard to the public policies that today constitute sustainable development as a regulatory idea (horizon of meaning and form of governance).

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Conflict of interest

The authors declare no conflict of interest.

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Natural Estuarine Flocculation Mechanisms and Dynamics: A Review

Andrew J. Manning, Claire Chassgne, Kate Spencer, Leiping Ye, Xiao Yu, Dan Parsons, Juliet Rounce, Jez Spearman, Jeff Peakall, Deng Zhirui and Tian-Jian Hsu

Abstract

Most estuarine deltas and coastal estuaries globally are dominated by muddy sedimentary mixtures; their transport and fate are the key factors for estuarine management and engineering projects. Mud is typically a combination of mineral particles and organic materials, resulting in sediments that have adhesive properties, and generically known as cohesive sediments. Contrarily to non-cohesive sediments, mud can flocculate into larger aggregates called flocs, posing a serious complication to modelers of estuarine sediment dynamics. Consequently, intensive research efforts in understanding mud processes reflect the pivotal role played by muddy sediments in aquatic environmental systems and the need for informed management and decision-making, especially in estuaries. This chapter aims to comprehensively review scientific progress made in understanding various aspects of muddy sediments over the past few decades. By covering topics such as estuarine sediment composition, cohesion, particle interaction, and flocculation dynamics, this chapter provides a holistic overview of the key subject matter. Background science and theory are included for each topic, along with the highlights from key research contributions and real-world examples. We envisage that this chapter will help readers grasp the complexity of muddy sediments and understand key advancements made in this field. This approach grants deeper understanding of the subject matter and its implications for research and practical applications.

Keywords: flocculation, flocs, settling velocity, cohesion, mud, cohesive sediments, suspended sediments

1. Introduction

Coastal estuaries, as described by Dyer [1], are essential coastal ecosystems characterized by their partial enclosure, direct connection to the open sea, and mixing of

seawater with freshwater from land drainage. An estuarine delta refers to subaqueous and subaerial deltaic deposits that have accumulated within the semiconfined and protected environment of an estuary [2]. These regions have a long history of serving as centres for shipping, commerce, and industrial activities. However, as economies expand, estuaries have become increasingly developed, leading to conflicts of interest between economic development and ecological conservation. The management of estuaries is a complex endeavor that involves balancing these competing interests while predicting the outcomes of various interventions in a continually evolving and complex environment [3].

The majority of estuarine deltas and coastal estuaries worldwide, including salt-marsh and mudflat environments [4] are characterized by the presence of cohesive sediments, often referred to as mud, which is composed of mineral grains from both fluvial and marine sources, as well as various biological matter in different stages of decomposition [5, 6]. Mud is one of the most ubiquitous and consequential materials on Earth [7]. It is the cohesive nature of these sediments that makes them particularly challenging to manage and understand.

The behavior of cohesive sediments in estuaries has significant implications for various aspects of estuarine management and marine engineering initiatives. For example, sediment accumulation in navigation channels and berths often necessitates costly dredging operations. Additionally, new developments can alter sediment transport patterns, making it essential to predict their effects on sedimentation patterns. Furthermore, these sticky muddy particles are known to adsorb contaminants from the water, which can have implications for water quality and environmental concerns [8–11].

Over the past few decades, intensive multidisciplinary research has significantly advanced our understanding of cohesive sediments in estuarine environments (e.g. [12–16]). Dyer [17] proposed key areas that would require research focus on cohesive sediments. Since then, researchers have delved into topics, such as sediment composition, suspended sediments, flocculation dynamics, cohesion, mixed sediments, hindered settling, and floc structure. These areas of study have provided crucial insights into the complex behavior of muddy sediments, and they have practical implications for estuarine management and environmental conservation.

This raises numerous related research questions, such as: How does turbulence influence the size and settling velocity of mud flocs across various riverine and estuarine settings? What are the relative roles of salinity, organic matter, and mineralogical composition in governing the flocculation and settling behavior of mud in freshwater and estuarine environments? In what ways do varying mud-to-sand ratios affect the flocculation process and the resulting settling velocities of mixed sediments? How do biological factors, such as microbial activity and the presence of microorganisms, impact the formation, structure, and stability of mud flocs? What is the impact of flocculation on the settling velocity and spatial deposition patterns of mud in river and estuarine systems? How is floc size distribution related to the development and characteristics of fluid mud layers in cohesive sediment environments? How does the flocculation process affect the resuspension and transport of mud under varying hydrodynamic flow conditions?

The primary aim of this chapter is to present a state-of-the-art review of key scientific advancements in the understanding of cohesive sediment flocculation processes within estuarine and deltaic environments. Framed around the core research questions outlined above, this review seeks to synthesize current knowledge and recent developments while also introducing fundamental concepts of estuarine flocculation to researchers who may not be fully familiar with the complex mechanisms governing muddy sediment dynamics. The specific objectives of this chapter are to:

- i. Summarize the theoretical background underpinning flocculation processes;
- ii. Identify and critically discuss major contributions from empirical, experimental, and modeling studies;
- iii. Illustrate the real-world implications of flocculation dynamics through selected case studies;

Highlight the roles of key-controlling factors, such as turbulence, salinity, organic matter, mineralogy, biological activity, and sediment composition in influencing floc size, structure, settling velocity, and transport behavior.

This review not only serves as a reference point for scientists engaged in estuarine research and management but also aims to guide readers towards relevant and more detailed studies for each aspect of flocculation discussed. In doing so, it underscores the importance of flocculation processes in shaping sedimentary environments and informs strategies for effective estuarine monitoring, modeling, and management.

2. Composition of sediments

2.1 Overview

The lower layers of mudflats often exhibit a dark hue and emit a potent odor, which is a result of the anaerobic decomposition of organic material. In these mudflats, the primary mineral constituent in cohesive mud is clay. While the terms “mud” and “clay” are related, they are not exactly interchangeable. Mud is a more general term that typically refers to a mixture of water, fine-grained sediments, including clay and silt (and even some sand grains), and may also contain organic matter (such as humic acids, fulvic acids, and other decomposed plant and animal material) together with gases such as hydrogen sulphide, which are produced during organic decomposition. Clay particles have a plate-like structure (**Figure 1a**) and are known for exhibiting electrochemical cohesion. Median particle size distributions for clay particles mostly falls between 1 and 2 μm , with diameters spreading between 0.1 and 10 μm . According to conventional soil- and sediment-based classification [19], based on a geometric progression, with each size class being twice the size of the previous one, individual clay particles are smaller than 4 (0.002 mm) and silt particles range from 4 to 62.5 μm (0.002–0.0625 mm), with the division at 62.5 μm , marking the transition from silt to sand grains (> 62.5 μm).

Clay particles possess ionic charges on their surfaces, creating forces that can be as significant as or even surpass gravity. As a result, these clay particles interact electrostatically. In estuarine and coastal environments, these sediment particles do not behave as isolated, dispersed entities but tend to clump together (**Figure 1b**). This phenomenon is called flocculation, and the resulting clusters are referred to as flocs (**Figure 1c**). These flocs are considerably larger in size and settle at a much faster velocity compared to individual particles. However, it is important to note that the overall density of these flocs is lower. Recent research has shown that natural estuarine floc aggregates can reach sizes of several millimeters, which is significantly larger than the 200- μm floc depicted by McDowell and O'Connor [20].

In estuarine (both coastal and deltaic) environments, mud and sand are often found together despite their different physical characteristics. Scientists and

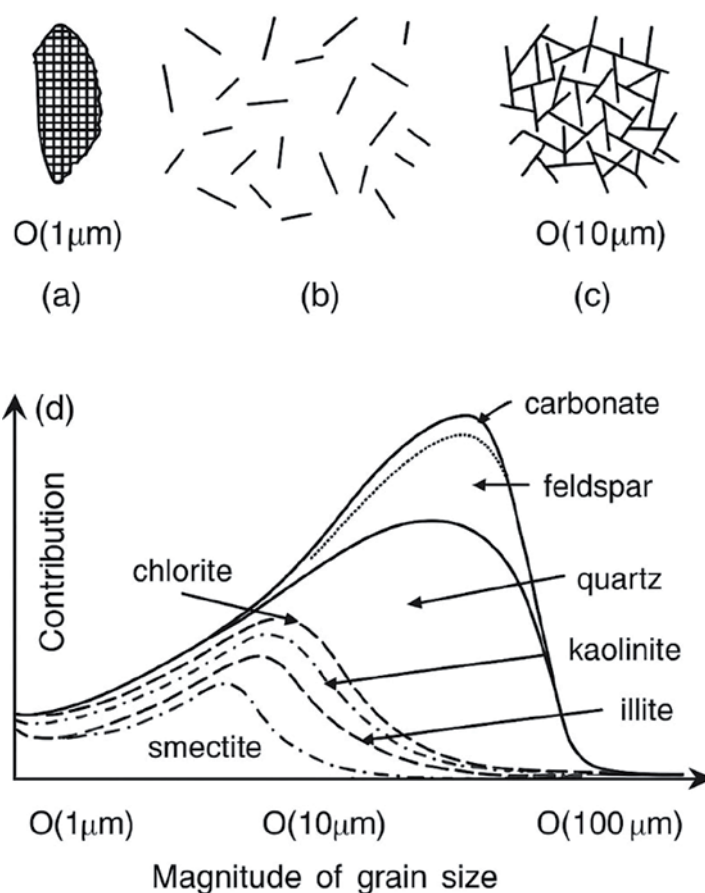


Figure 1. This diagram illustrates some fundamental sediment particle properties ('O' indicates 'order of magnitude'). (a) Individual clay particle; (b) dispersed clay particles; (c) individual floc; (d) Qualitative and conceptualized illustration of the distribution of minerals and mineral grains as a function of grain size for an alluvial mud (loosely based on data for Mississippi alluvial mud as illustrated in [18]). All aspects of this figure have been redrawn and adapted for this article.

engineers use granular classification to evaluate the behavior of sediment, whether it is cohesive, granular, or a mixture of sediments. This classification is important when considering the mechanical and erosion properties of sediment, as emphasized by Winterwerp and van Kesteren [16]. In estuarine areas, mixed sediments typically consist of a combination of clay, silt, and sand grains. It is worth noting that gravel sediments with a diameter greater than 2 mm are rarely found in regions where cohesive sediments are prevalent.

The degree of cohesion becomes more pronounced when the sediment contains a higher percentage of clay, becoming significant when the clay fraction is in the range of 5–10% by weight [6, 21]. Within the clay fraction, there is a subfraction known as the colloidal fraction. Colloidal particles are typically smaller than 0.1 μm in diameter and are usually removed during gravimetric analysis. Due to their extremely small size, colloids are kept in suspension by Brownian motion. Organic colloids are referred to as dissolved organic carbon (DOC) because they are not retained by filter paper during filtration. The interaction of these various sediment components,

including clay, silt, and organic colloids, plays a crucial role in the behavior of estuarine and coastal sediments.

2.2 Mineral composition

Sediments can also be classified by their mineral composition, sometimes referred to as their genetic origin. Lithogenous sediment, such as sands and clays, originate from eroding rocks. Biogenous sediments (organic material) are remnants of organisms and consist mainly of carbonate, opal, and calcium phosphate. Hydrogenous sediments are precipitates from seawater or interstitial water [22]. Mineral composition determines characteristics concerning shape, specific surface, etc. Based on the mineral composition, sediments can be primarily divided into silicates and non-silicates.

