Coastal Processes and Sediment Transport: A Synthesis

Executive Summary

Coastal processes are the physical mechanisms governing the dynamic interplay of energy, sediment, and morphology that shapes coastlines. The primary drivers are wind-generated waves, gravitationally forced tides, and various currents, which collectively dictate erosion, accretion, and long-term coastal evolution. Sediment transport, the core process of morphological change, occurs in two fundamental directions: cross-shore and longshore.

Cross-shore transport, the movement of sediment perpendicular to the shoreline, controls the beach profile's response to changing energy conditions. During storms, high-energy waves move sediment offshore, flattening the beach and forming bars. In calmer, fair-weather periods, lower-energy waves gradually move sediment back onshore, rebuilding the berm. This process is oscillatory, event-dependent, and non-linear, making it difficult to capture with simple empirical formulas. Consequently, modern coastal engineering relies on process-based numerical models (e.g., XBeach, SBEACH) that simulate the complex hydrodynamics.

Longshore transport, or littoral drift, is the movement of sediment parallel to the coast, driven by a longshore current generated by obliquely breaking waves. This process is the primary driver of planform shoreline evolution, responsible for forming and reshaping features like spits and inlets. Unlike cross-shore transport, it is a more continuous, one-way drift that can be effectively estimated with well-calibrated, wave-energy-based empirical models. Understanding both transport mechanisms is essential for designing resilient infrastructure, managing erosion, and ensuring the sustainable development of coastal zones.

1. Fundamental Coastal Forcing Mechanisms

The evolution of coastal environments is dictated by a set of primary physical drivers that transfer energy and mobilize sediment. These mechanisms operate over various time and spatial scales, from seconds to centuries.

Process	Driver	Typical Time Scale	Main Effect
Wave action	Wind	Seconds to days	Sediment transport, erosion, accretion
Tides	Gravitational forces	Hours to days	Flooding, mixing, tidal currents
Storm surges	Wind + pressure	Days	Coastal flooding, dune erosion
Longshore drift	Oblique waves	Days to years	Alongshore sediment movement
Sea-level rise	Climate & tectonics	Decades to centuries	Coastal retreat, inundation

1.1 Waves

Waves, generated primarily by wind acting on the sea surface, are the dominant energy source for coastal change.

- **Key Parameters:** Wave height (H), period (T), and length (L).
- **Wave Transformation:** As waves travel from deep to shallow water, they undergo significant changes:
  - **Refraction:** The bending of waves as their speed changes with water depth.
  - **Shoaling:** An increase in wave height as water depth decreases.
  - **Breaking:** Occurs when wave steepness becomes unstable, typically when the ratio of wave height to water depth (H/d) approaches 0.78.
  - **Set-down and Set-up:** A lowering of the mean water level before breaking and a rise after breaking, caused by gradients in radiation stress.

1.2 Tides

Tides are the periodic rise and fall of the sea level caused by the gravitational forces of the moon and sun.

- **Types:** Semidiurnal (two high and two low tides per day), diurnal (one high and one low tide per day), and mixed.
- **Effects:** Tidal currents are a significant agent for sediment transport, particularly in estuaries and inlets.

1.3 Currents

Currents are responsible for transporting sediment once it is mobilized by wave action.

- **Types:** Include tidal currents, wind-driven currents, rip currents, and longshore currents.
- **Longshore Current:** Generated by obliquely breaking waves, this current is the primary driver of sediment transport parallel to the coastline (littoral drift).

1.4 Storm Surges and Sea Level

These factors influence coastal processes over both short and long timescales.

- **Storm Surge:** A short-term rise in sea level caused by a storm's strong onshore winds and low atmospheric pressure.
- **Sea-Level Rise:** Long-term trends in relative sea level influenced by climate change and local factors like land subsidence.

2. The Mechanics of Coastal Sediment Transport

Coastal sediment transport is the process by which particles like sand, silt, and gravel are moved by waves, currents, and tides. The behavior of this sediment is fundamentally tied to its physical characteristics.