Silicate sediments are composed of minerals that originate from the erosion of rocks. Silica (SiO_2) is the most abundant mineral in the Earth's crust and plays a major role in silicate sediments. Silicates, including quartz, feldspar, and clay minerals, result from the weathering of rocks and are common in estuarine and coastal environments. Silicates have various structures, with silica tetrahedra being a fundamental molecular building block. Quartz has a closely packed structure with a hard, stable configuration. While clay minerals, such as phyllosilicates, are composed of 2D silica tetrahedra sheets linked together, they are derived from feldspars, micas, and aluminosilicate.

Contrastingly, non-silicates in cohesive sediments consist of precipitates formed from salts, carbonates, sulphides, oxides, and hydroxides. Their presence depends on specific chemical conditions in the local environment, such as the availability of oxygen, iron, magnesium, calcium, and manganese.

2.3 Clay mineralogy

Clay minerals commonly found in muddy sediments include kaolinite, illite, chlorite, smectite (e.g. montmorillonite), and bentonite. They are easily broken up by natural degradation processes, which act along cleavage planes [12]. Therefore, clay minerals generally occur as plate-like fragments.

Kaolinite originates from alkali feldspars under acidic conditions, such as the weathering of granite in humid tropics. Kaolinite is the principal constituent of English China clay (quarried in the southwest of England, UK). Montmorillonite originates from volcanic activity and is part of a group of clays known as smectites. Illite is formed from montmorillonite that has been buried at great depths (> 2000 m) and chemically through the adsorption of potassium. Chlorite is also formed from montmorillonite, but in this case, it has adsorbed magnesium.

Given that kaolinite and bentonite (montmorillonite) represent end-member clay minerals with respect to viscosity and yield stress, it is postulated that clay minerals exhibiting cohesive properties intermediate to these two – particularly those within the smectite group – are likely to conform to similar threshold Reynolds numbers characterizing the transition to turbulent flow. Common examples of such intermediate clays include illite and vermiculite, whose cohesive strengths are between those of kaolinite and bentonite and thus are expected to align with this hypothesis [23]. This study underscores the pronounced influence of clay mineralogy on flow behavior and transitional flow dynamics.

The structural differences among these clay minerals are in the way their layers are joined, with variations in metal ions and water molecules. The charge of clay mineral layers may be balanced by interlayer cations, such as Na⁺ or K⁺. The crystal structure results from the stacking of these layers with interlayers in between.

2.4 Examples of sediment mineralogy

Different estuarine systems and rivers exhibit variations in clay mineral composition. The relative proportions of various minerals in sediments can vary based on their grain size. For example, clay minerals are often a distinguishing factor between sand and mud.

Whitehouse et al. [6] tabulate the various clay mineral contributions to mud samples from three estuarine systems and demonstrate the importance of montmorillonite, kaolinite, illite, chlorite, and smectite. Uncles et al. [24] investigated the mineralogy of suspended sediment in the turbidity maximum of the Humber-Ouse Estuary, UK. The non-clay mineralogy was formed of quartz, carbonates, mica, and feldspar, and the clay mineralogy was dominated by chlorite and illite. Similarly, the clay mineralogy of intertidal mud in the Tamar Estuary, UK was found to be dominated by chlorite, montmorillonite, and illite [25], while Manning [26] and McAnally et al. [27] report that there is an abundance of kaolinite present within the resuspended mobile sediments in the Tamar estuary.

Results from a mineralogical analysis by Potter et al. [18] of alluvial sediments from the Mississippi River, USA are often thought to be illustrative of alluvial mud from other systems [28]. A qualitative, conceptual plot of the distributions of different minerals as a function of grain size illustrates a clay-sized fraction that is primarily composed of the clay minerals, such as kaolinite, illite, smectite (e.g., montmorillonite), and chlorite (**Figure 1d**). The silt-sized fraction is shown to comprise quartz, feldspar, and carbonates, but clay is still present, whereas clay minerals are non-existent in the sand-sized fraction, so that the distinction between sand and mud is governed by the presence of clay minerals.

2.5 Composition of biological material

Natural sediments in estuaries and coastal environments are typically a mixture of sediment minerals and biological material. The interactions between minerals and organic matter in estuarine and coastal sediments are highly complex and typically influence the behavior of these muddy sediments. Biology can influence all aspects of a sediment mixture's physical behavior, including deposition [29], sediment compositional matrix, bed features, consolidation, and erodibility [30].

The organic component can be as high as 30% by dry weight and may be present in the form of particulate organic matter (POM) or dissolved organic matter (DOM). The organic matter in mud can make up a significant portion of the sediment and regionally can be present in various stages of decomposition. Organic matter consists mostly of organic polymers that are either transported throughout an estuary or are produced locally by biological activity in the sediment bed or water column (see [31, 32]). Organic matter is subject to degradation and alteration during both transport and sedimentation.

Organic substances resulting from metabolic processes of an individual organism are generically termed extracellular polymeric substances (EPS). Berner [33] suggests

that the principal organic materials within the structure of natural cohesive sediments comprise three groups: (a) polysaccharides and proteins composed of peptides and amino acids; (b) lipids and hydrocarbons (e.g., cellulose, lignin); and (c) humic acids. Of the three groups, the first represents organic substances that are recognized as flocculants, the second group is neutral, and the third comprises deflocculants [16]. Different organic substances can either flocculate or deflocculate the sedimentary material, thus impacting their net cohesion and sediment properties.

When organic matter is present in the water column, it is oxidized. However, once it is deposited to the bed and begins to undergo consolidation, it starts to reduce its levels of nitrate, manganese, iron, and sulfur [34]. As these chemical components continue to deplete, the underlying mud layers start to appear dark in color and emanate a strong odor. This process of anaerobic decomposition of organic matter in sediment layers can lead to the formation of gases, such as methane, carbon dioxide, and hydrogen sulphide. The role of biology on the flocculation process is further examined later in this chapter.

3. Estuarine suspended sediment classifications

There have been many attempts to classify the variety of suspended sediment concentration ranges within estuaries. A framework was proposed by the COSINUS – Prediction of COhesive Sediment transport and bed dynamics in estuaries and coastal zones with Integrated NUmerical Simulation models – project, which contributed to the European Commission MARine Science and Technology (MAST) III Research Task B.1.1: Coastal Processes and Morphodynamics.

COSINUS covered the numerical, theoretical, and experimental studies of the processes, which play a key role in sedimentary flocculation, the interactions between turbulent flow and suspended sediment, and the formation of layers of high-sediment concentration in close proximity to the bed (including lutocline generation; [35] – a sharp interface between layers with different suspended sediment concentrations; [36]) and the transition between fluid mud conditions and the formation of the sediment bed [37].

The COSINUS classifications were primarily based on the gradient Richardson number, Ri_g . The Ri_g is a comparison of the destabilizing influences of velocity shear to the stabilizing forces of density stratification, that is, Ri_g is a turbulence indicator and also an index of stability of the flow, and is defined as follows

$$Ri_g = \frac{-g \cdot \delta\rho / \delta z}{\rho_w (\delta U / \delta z)^2} \quad (1)$$

where z is the height above the bed (i.e. positive upwards), g is the acceleration due to gravity, U is the along-stream current velocity, and ρ_w is the density of the sediment-laden water – both at a height z .

Dyer [1] summarizes that when the fluid is unstratified between the two depths, $Ri_g = 0$ (i.e. neutral) and when $Ri_g < 0$ and $Ri_g > 0$, this indicates unstable and stable stratification, respectively. In the main, flow is fully turbulent when values of $Ri_g < 0.03$ (i.e. the shear forces in the flow play a significant role in generating turbulence, potentially outweighing the stabilizing influence of density stratification) and thus under these flow conditions, inconsequential stratification exists.

Effects of turbulence damping attributable to density stratification mostly escalate with Ri_g until the measure approaches 0.1–0.3, where the density is suitably robust that the turbulence is damped out and the flow for the most part becomes laminar in formation.

A detailed overview of the COSINUS classification framework for estuarine-suspended sediment concentration ranges based on the gradient Richardson number (Ri_g) and describes four primary categories. Here is a summary of the key points:

3.1 Dilute suspension

Concentrations generally below 1 g/l and Ri_g are low. These suspensions will have minimal impact on the turbulent flow field. Turbulence is the main mechanism driving suspension. Their behavior is similar to Newtonian fluids, with linear shear stress increase with rising shear rate. They have a constant effective molecular viscosity.

3.2 Concentrated benthic suspension (CBS)

Their concentration can be up to 10 g/l. and Ri_g is now higher than in dilute suspensions. There is notable stratification in the flow, including the formation of the lutocline, and turbulence now plays a crucial role in keeping sediment in suspension. Turbulence is important to keep sediment suspended below the lutocline. Turbulence above the lutocline is attenuated by sediment-induced stable density stratification. CBS layers tend to behave like a Newtonian fluid, but with an elevated viscosity, and are transported within the main flow.

3.3 Fluid mud

Once the suspended concentration exceeds a critical value, typically a few tens of 10's g/l, the particle interactions start to modify the properties of the suspension. Alterations in suspension properties include: floc-hindered settling effects. Ri_g is even higher than within a CBS. The turbulence energy required to maintain a CBS layer with high concentrations is being dampened by buoyancy effects, with energy dissipating due to higher particle collisions. Rheologically, a fluid mud is classified as a non-Newtonian fluid [38]. It has a high viscosity compared to clear water, typically leading to laminar flow. The flocs within a fluid mud form a network structure over time, gradually developing strength and resistance to entrainment, although Toorman [39] indicates that this takes time.

3.4 Consolidated bed

This is typically the formation of a weakly saturated soil (sediment bed), referred to as a gel or gel-like structure. Alternatively, a consolidated bed may result from settling from suspension or transition from fluid mud. When at rest, the weak gel structure can collapse under its own weight. The interparticular bonds within the gel increase in strength over time, expelling pore water. This results in the gradual process known as 'consolidation'.

The COSINUS framework helps categorize estuarine-suspended sediments based on their concentration and behavior in response to turbulence and stratification. These categories are crucial for understanding sediment transport and deposition processes in estuarine and coastal environments.

4. Flocculation process

4.1 Overview of flocculation

Unlike purely non-cohesive sandy sediments, muddy sediments can flocculate into larger aggregates called flocs. In most estuarine (deltaic and coastal) locations, the majority of suspended particulate matter (typically over 90%) exists in the form of flocs [40]. Flocculation is a dominant mechanism governing fine sediment transportation within an estuary. Flocculation is primarily affected by a combination of physical, chemical, and biological factors [16, 41–44]. The flocculation process and mechanisms are depicted in **Figure 2**.

The dynamics of flocculation are crucial for accurate modeling of estuarine sediment behavior, including transport, erosion, and deposition. The entire cycle of sediment movement in estuaries is complex and interrelated, with processes including settling, entrainment, consolidation, erosion, and biological influences affecting each other. Among others, Van Leussen [55] and Kirby [56] conjectured that a quantitative apprehension of the dynamics of the vertical structure of suspended muddy sediments is a requisite for an explicit estuarine sediment transport model.

This necessitates an appreciation of the physical processes coupled with the deposition, erosion, and conveyance of cohesive sediment. In point of fact, the entire sequence of events is particularly convoluted because it does not as a matter of course have to be closed, and processes are mutually dependent. For instance, flocculation

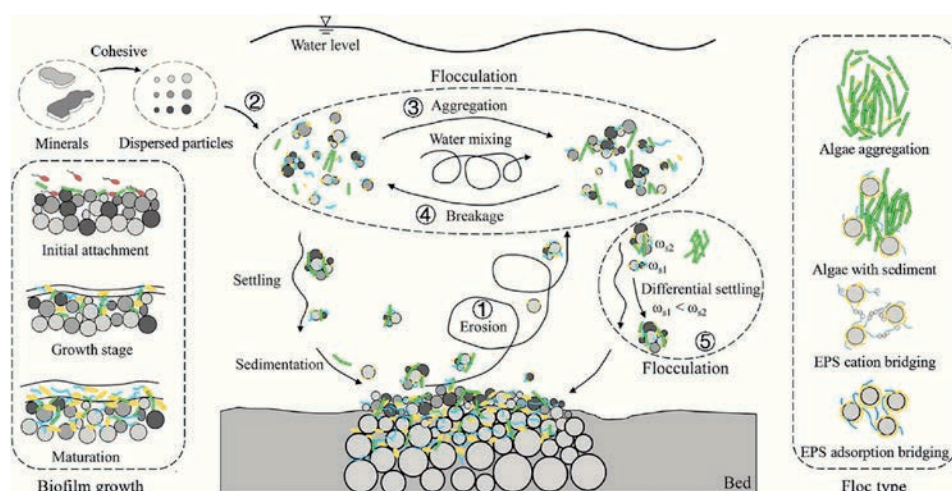


Figure 2.

Flocculation processes including biological influences (Figure modified after [45–48]). The main processes are as follows: (1) Erosion: In the original illustration, particles were depicted solely as mineral clay. However, it is now recognized that organic matter, particularly in the form of biofilms, plays a pivotal role in erosion dynamics [41, 49]. Biofilm development is shown on the left side of the Figure 2. Introduction of mineral particles: Mineral clay particles enter the aquatic system via advection. These clay and silt-sized particles consist of aluminosilicate layers, the cohesion of which depends on their mineralogical composition. The surface charge of these particles governs their propensity to flocculate. (2) Aggregation: While mineral clays can aggregate through salt-induced processes, in coastal environments, they more commonly bind with organic matter [50, 51]. Various floc types are depicted on the right side of the Figure 4. Break-up: Flocs are subject to disintegration under shear forces. Recent studies show that in the presence of organic matter, flocs tend to become smaller primarily through structural reconfiguration rather than complete disintegration [52, 53]. (3) Differential settling: Owing to variations in floc density – largely driven by their organic matter content – flocculation may also proceed through differential settling mechanisms [50, 51]. Original source: [54]; figure redrawn and adapted for this article.

processes within the water column can exert influence on estuary bed consolidation, and sequentially erosion processes are administered by consolidation processes and mediated by the estuarial flora and fauna [57]. In the same way, floc settling does not invariably pave the way to deposition, that is, when entrainment subjugates, and the sedimentary particles/flocs endure in suspension.

There are a number of key factors that influence flocculation: the type of minerals present in sediment significantly influences flocculation [16], and changes in electrolyte levels due to salinity stratification and resultant acclivity/declivity [14, 58] can directly influence the zeta potential of individual clay particles [59]. The amount of solid particles [60] in the water plays a role in flocculation, and the presence and quantity of organic material [61, 62] in the sediment influence flocculation, including enhancing particle cohesion. Hydrodynamic factors, such as flow velocity and turbulence in the water column, impact flocculation (e.g., [32, 63–67]), for example, in terms of particle collisions (e.g., [68]), see **Figure 3**.

Clays are the primary sedimentary mineral elements in cohesive muddy sediments. They possess a plate-like form and can be less than 2 μm in diameter. Flocculation in estuaries involves a combination of electrostatic charging of clay minerals in saline water and the presence of biologically based, sticky molecules on clay particle surfaces. Sticky organic matter can significantly enhance the fall rate of flocs. The efficiency of the flocculation process reflects the suspension's stability. A higher concentration of particles leads to more inter-particle collisions and greater

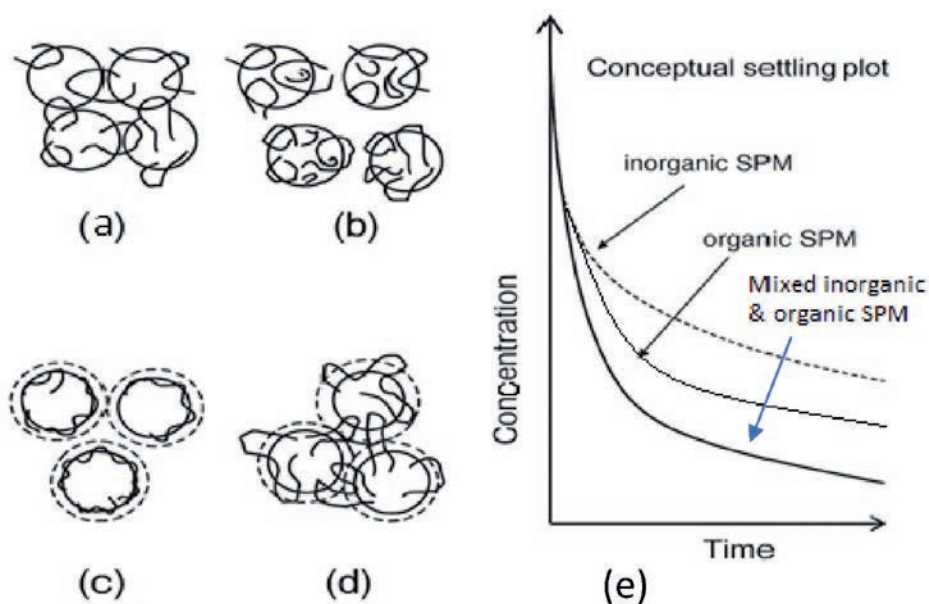


Figure 3.

Some schematic examples of the effects of organic matter on sediment particle properties are given: (a, b) Flocculation and deflocculation by adsorbed polymers; (c, d) schematic diagram of polymer bridging and the repulsive energy barrier (dotted line) at the particle surface for: (c) low ionic strength (bridging prevented by electrical repulsion); and (d) high ionic strength (bridging across the effective repulsion distance) after [61]; (e) the conceptual relationships between concentration and time for settling suspensions of suspended particulate matter (SPM) consisting of inorganic (single mineral) particles, organic matter, and flocs consisting of a 50:50 mixture of organic matter and mineral particles (original data source: [62]). Figure redrawn from Manning et al. [15] for this article.

flocculation. A fully flocculated suspension is considered unstable, compared to a fully stable suspension where all particles remain as individual (i.e. unflocculated) entities.

4.2 Aggregational mechanisms

Fine sediment particles possess two crucial parameters related to their ability to flocculate: collision frequency and collision efficiency. The rate at which these particles aggregate depends on the interplay between these two factors [45]. In essence, these parameters govern how particles come together to form flocs, which plays a pivotal role in sediment dynamics and transport processes.

4.2.1 Particle collisions

Particle collisions play a crucial role in the process of flocculation, which is central to the transportation of fine sediments within an estuary. Flocculation involves the clumping together of fine particles to form larger aggregates known as flocs. Various mechanisms drive these particle collisions, and the frequency of collisions is influenced by factors, such as particle size, concentration, and the specific mechanism at play. The three principal mechanisms of collision discussed are Brownian motion (BM), differential settling (DS), and velocity gradients generated within the suspended fluid, particularly related to turbulent shear (TS; [32, 63, 69]).

In the theoretical modeling of flocculation by two body collisions, when a collision transpires amid two particles of diameters d_i and d_j , respectively, the collision frequency can be determined by obtaining the product of the number concentrations of interacting particles $n_i n_j$ and a collision frequency function $K(d_i, d_j)$. This is shown as Eq. 2

$$N_{ij} = K(d_i, d_j) n_i n_j \quad (2)$$

where N_{ij} is the number of collisions occurring per unit time and per unit volume between two classes of particles of diameters d_i and d_j . The collision frequency functions for three mechanisms can be enunciated as outlined in **Table 1** [69, 70]:

Particle collisions caused by Brownian motion result from the random impacts of thermally agitated water molecules on particles in suspension. This mechanism

Collision mechanism	Collision frequency function
Brownian motion	$K_{BM} = \frac{2kT(d_i + d_j)^2}{3\mu d_i d_j}$
Differential settling	$K_{DS} = \frac{\pi \cdot g}{72\nu \cdot \rho_w} (d_i + d_j)^2 (\Delta\rho_i d_i^2 - \Delta\rho_j d_j^2)$
Turbulent shear	$K_{TS} = \frac{1}{6} (d_i + d_j)^3 G$

k = Boltzmann's constant, *T* = absolute temperature, μ = dynamic viscosity of the liquid, ν = kinematic viscosity of the liquid, ρ_w = water density, ρ_i = density of particle *i*, $\Delta\rho_i = \rho_i - \rho_w$ and *G* = turbulence parameter.

Table 1.
 Collision frequency functions (from [69]). Table redrawn for this article.

leads to perikinetic flocculation, which occurs for particles smaller than 0.5–2 μm in size in typical estuarine conditions [71–73]. Flocs formed through Brownian motion are often fragile, have a jagged structure, and can be easily dispersed or crushed upon deposition (e.g. [32, 74]). Differential settling involves larger particles with higher settling velocities falling onto smaller particles [32]. This mechanism imposes little stress on particles during collision, leading to the formation of loosely bonded flocs with low density (e.g. [32, 75, 76]). Stolzenbach and Elimelech [77], following research by Wacholder and Sather [78], have suggested that a limiting factor for differential settling is when one or both particles have a very low density (i.e. close to water), there are minimal collisions between particles and negligible flocculation. Differential settling tends to be more effective in low-flow velocity conditions, and it can play a significant role in floc growth as shear rates decrease [79, 80], and this was demonstrated experimentally by Lick et al. [73].

Turbulent mixing in the water column generates velocity gradients, leading to particle collisions through two sub-mechanisms: inertial collision and shear-induced collision. Inertial collision involves larger particles responding more slowly to local accelerations due to inertia. Shear-induced collisions occur when particles come into contact as a result of the presence of a velocity gradient. Flocculation, induced by way of this orthokinetic means, tends to produce flocs that are more strongly bonded. The rate of turbulent shear and particle size influences this mechanism. Numerous research studies have provided a more acceptable perception about the association between shear rate and flocculation [17, 44, 79, 81–83].

These collision mechanisms are interrelated, and their importance can vary depending on factors, such as turbulent shear stress, suspended sediment concentration, and particle characteristics. The collision frequency functions offer insights into how collision frequency varies based on the specific mechanism and particle sizes involved. However, it is important to note that collision efficiency, which accounts for the fraction of collisions contributing to aggregation, can vary widely and depends on particle characteristics and the presence of natural polymers [84–87].

The complex interactions among these mechanisms and factors impact floc structure and behavior, including sediment settling flux and vertical sediment distribution within an estuary. Understanding the dynamics of particle collisions and the mechanisms driving them are essential for studying sediment transport in estuarine environments.

4.3 Break-up mechanisms

Floc break-up is a significant process influenced by the level of turbulent shear in estuarine systems, although the process is still not completely understood [88]. While moderate levels of turbulent shear can promote floc growth, high levels of turbulence commonly experienced during a tidal cycle can disrupt flocculation by causing floc break-up. Floc integrity plays a crucial role in determining whether flocs will fracture in the presence of turbulent shear stress, which can impose limitations on the floc population.

Several factors contribute to floc break-up, and we start with turbulent shear stress. As turbulence in a fluid flow increases, both turbulent pressure differences and turbulent shear stresses rise. If the structural integrity of a floc is weaker than the ambient turbulent shear stress, the floc is prone to fracture. The break-up of flocs is traditionally regarded as a function of shear and particle sizes [89]. Floc break-up

(i.e. particles departing a specific size class) is often described in terms of the turbulent shear rate [90] but not by the particles leaving a particle size class by collision [91].

An increase in shear rate leads to higher collision frequencies between particles, promoting flocculation and particle size growth. The turbulent shear stress acts as a maximum size limit for flocs [92], and when floc size exceeds this limit, it is likely to break apart. The Kolmogorov microscale [93, 94] of turbulence is a key parameter in this relationship. When floc size approaches the Kolmogorov microscale [93, 94], further increases in shear rate have limited effects on floc size. It is expected that flocs whose size exceeds the Kolmogorov microscale are prone to break into smaller, denser flocs. Both Eisma [13] and van Leussen [95] postulated that the maximal floc size is comparable to the Kolmogorov microscale (i.e. the minimal turbulent vortex scale). Van der Lee et al. [96] and Fettweis et al. [97] each quantitatively demonstrated that both the Kolmogorov microscale and floc diameter fluctuate in a kindred manner with the root mean square (RMS) of the gradient in the turbulent velocity fluctuations. Nonetheless, Kranck and Milligan [98] and Puls et al. [99] have each postulated that both turbulence and suspended sediment concentration (SSC) are perceived to have an influence on the uttermost floc diameter and the resultant size spectra. Research by Dyer [17] first proposed the existence of an explicit value/region of turbulent shear stress, below which the floc diameter grows and beyond which floc sizes steadily diminish (**Figure 4a**). Some examples of actual floc images are also presented in **Figure 4b-e**.

Drawing on an extensive floc dataset, Manning et al. [15] proposed a classification of nominal turbulent shear stress “regions” typically associated with mud flocculation processes (where $1 \text{ Pa} = 1 \text{ N m}^{-2}$):

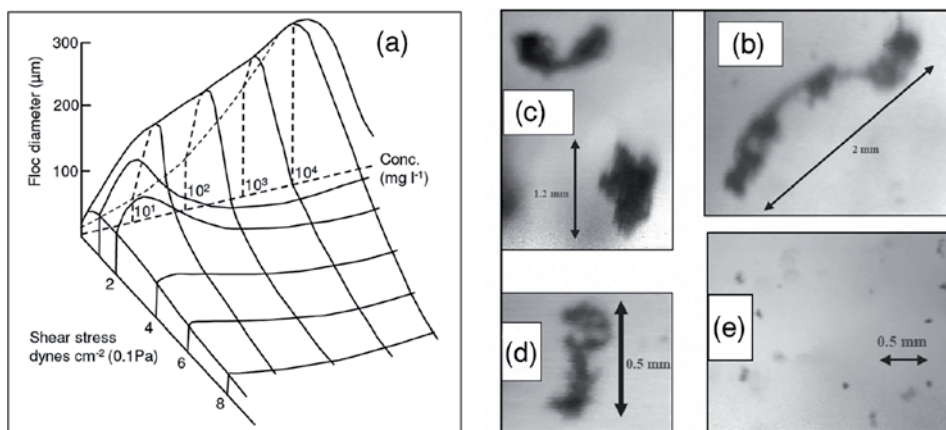


Figure 4.

An illustration depicting the dependence of floc size on shear stress and suspended particulate matter (SPM) concentration is presented. (a) A conceptual diagram illustrates the relationship between floc modal diameter, suspended sediment concentration, and shear stress (original data from [17] and redrawn for this article). Subplots (b–e) offer representative examples of real estuarine flocs, showing associated ambient shear stress, SPM concentrations, and settling velocities: (b) Shear stress of 0.3 N m^{-2} , SPM concentration of 3.5 gl^{-1} , and a settling velocity of 5 mm s^{-1} ; (c) Shear stress of 0.3 N m^{-2} , SPM concentration of 3.5 gl^{-1} , and a settling velocity of 8 mm s^{-1} ; (d) Shear stress of 0.45 N m^{-2} , SPM concentration of 0.25 gl^{-1} , and a settling velocity of 1.8 mm s^{-1} ; (e) Shear stress of 0.45 N m^{-2} , SPM concentration of 0.25 gl^{-1} , and a settling velocity of 0.2 mm s^{-1} . It should be noted that slight blurring in the floc images (from [26]) results from the downward movement of flocs through the water column during image capture in the settling apparatus.

- Low-turbulent shear stress: < 0.2 Pa
- Moderate-turbulent shear stress: $0.2\text{--}0.45$ Pa
- Moderate-to-high turbulent shear stress: $0.45\text{--}0.7$ Pa
- Very-high-turbulent shear stress: > 0.7 Pa

While low-to-moderate shear stress levels are generally conducive to floc formation and growth by facilitating particle collisions and aggregation, high shear stress conditions – often occurring during tidal cycles – can inhibit flocculation by inducing floc disaggregation. As turbulent intensity increases, both turbulent pressure gradients and shear stresses rise accordingly. When the structural integrity of a floc is insufficient to withstand the imposed hydrodynamic forces, floc fracture occurs, ultimately leading to the disintegration of the floc into its constituent particles.

Energy dissipation during rupturing of a floc results in the removal of energy from the surrounding turbulent shear field. During rupture, energy is dissipated in stretching the internal bonds of the floc to the point of tensile strength [100]. Additionally, viscous dissipation occurs as interstitial water flows in response to changes in floc form as it is distorted and contorted. Even as particle concentrations rise, the influence of inter-particle collisions can similarly have a contributing factor as a floc break-up mechanism. The rate of floc break-up due to fluid shear is directly proportional to the concentration, while floc break-up due to inter-particle collisions is proportional to the square of the concentration [60, 69].

Floc break-up can occur through various physical mechanisms, including turbulent shear-induced break-up and three-particle collisions [60, 89]. The type of mechanism and its relative importance can depend on the conditions in the estuarine system. For instance, if turbulent shear dominates the floc break-up process, the median floc diameter is expected to increase with concentration [101]. However, if particle collisions due to velocity gradients are the dominant mechanism, the median diameter would remain relatively constant with increasing concentrations.

Floc strength is closely coupled with flocculation, particularly to the diameter and structure of individual flocs [102]. Similarly, the adhesion created by organic matter and microorganisms deposited on the surface of each individual particle, and the relative electrochemical attraction between the various clay minerals all contribute towards the total strength of a floc [103, 104]. Through biological decay, flocs can break without the influence of shear, simply by biomatter degradation [105]. The rate of microbial degradation, leading to catabolism [106], varies considerably for different types of EPS [107]. Living microorganisms (that excrete EPS and other varieties of polyelectrolytes) are apposite to the levels of water nutrients [108] and their grazing habits [109].

In estuarial and coastal regions, velocity gradients, particularly in the lower 10–20% of the water column, play a significant role in controlling the maximum size of suspended flocs. The near-bed region, where turbulent energy is concentrated, experiences the strongest lift and shear forces, making it crucial for understanding the dynamics of flocs [82]. Floc break-up mechanisms also include surface erosion due to turbulent drag, which can lead to the reduction of floc size [64]. These mechanisms are particularly relevant at low suspended sediment concentrations.

Overall, understanding the complex interplay between flocculation and floc break-up is essential for comprehending sediment dynamics in estuarine environments, where turbulent shear and other environmental factors influence these processes.

4.4 Cohesion mechanisms

As we have reported in this chapter, fine-grained particles in estuarine sediments have the ability to coagulate and form larger aggregates due to their cohesive nature. This cohesion can occur through two main processes. The first is *salt flocculation*; this is a physicochemical process where the presence of salts, typically divalent cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), can neutralize the negative charges on clay particles. When the electrostatic repulsion between clay particles is reduced, they can come closer together and form aggregates. This process is often observed in estuarine environments where the salinity levels fluctuate, leading to changes in the concentration of these divalent cations, which in turn affect the flocculation of fine sediment particles.

The second cohesion process, *bioflocculation*, has a more significant efficacy in estuarine sediments and is enhanced by organic matter. Organic materials, such as microbial exopolymers, algae, and detritus, can act as binding agents that help particles stick together. Microorganisms play a crucial role in producing these organic substances, which can create bridges between particles, facilitating their aggregation into larger flocs. Bioflocculation is particularly important in estuaries because of the high input of organic material from both terrestrial and marine sources.

Together, both salt flocculation and bioflocculation contribute to the formation of larger cohesive aggregates in estuarine sediments, influencing their transport and settling behavior in these dynamic coastal environments. Each process will be examined in more detail in the next sub-sections.

4.4.1 Salt flocculation (physical bonding)

Salt flocculation, driven by physical bonding forces, is an important process that influences the behavior of fine-grained sediment particles, particularly clay particles, in aquatic environments. These particles carry ionic charges on their surfaces, which give rise to attractive and repulsive forces between them [31]. The balance between these forces is crucial in determining whether particles come together to form flocs or remain dispersed (e.g., [26, 58]; **Figure 5**). Here, we review the key points regarding salt flocculation:

The *Attractive Forces* (VA) are London-van der Waals forces, representing gravitational attraction between particles. They tend to pull particles together. In contrast, the *Repulsive Forces* (VR) are electrostatic Coulombic forces due to the presence of like-charged ionic species on the particle surfaces. In the presence of these forces, positive ions form a cloud around negatively charged clay particles.

The balance between attractive and repulsive forces is influenced by factors that include the distance between particles and the electrolyte concentration in the surrounding medium. The thickness of the electrical double layer around clay particles plays a significant role in determining whether particles will aggregate or repel each other.

At low electrolyte concentrations, the electrical double layer around clay particles is thick. This results in strong repulsion between particles as they approach each other. The dominant force is repulsion, which keeps particles dispersed. Whereas at higher electrolyte concentrations, as the electrolyte concentration in the medium increases, the electrical double layer becomes thinner. The electrical repulsion primarily occurs at very close distances to the particle. At this point, the attractive London-van der

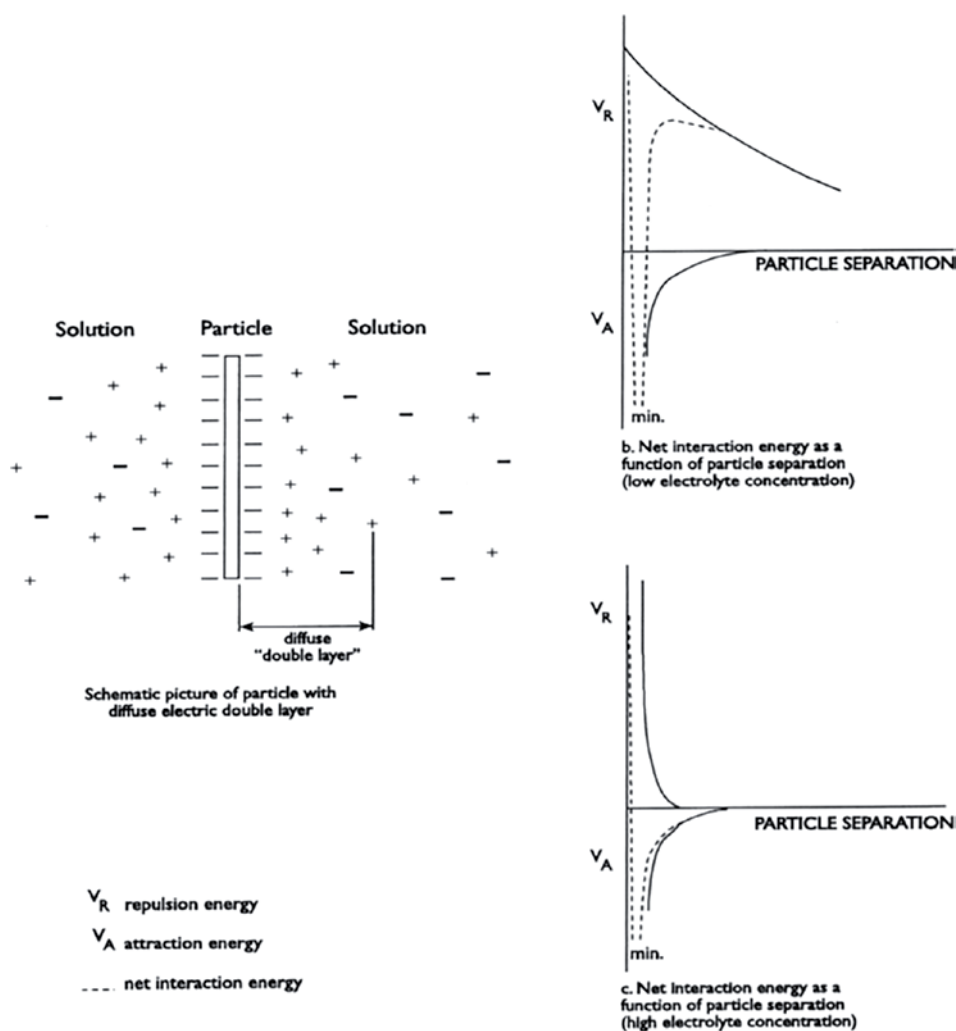


Figure 5. Idealized model of particle diffuse electric double layer and interaction (original data source: [58]). Figure redrawn for this article.

Waals forces [110] become dominant, leading to particle flocculation (aggregation) when particles approach each other.

Saline waters rich in sodium ions, such as estuarial zones, can promote clay particle flocculation [111, 112]. In high electrolyte conditions, the attractive forces predominate due to the presence of positively charged ions forming a cloud around the negatively charged clay particles, resulting in floc formation (e.g., [65]). In contrast, freshwater has fewer positive ions, leading to a dominance of repulsive forces between negatively charged clay particles. This causes particles to repel each other and remain dispersed. Critical salinities, expressed in parts per thousand (ppt), practical salinity units (psu), or milli-equivalents per liter (mEq/L) indicate the concentration of salts required to induce clay particle coagulation. The critical salinity values vary depending on the type of clay. Here are some approximate critical salinities [16]:

- Kaolinite clay: Critical salinity ranges around 8–10 ppt or 0.4–0.5 mEq/L.
- Montmorillonite clay: Critical salinity varies but is typically higher than kaolinite, around 20–26 ppt or 1.3–2 mEq/L.
- Illite clay: Critical salinity is intermediate, ranging 10–15 ppt or 0.5–1 mEq/L.

These values indicate the salinity level required to induce coagulation of clay particles under typical conditions. For example, Krone [14] ascertained (from empirical analysis) that flocculation rapidly attains an equilibrium when the ambient salinity reaches 5–10 ppt, which is significantly less electrolytic than most sea water (~35 ppt). Nevertheless, factors such as the presence of other ions and the pH of the medium can influence these values. In marine environments, critical salinity values are generally exceeded, making salt flocculation a significant factor in the aggregation of fine sediment particles. This process is less dependent on the specific mineral type in seawater, but in brackish environments, mineral type can influence the critical salinity for flocculation. For example, physical cohesion has been demonstrated to have an important effect on ripple and dune formation in clay–sand mixed environments [113], and this influences the floc formation of locally resuspended sediments. Salinity values are explored further in Section 6.

4.4.2 Collision efficiency

Van Leussen [32] stated that the stability of a suspension of particles is a reflection of efficiency with which those suspended particles flocculate. As the profusion of suspended particles arises, this elevates the probability of particle collisions. A suspension of particles that remains entirely as individual entities is defined as being ‘stable’; in contrast, a fully flocculated suspension is classified as being ‘unstable’. The stability (i.e. the degree of flocculation) of suspended particles in a fluid is influenced by various factors, and understanding these factors is crucial for predicting the behavior of particles in aquatic environments [32]. For example, Yu et al. [114] have demonstrated that turbulence is an important factor in producing stable floc populations.

Since the mid-twentieth century, numerous research scientists have proposed theoretical and modeling frameworks to mathematically elucidate sedimentary flocculation, amidst which there is the conventional electrokinetic theory – widely known as DLVO (for Derjaguin, Landau, Verwey, and Overbeek), sweep flocculation, polymer bridging, cation bridging, and a plethora of other approaches [32, 115, 116].

The type of clay minerals present in the suspended particles can significantly affect their behavior. For example, Edzwald and O’Melia [117] conducted controlled laboratory experiments with pure kaolinite clay minerals and findings revealed that flocculation efficiency was consistently lower than 10%. Different clay minerals have varying surface charges and reactivity, which can influence their tendency to flocculate or remain in suspension. The concentration of ions in the water (i.e. the electrolytic levels), often related to water column salinity, can alter the ζ -potential (or zeta-potential) of clay particles. Increasing salinity tends to reduce the absolute value of the ζ -potential, whereby a low ζ -potential often leads to weaker Coulombic repulsion, thereby potentially promoting flocculation (see [59, 118]).

Turbulence in the water column, driven by factors such as tidal flow or wind, can lead to collisions between suspended particles. Turbulent shear stresses can promote flocculation, especially in the lower part of the water column, where velocity gradients are largest.

The DLVO theory describes the interaction potential between colloidal particles in a solvent. It includes Coulombic repulsion and van der Waals attraction [119]. Changes in ionic strength, pH, and other factors can affect the DLVO interaction energy curve and influence flocculation behavior. The ζ -potential quantifies the surface charge of particles and is used to assess their interaction potential. Changes in ζ -potential, often related to changes in salinity or pH, can influence particle aggregation.

The concentration of suspended particles in the water column plays a role in flocculation. As the abundance of particles increases, the statistical occurrence of collisions also increases, potentially leading to more flocculation events. Organic matter, such as polysaccharides, and microbial organisms, such as diatoms, can coat sediment particles. These organic coatings can influence the surface properties of particles and act as flocculating agents. Polyelectrolytes in the form of gelatinous organic matter known as transparent exopolymer particles (TEP) or EPS (*also see sections 2.5 and 4.3*) and microorganisms can change the interaction forces between particles, promoting flocculation.

According to DLVO theory, within estuarine regions, sedimentary particles in suspension will be progressively destabilized and flocculate as a result of the relative rise in salinity between the fresh riverine water and the sea water. However, when organic matter is present, DLVO theory cannot be implemented, as the flocculation mechanisms will be orchestrated by the presence of microorganisms and polyelectrolytes, which are not considered within the DLVO theory framework (see [120]). Microbial organisms can produce EPS, which are anionic polysaccharides (i.e. polyelectrolytes). EPS can form biofilms on particle surfaces, increasing their negative charge density [121], and anionic polysaccharides actively encourage flocculation with negatively charged sediment particles by way of cationic bonding with salt ions present within the water [122]. In order to model biological interactions (including effects from microbial communities), DLVO theory has been extended as XDLVO [123] to include biological mechanisms, such as bridging effects and acid-base energy from hydrogen bonding [124, 125].

Cationic polymers can be present in the form of mucus secreted from microorganisms [126]. Aly and Letey [127] deduced that flocculation by cationic polymer types differs from flocculation that occurs by anionic polymers. Some flocculation can occur through charge neutralization, particularly with cationic polymers. These polymers can interact with negatively charged particles and promote aggregation. The presence of divalent cations can enhance flocculation, potentially by bridging mechanisms [53].

Overall, these factors interact in complex ways to influence the stability and flocculation of suspended particles in aquatic environments. Understanding these processes is essential for modeling sediment transport, water quality, and the behavior of suspended particles in estuarine and coastal regions.

4.4.3 Organic bonding

In estuaries, the importance of salt flocculation has progressively been called into question because of the inherent ascendancy of organic matter present in the aquatic environment. To reiterate, electrostatic bonds are very weak when compared to bio-cohesion, and back in the 1980s, large macroflocs (see Section 5.0 for more

details) were observed (by way of *in situ* photography) in predominantly fresh (i.e. very low salinity) estuarine waters [128]. The role of organic matter – particularly EPS (e.g. [129]), such as mucopolysaccharides produced by microphytobenthos – is of great significance in sediment dynamics and flocculation (*also see sections 2.5, 4.3, and 4.4.2*). EPS, including mucopolysaccharides produced by microphytobenthos, have a stabilizing effect on cohesive sediments. EPS can enhance the cohesion of sediment particles, preventing their easy detachment and erosion. This stabilization effect is especially pronounced in muddy sediments. In estuaries and coastal regions, there is a high level of biological activity present; this in turn generates a large volume of organic matter, and it has long been recognized that this has a pronounced impact on mud flocculation [130].

The presence of microphytobenthos and their secreted EPS can significantly increase the erosion threshold of muddy beds. This means that it takes higher shear forces to resuspend sediment particles when EPS is present. The stabilization effect can be several times stronger, up to a factor of five, in the presence of EPS [129, 131–134]. The development of benthic diatoms, which are known to secrete EPS, tends to be seasonal (e.g. [135]). As a result, the stabilizing effects of EPS may vary throughout the year, with minimal effects in the winter when diatom growth may be reduced. Such seasonal differences in erosion thresholds have been shown to be a complex combination of factors, such as vegetation cover, ecology, and the relative seasonal change in EPS content, which influence the degree to which EPS impact sediment stability (e.g. [4, 136, 137]).

In estuarine environments dominated by mud and silt sediment types, microphytobenthos and their EPS can contribute significantly to autotrophic production [138]. EPS can help stabilize these sediments, influencing their behavior during tidal and flow-driven processes. Organic polymers, including those produced by microorganisms, can enhance flocculation by binding to sediment particles. For example, Paterson and Hagerthey [139] found epipelagic diatoms can secrete long-chain molecule EPS as they locomote within sedimentary layers. EPS is considered as an extremely efficacious biostabilizer of estuarine cohesive sediments (e.g. [140–142]) and can significantly enhance inter-particle cohesion. Floccs bonded with polymeric substances can display elastic properties and show a high resistance to shear [53].

For example, Gibbs [143] reported the existence of metallic coatings on clay fractions. He postulated that the coatings, with thicknesses ranging from 210 molecular layers on the 0.1 μm size fraction to 4000 molecular layers on the 3.5 μm fraction, would effectively blanket the differing electrostatic properties of the various mineral particles. This signifies that when a coated clay particle transits from fresh to saline water, their surface charge not only becomes less negative but also remains negative [144].

The way polyelectrolytes bind to sediment particles depends on their polymeric chain length, which is defined by their molecular weight. The charge groups present in the polyelectrolytes also play a role in their binding behavior. Salinity, pH, and shear stresses can all affect the way EPS bind to sediment particles. Depending on the polymers (i.e. EPS), flocculation can mostly occur through bridging [16, 145] or patching mechanisms [146, 147].

Polymeric bridging aggregation occurs when polyelectrolytes – which may carry surface charges of the same polarity as sediment particles – facilitate particle binding through interactions mediated by oppositely charged ions in the surrounding water. The loops and tails of a polymer chain (i.e. polyelectrolyte) can extend from one particle and adsorb onto the surface of another, thereby forming inter-particle

bridges that promote aggregation [148]. This mechanism of flocculation is highly dependent on the availability of particle surface area to which polymer chains can attach. Optimal flocculation generally occurs at approximately half surface coverage by the polymer. For effective bridging to take place, the adsorbed polymers must be capable of spanning the separation distance dictated by electrostatic double layer repulsion between particles.

According to the classic interparticular bridging model [149], to bridge the respective particles, the adsorbed polymers must first span the expanse over which the repulsion effects of the double layer operates; see example demonstrated schematically in **Figure 3c-d**. Optimum polymer concentration to achieve flocculation corresponds to half surface coverage for the polymer. Bridging flocculation typically results in flexible and stretchable flocs. Although there has been much research performed on flocculation, the effect of biological processes was seldom taken into account [48, 150, 151].

In contrast, patching aggregation happens when polyelectrolytes have charges opposite to those of sediment particles. The polyelectrolyte strongly binds to sediment particles, forming patches [152]. Aggregation occurs between one polymer patch and the bare surface area of another particle. Flocs formed through patching aggregation are less flexible and stretchy and thus tend to have a higher overall strength. The force is dependent on the number of bound segments [153].

Microorganisms, by producing EPS, can create a polymeric network with holes and channels [154] through the bridging of their EPS [155]. This matrix has a sizeable surface area and can adsorb pollutants, minerals, and nutrients [156]. During sedimentation, fine particles can be trapped and embedded in this network, a process known as sweep flocculation. This mechanism has been documented in both sewage treatment processes and natural estuarine environments, indicating its relevance across engineered and coastal sedimentary systems [157]. Deng et al. [50] report that sweep flocculation is primarily a function of electrochemistry and a great number of the network characteristics, and as a consequence, the network floc grows in size.

It is important to note that the behavior of EPS-bound flocs can be sensitive to shear forces [158]. While polymers can strengthen flocs, their rupture during high shear events can be irreversible. This means that once flocs break up under high shear, they may not reassemble into their original form. Studies have shown that even a small concentration of EPS (0.1%) can prevent the formation of significant bedforms, such as ripples and dunes, in sedimentary environments with sand and mud [159, 160]. Kranck and Milligan [161] reported that microorganisms, such as diatoms and coccolithophorids, can influence flocculation during algal blooms. These organisms may act as nuclei around which flocs are created, affecting the size and stickiness of the resulting aggregates. Wolanski [162], using microscopic photographic techniques, reported the emergence of sizeable estuarine macroflocs (see Section 5.0 for more details) that were primarily formed by mud creating a sticky membrane encompassing large predominantly non-cohesive silt particles.

Flocculation under biological action is influenced by various factors, including electrochemistry, charge distribution on sediment surfaces, and the charge distribution of EPS, especially those produced by microorganisms. The mechanisms are interconnected, making it challenging to perform a quantitative analysis. Moreover, the colony formation and growth of microorganisms are dynamic processes that influence sediment flocculation. Quantitative studies of biological activity in field observations are complex, and the relationship between biological activity and sediment flocculation remains an open question in the study of sediment transport

dynamics. Understanding the complex dynamics of bio-sedimentary flocculation is crucial for assessing the environmental impact of sediment transport in various estuarine aquatic systems.

5. Flocculation characteristics

This section explores the complex behavior of flocs, their sizes, settling velocities, and effective densities in estuarine and deltaic aquatic environments, emphasizing the differences between cohesive and non-cohesive sediments and the impact of particle interactions and other factors contributing towards their behavior. Flocs can vary significantly in size, ranging from individual clay particles to stringer-type floc structures several centimeters in length (e.g. **Figure 6a**). The size (D) of an individual floc can comprise up to an order of 10^6 individual particulates [81].

Settling velocity (W_s) is an important variable in understanding how suspended sediments deposit in water bodies. Lick [168] reported that in a similar way to floc diameters, floc settling velocities can span over four to five orders of magnitude, from small flocculi/primary particle clusters settling at 0.001 mm s^{-1} quickening up to several cm s^{-1} . As a result, floc settling velocities and their sizes are crucial parameters required for modeling cohesive sediment transport in estuarine and coastal aquatic environments (e.g. [169, 170]). Flocculation settling dynamics play a crucial role in determining the rate at which sediment settles out of suspension and accumulates (i.e. accretes) on the bed.

Both floc sizes and settling velocities are influenced by variations in the concentration of SPM. Field experiments have shown relationships between median floc

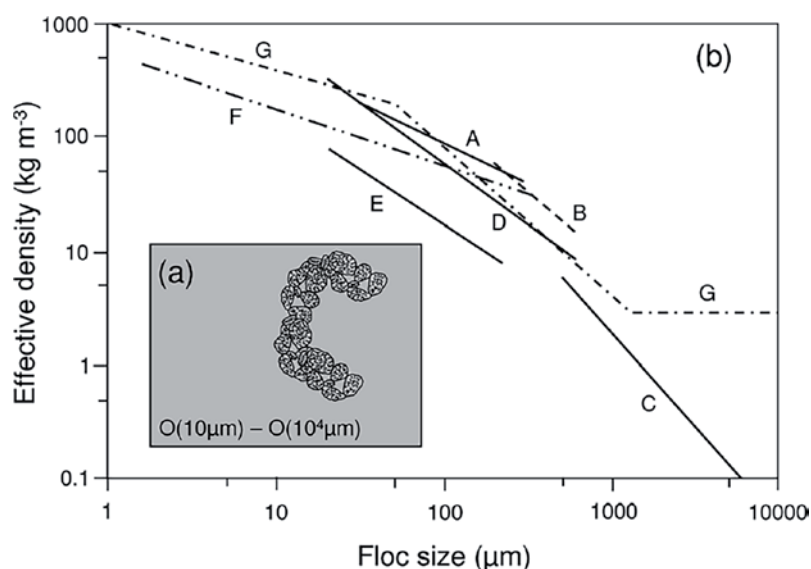


Figure 6. Some examples of the shapes and sizes of flocs and their effective densities. (a) Schematic of an individual floc and its potential order of magnitude size range; (b) comparative results of effective density against floc size (listing original data sources): A = Manning and Dyer [81], B = Al Ani et al. [163], C = Alldredge and Gotschalk [164], D = Fennessy et al. [165, 166], E = Gibbs [42], F = McCave [167], and G = McCave [63]. Figure redrawn from Manning et al. [15] for this article.

settling velocities and SPM concentration (see **Figure 6**). At high SPM concentrations (beyond 10 g/l), hindered settling conditions occur, and the rheological behavior of the suspension becomes non-Newtonian.

Stokes' law [171] is often used as a method for calculating the settling velocity for individual particles small enough to not generate appreciable wakes. This is around 0.1 mm, so only goes up to very fine sand grains. Beyond that, you move into the impact-based formula (see, for instance, [172]). It is, however, suitable for situations where gravity and flow resistance are the primary forces involved. For cohesive sediments in estuaries and river deltas, floc settling velocities are significantly greater than those of individual constituent particles. This increase is attributed to the size-dependent relationship described by Stokes' law [43, 170]

$$\rho_e = (\rho_f - \rho_w) = W_s \cdot 18 \mu / (D^2 \cdot g) \quad (3)$$

where g is the gravitational acceleration, μ is the molecular viscosity, and D is the particle (floc) diameter. The effective density of flocs, denoted as ρ_e (the difference between the water density, ρ_w , and the floc bulk density, ρ_f), generally decreases as floc size, D , increases [173], since the voids are filled with interstitial water; this is a characteristic trend observed in various studies (**Figure 6b**). Drawing on the research from both Gregory [61] and Stolzenbach and Elimelech [77], Winterwerp and van Kesteren [16] conjectured that although estuarine mud flocs are predominantly porous in formation, they can be considered as impermeable bodies when giving consideration to their fall velocity dynamics. Within a floc population, for a constant floc settling velocity, there is generally a wide range of both ρ_e and D present. Similarly, for a constant D , there is a large spread in both settling velocity and ρ_e [15].

Flocs are often categorized into two distinctive groups: macroflocs and microflocs (e.g. [13, 26]), and this parameterized approach has been adapted for depositional modeling purposes [83, 174, 175]. Characteristically, macroflocs are large (typically the same size scale as the turbulent Kolmogorov microscale), porous, and fast-settling aggregates, while microflocs are smaller, more resistant to breakage, and have slower settling velocities. Flocs are formed through the collision and aggregation of particles, with organic substances often acting as binding agents. The strength of the organic adhesives influences the stability of microflocs. The clustering of different varieties of individual mineral particles combined with microflocs, for the most part, forms the rudimentary constituents of the larger macroflocs.

In spite of the fact that the organic material is once more utilized as the foremost binding medium that couples the smaller microfloc fraction together in a network in order to form a larger macrofloc, the bonding strength of the adherence within the macrofloc matrix is notably lower than the adhesion, which maintains the coherence of the individual microflocs. Krone [14] advocated that muddy flocs grow in a sequentially hierarchically manner: primary particles affix together to form zero-order flocs (often referred to as floccule), which in turn combine to form first-order flocs. This was frequently referred to as Krone's [14, 176, 177] classic 'Order of Aggregation' theory. Low effective densities mean that macroflocs become extremely fragile and prone to progressive breakage as they pass into regions of higher turbulence and thus return to their lower-order microfloc form [178].

Macroflocs and microflocs have been quantitatively defined and parameterized by Manning [26] as flocs with diameters of $D > 160 \mu\text{m}$ and $D < 160 \mu\text{m}$, respectively. As a dynamically active process, flocculation willingly reacts to exchanges in turbulent hydrodynamic conditions (e.g., [63, 65–67]). For example, Uncles et al. [179]

observed during spring tides in the Tamar Estuary (UK) that the floc sizes could surpass 700 μm median diameter. Similarly, Tamar macroflocs could grow beyond 1–2 mm in diameter and settle as fast as 20 mm s^{-1} [180]. Despite their large size, the typical Tamar macroflocs possessed effective densities less than 50 kg m^{-3} , making them extremely susceptible to breaking as they pass through regions of higher turbulent shear.

To quantitatively describe the relationship between floc size and effective density, a mathematical fractal approach is often proposed (e.g. [67, 83, 181]). Among others, Mandelbrot [182] defines a fractal as a self-similar entity. In current academic work, there are two foremost descriptions of fractals: the first is the three-dimensional fractal dimension N_f based on the volume of particles contained within a floc, and the other elucidation is the two-dimensional fractal dimension N_p derived from the floc perimeter and surface area. It is the former that is of prime curiosity to determine the flocs' density [45, 183]. The effective density of flocs can be related to the fractal dimension, allowing for the fitting of effective densities as a function of floc sizes. However, some authors such as Spencer et al. [184] suggest that bio-sedimentary flocculation processes mean that most natural flocs do not conform to fractal structural configurations, and a more emergence-based approach [185] is required. Goldstein [186] explains that emergence delineates how complex systems arise from their fundamental constituent components, exhibiting unanticipated patterns, behaviors, and functions that are incapable of being predicted solely from a comprehension of the individual system constituents.

6. Mud floc composition

This section discusses the composition of mud flocs, including the various factors and components that influence their formation and behavior. Mud flocs in estuaries are primarily composed of fine sediment, including clay and silt fractions, together with a fraction of organic matter. In some cases, sand particles can also be entrapped within these flocs [6, 187]. The composition ratio of mud to sand can influence the settling velocity of flocs [188, 189].

Mud flocs may contain different clay minerals with varying particle sizes and surface charges [190]. The optimal salinity for flocculation can differ for different clay minerals. For example, Deng [54] found that illite and kaolinite may have an optimal flocculation salinity of 9–13 ppt, while montmorillonite may require a higher salinity of 20–24 ppt (*also see Section 4.4.1*). This conclusion is derived from Goldberg [190]. In Deng et al. [120], they posit that, in addition to cation concentration, the type of cation impacts sediment flocculation, with divalent cations such as Ca^{2+} and Mg^{2+} exhibiting greater flocculation efficacy compared to monovalent Na^+ . These differences align with the DLVO theory (*see Section 4.4.2*), where surface charge interactions play a role.

The suspended sediment in estuaries can contain a significant proportion of clay minerals, such as illite, chlorite, montmorillonite, and kaolinite. The type and content of clay minerals can vary with tidal periods due to different sediment transport and deposition mechanisms [191]. Microbial communities, including microscopic algae such as diatoms, can produce EPS and other polymeric substances ([50]; *see Section 4.4.3*). These microorganisms can form flocs by themselves and also capture sedimentary particles. Seasonal algae blooms, which can lead to the formation of large flocs due to biologically induced aggregation of algae, have been observed to promote clay

flocculation in the presence of electrolytes [130]. Diatoms, a type of microalgae, are often studied for their effects on sediment flocculation in estuaries.

The presence of organic matter like EPS promotes the flocculation of fine sediment (e.g. [44, 192]). Through observations of seasonal variations of flocs, Lee et al. [193] ascertained that organic material plays a vital role in both the floc strength and floc collision rate. The largest flocs, mostly appeared during seasonal algae bloom, result from biologically induced flocculation. Furthermore, the biological effects on sediment flocculation can also be found in freshwater environments [194].

Similarly, the presence of humus (dark organic matter present in soils formed through the decomposition of animal and plant matter) in estuarine water can also influence sediment flocculation [195]. Humus, with its strong negative charge, can be adsorbed onto suspended particles, increasing their negative charge and stability.

More often than not, temperature has a negligible direct effect on flocculation [196]; the influence of turbulence-induced shear is more pronounced on flocculation than the action engendered by temperature. However, temperature plays a significant role in the distribution and behavior of algae and microorganisms, and these may have an impact on flocculation due to EPS production rates (e.g. [197, 198]). Different algal species have varying temperature preferences, which can lead to changes in species composition throughout the year (e.g. [199]). Seasonally, there are warm-water algae present in summer and cold-water algae in the winter (where their optimum temperature for growth and reproduction are approximately 20 and 4°C, respectively), and they can complete their life cycle in a short time. The majority of freshwater microalgae appear in spring and autumn [54].

Some cyanobacteria only appear when the water temperature is high in summer. Temperature can affect the thickness of the electric double layer of particles and their collision frequency, influencing flocculation [200]. Similarly, the pH of water can impact the physiological activities of bacteria and microorganisms on the surface charge of mineral sediment [201]. Changes in pH can alter the surface charge of particles, affecting their interactions and flocculation.

7. Hindered settling

When cohesive sediment concentrations exceed approximately 10 g/l, the settling velocity of flocs decreases with increasing concentrations due to the hindered settling effect. Hindered settling occurs because the settling flocs displace upward-flowing fluid as they settle. The viscosity of high-concentration mixtures increases significantly (by a factor of 10–100) compared to that of clear water [9, 202].

Under laboratory conditions, the floc-hindered settling velocity can be accurately deduced from a series of settling/consolidation experiments through the measurement of the slowly descending sediment-fluid interface. An experimental protocol to measure the settling rate of muddy suspension interfaces, for both hindered and dilute settling conditions, was proposed by Manning et al. [15].

Owen tube measurements reveal an exponentially increasing relationship between median floc settling velocity ($W_{s,50}$) and suspended particulate matter (SPM) concentration (C) for concentrations below 10 g/l. The relationship is expressed as $W_{s,50} = kC^m$, with the exponent m varying between estuaries [31, 203, 204]. For example, field settling tube measurements conducted in the Severn Estuary (UK) revealed an m value of 1.05 and a lower m value of 0.69 for the adjacent Parrett

Estuary (UK); differences are possibly due to a combination of floc density and hydrodynamic condition dissimilarities (see **Figure 7a**).

Once SPM concentration reaches 5–10 g/l (CBS region), floc interactions occur, and further increases in concentration > 10 g/l lead to a gradual slowing in floc settling velocities (see **Figure 7b** and Section 3.0). A modified exponential relationship [210] is often used to account for hindered settling, and it has been integrated into sediment transport software. At very high concentrations, typically a few tens of 10's g/l, strong upward fluid flow can balance downward gravity forces, resulting in a state of dynamic equilibrium with no net vertical floc movement. This state is referred to as “fluid mud.” Fluid mud can display non-Newtonian rheological behavior ([211, 212]; also see Section 3.0). The data illustrated in **Figure 7b** indicate that when the SPM concentration is 65 g l⁻¹, the median settling velocity is approx. 0.1 mm s⁻¹, which is the same settling velocity as a relatively dilute 250 mg l⁻¹ suspension.

High-concentration suspensions (that include both CBS and fluid mud) can exhibit different settling behaviors based on the initial condition. Above a critical volume concentration ($\phi > \phi_{crit}$), only one interface (between clear water and the settled bed) is created. Below this critical volume concentration ($\phi < \phi_{crit}$), two interfaces are formed [213]: one between the overlying clear water and the settling suspension and the second between the suspension and the bed. When the average distance between flocs becomes sufficiently small, they join together to form a volume-filling network. Known as the ‘gel point’ (ϕ_{gel}), this marks the transition between hindered settling and the permeability phase of consolidation, where the settling velocity function is mainly driven by the compression of flocs and expulsion of pore water (i.e. where effective stresses are non-zero; [214]; see **Figure 8**).

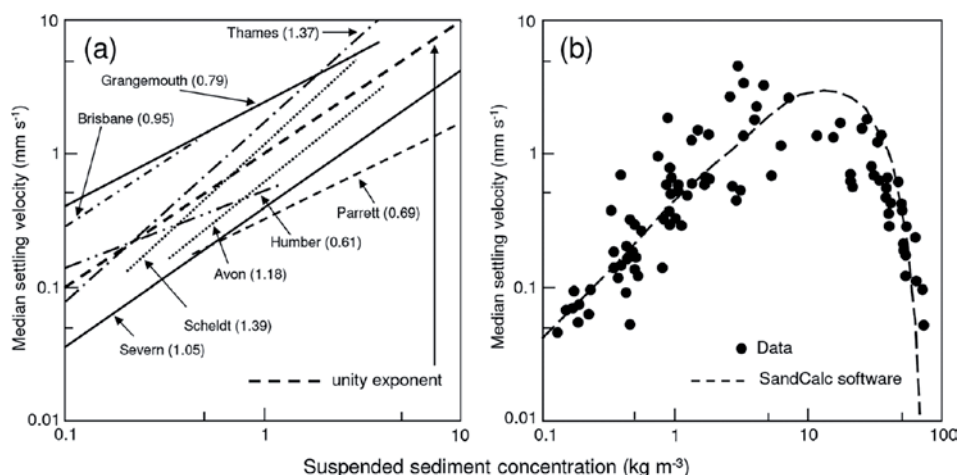


Figure 7.

Some examples of floc settling velocity measurements are shown. (a) Owen tube (a type of field settling tube; see [205, 206]) determinations of median settling velocity as a function of suspended sediment concentration for different estuaries; the bold dashed line represents an exponent of unity (original data source: [203]). Owen tube measurements generally show an exponentially increasing relationship between median floc settling velocity SPM concentration for concentrations <10 g l⁻¹; (b) Median settling velocity of Severn Estuary mud as a function of SPM concentration; the Owen-tube data (original data source: Odd and Roger [207], and the dashed line represents results based on the SandCalc software [208] sediment-transport computational algorithm (original data source: [209]), which incorporates the hindered settling effect at high concentrations. Figures redrawn for this article.

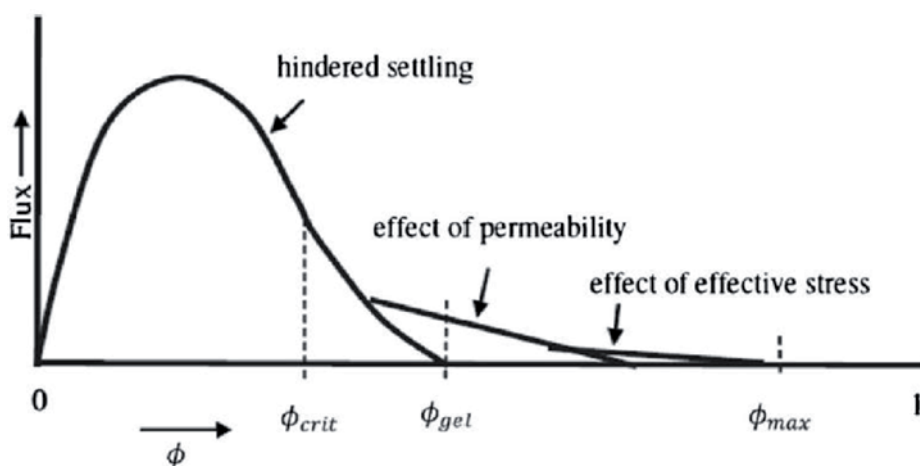


Figure 8. Schematic representation of settling flux variation with volumetric concentration (ϕ) showing effects of hindered settling, permeability, and consolidation (original data source: [214]). Figure redrawn for this article.

Understanding hindered settling is essential for accurate predictions of sediment settling rates and transport behavior in estuarine environments. The non-Newtonian rheological behavior and the complex interplay of factors at high sediment concentrations contribute to the challenges and intricacies of modeling sediment dynamics in estuaries.

8. Floc microstructure

The microstructure of flocs, particularly the arrangement and composition of particles within them, can offer valuable insights into sediment behavior and help elucidate the complex processes involved in flocculation, especially how flocs are formed and structured at the nanoscale. Microstructure analysis involves examining the internal matrix of flocs at a submicron level, typically ranging from 1 to 2 nanometers (nm; [215]). This analysis provides detailed information on how different sediment compositions flocculate at both the floc-floc and primary particle levels. To investigate the microstructure of flocs at such a fine scale, researchers have employed transmission electron microscopy (TEM); see **Figure 9**.

TEM is a powerful imaging technique that uses electrons to visualize extremely small structures with high resolution. TEM images have been used to visually identify the presence of specific minerals within natural microfloc structures. In the mentioned experiments by Spencer et al. [216], the results suggest the presence of clay minerals and quartz mineral fragments within these microflocs. The research findings suggest that in mixed sediments, sand particles tend to favor the microfloc fraction during flocculation. This observation is logical because microflocs have stronger bonding potential due to the closeness of their bonds. The observed phenomenon aligns with the “order of aggregation theory” proposed by Krone [65] and Eisma [13]. According to this theory, microflocs have the tendency to flocculate into larger macroflocs when favorable [13, 32, 174, 217–221] localized aquatic conditions exist. This process provides a more effective mechanism and route for fine-grained sand particles to be incorporated within the macrofloc fractions.

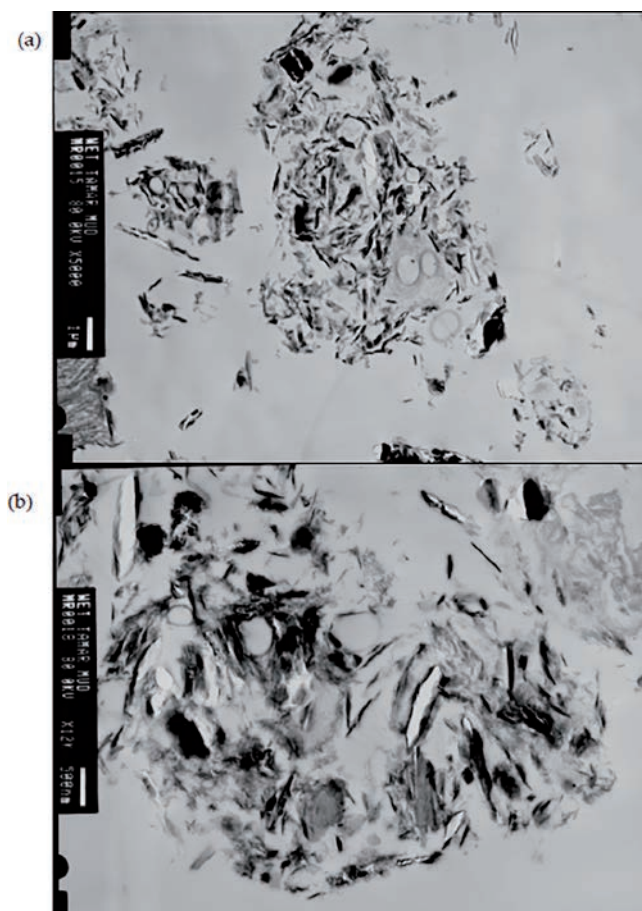


Figure 9. Low resolution – scale bar = 1 μm (a) and high resolution – scale bar = 500 nm (b) TEM images of a natural microfloc composed of a mud:sand mixture (original image source: [216]). Figure adapted for this article.

Novel 3D imaging techniques and protocols and workflows (including micro-computerized tomography - μCT , X-ray microtomography, and focused ion beam nanotomography) have been developed and are providing more details on the collective external and internal floc structure (e.g. [222–225]) including floc porosity [226, 227]. Spencer et al. [222] report that three-dimensional floc data exhibit a measure of irregularity and complexity in the characteristic shape of a floc that cannot be adjudged in less-complex two-dimensional shape descriptors. These new 3D data and approaches offer the possibilities to surpass the current methods of floc parameterization for sediment transport models and to enhance the precision and accuracy of present *in situ* field-monitoring techniques.

9. Summary and conclusion

This chapter highlights the complex interplay of physical, chemical, and biological factors involved in the flocculation process of estuarine mud, and their role in promoting aggregation or decay of flocs. It can be summarized that for the flocculation

of cohesive sediment, there are two primary processes: (i) aggregation, where smaller particles come together to form larger flocs, and (ii) decay, where flocs may break up due to the factors, such as biodegradation or shear forces.

Flocs exhibit substantial variability in size, ranging from individual clay particles and small flocculi to elongated, stringer-type aggregates that can extend several centimeters in length. Correspondingly, floc settling velocities span four to five orders of magnitude, with the smallest clusters settling as slowly as 0.001 mm s^{-1} , and larger, more complex aggregates reaching several centimeters per second. As floc size increases, their effective density generally decreases due to an increasing proportion of interstitial water within the floc structure. This inverse relationship reflects the modified Stokesian behavior of flocs, often approximated by a 'floc size² $\propto$ settling velocity' relationship.

Within any given floc population, there is typically a wide distribution of both floc effective density and size for a constant settling velocity. Conversely, flocs of similar size may exhibit a broad range of settling velocities and densities, due to differences in internal structure, porosity, and composition. Because of these complexities, floc size and settling velocity are key parameters in the numerical modeling of cohesive sediment transport in estuarine and coastal systems. For modeling purposes, flocs are commonly classified into two distinct categories:

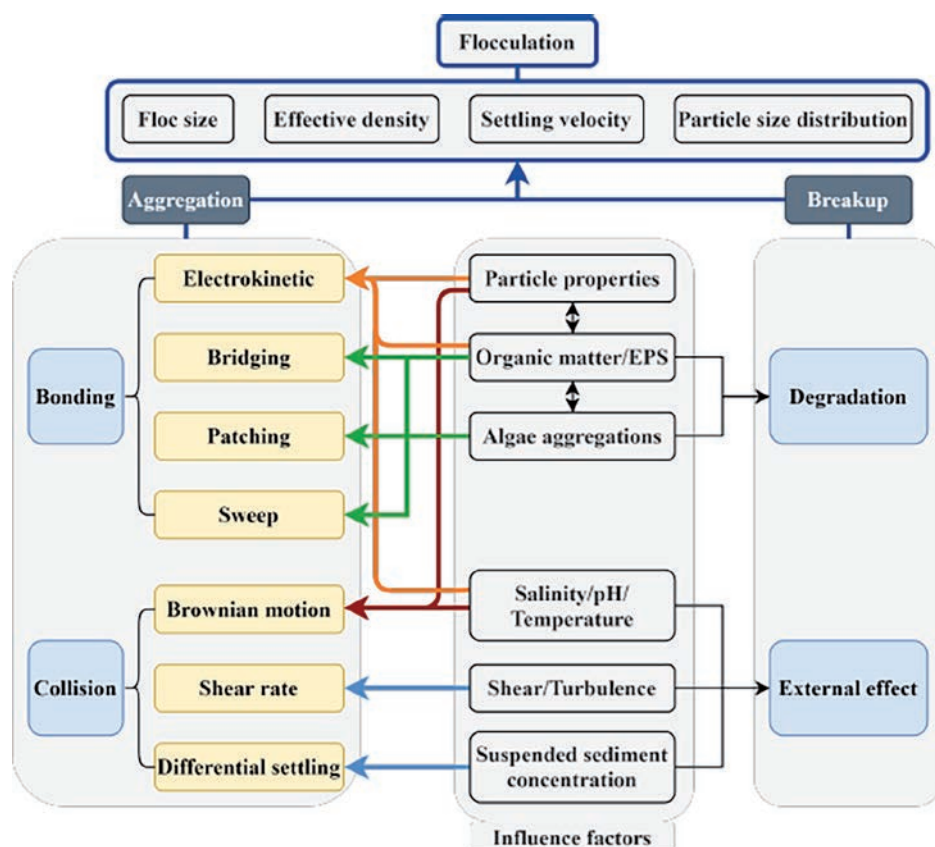


Figure 10. Influence factors and their interactions in the flocculation process (original source: [45]). Figure redrawn and adapted for this article.

- Macroflocs, which are large aggregates—typically comparable in scale to the turbulent Kolmogorov microscale—with high porosity (>90%), low-effective density (<100 kg m⁻³), and relatively fast settling velocities (>2–5 mm s⁻¹); and
- Microflocs, which are smaller, more compact aggregates that are more resistant to shear-induced breakage and settle more slowly.

This classification scheme serves as a practical framework for parameterizing floc behavior in sediment deposition and transport models.

In terms of the *Interactions of Factors*: physical, chemical, and biological factors interact and can either encourage flocculation or decay. For instance, the combination of suspended sediment concentration (0.2–5 g/l) and turbulent shear stress (~0.2–0.5 Pa) can effectively increase the particle collision frequency, thus promoting flocculation. Nonetheless, inordinately high levels of turbulent shear can curb overall floc growth. Salinity (~5–20 ppt) has an optimal span for promoting sediment flocculation. Organic matter, such as EPS, typically enhances sediment stability but can degrade over time, leading to floc decay.

When considering the range of *Biological Factors*: while many studies have focused on physical and chemical aspects of sediment flocculation, there has been a growing interest in understanding the role of biological factors. However, these studies often do not distinguish between the effects of organic matter and microbial communities. It is essential to differentiate between the effects of these two factors in the context of sediment flocculation.

In the context of sediment flocculation, microbial communities, particularly microalgae, can form large flocs that catch sediment particles within their network. EPS can also influence the surface properties of sediment. The effects of these two biological factors are typically studied separately.

To conclude, this chapter provides a clear overview of the various aspects of estuarine sediment flocculation, emphasizing the complex nature of this process and the need for a more nuanced understanding of the role of biological factors. Inevitably, flocculation is controlled by a series of interrelated kinetics that tend to be site-specific in nature [228]. The accompanying **Figure 10** provides a visual representation of the different processes involved in flocculation, further aiding in the comprehension of this complex phenomenon.

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River deltas are among the planet's most dynamic and vulnerable landscapes. These shallow yet highly productive environments sustain millions of people, support critical biodiversity, and underpin major economic activities - but they are also under intensifying pressure from human development, climate change, and environmental degradation. Managing them sustainably requires a deep, interdisciplinary understanding of the forces that shape them. *The Changing Function of River Deltas - Cross-Disciplinary Perspectives* brings together cutting-edge insights from leading scientists around the world to illuminate the latest developments in delta studies. Covering themes such as climate change impacts, water quality, geomorphology, sedimentation, flocculation, ecosystem dynamics, and the social dimensions of delta management, this volume offers a comprehensive and authoritative overview of the state of the field. Whether you are a researcher, practitioner, or policymaker, *The Changing Function of River Deltas - Cross-Disciplinary Perspectives* provides an essential resource for understanding, managing, and protecting one of Earth's most vital and threatened systems.

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