2.1 Characteristics of Coastal Sediment

- **Grain Size Distribution:** Coastal sediments typically follow a log-normal distribution. The phi scale is often used, where $\Phi = \log_2(D_0/D)$ with $D_0 = 1$ mm. Key parameters include D_{50} (median diameter) and the sorting range indicated by D_{16} and D_{84}. Typical beach sand has a D_{50} of 0.2-0.5 mm.
- **Density and Shape:** The density of quartz sand is approximately 2650 kg/m³. The particle shape factor influences drag and settling velocity.
- **Settling Velocity (w_s):** This is the speed at which a particle falls through the water column. For coarse sand, it can be calculated as `ws = sqrt((s - 1) * g * D)`, where *s* is the specific gravity ratio of sediment to water.

2.2 Beach Classifications and Sediment Properties

The type of sediment on a beach directly correlates with its physical profile, particularly its slope.

Beach Type	Typical Slope	Median Diameter (D_{50})	Sorting ($(D_{84}/D_{16})^{1/2}$)
Sand beach	1:100+	0.3 mm	1.3 → 3.0
Shingle/sand mixed beach	1:30	2.0 mm	> 14
Shingle upper/sand lower beach	Shingle 1:10, Sand 1:40	10 → 40 mm, 0.3 mm	Shingle 1.3 → 3.5, Sand 1.3 → 3.0
Shingle beach	1:6 → 1:10	10 → 40 mm	1.3 → 3.0

2.3 Initiation of Sediment Motion

Sediment begins to move when the force exerted by the fluid flow, known as the bed shear stress (τ), exceeds a critical threshold value (τ_c).

- **Shields Criterion:** This principle defines the critical condition for motion. The critical shear stress is given by `τc = θc * (ρs - ρ) * g * D`, where θ_c is the critical dimensionless Shields parameter.
- **Shields Parameter (θ_c):** This parameter is a function of the particle Reynolds number. Typical values for θ_c are ~0.05 for fine sand and ~0.06-0.08 for gravel.

3. Modes and Directions of Sediment Transport

Once in motion, sediment is transported in different modes and in two primary directions relative to the shoreline.

3.1 Modes of Transport

- **Bed Load:** Sediment moves by rolling, sliding, or saltating (bouncing) close to the seabed. The transport rate is often estimated using empirical formulas like the Meyer-Peter-Müller equation.
- **Suspended Load:** Finer sediments are carried higher in the water column, supported by turbulence. This is governed by a balance between upward turbulent diffusion and downward settling. The vertical distribution of sediment concentration is often described by the Rouse profile.
- **Total Load:** The sum of bed load and suspended load ($Q_t = Q_\beta + Q_s$).

3.2 Directional Components: Cross-Shore vs. Longshore

Sediment transport is best understood by separating it into its cross-shore and longshore components, which operate on different principles and timescales.

Aspect	Longshore Transport	Cross-Shore Transport
Dominant Driver	Wave energy flux alongshore (steady component)	Oscillatory flow and wave breaking across the beach profile
Primary Motion	Continuous current-driven sediment drift	Alternating onshore/offshore sediment movement
Transport Direction	Largely one-way (net littoral drift)	Two-way, strongly time-varying
Modeling Feasibility	Can be related to steady energy flux (well-calibrated models exist, e.g., CERC)	Depends on wave asymmetry, undertow, and return flow (not easily generalized)
Morphologic Effect	Governs planform evolution (spits, inlets) over months to years	Dominates profile response (berm/bar migration) over days to months

4. Cross-Shore Sediment Transport and Beach Profile Dynamics

Cross-shore transport governs the short-term changes to the beach profile, acting as a dynamic exchange of sediment between the dune, beach, and offshore regions.

4.1 The Storm-Recovery Cycle

The beach profile adapts to alternating high- and low-energy conditions.

- **Storm Conditions (Erosion Phase):** High waves and surge erode the dune and berm. Sand is transported offshore, forming nearshore bars, and the beach profile flattens.
- **Calm Conditions (Recovery Phase):** Smaller, asymmetrical waves drive onshore transport. Bars migrate landward, rebuilding the berm. The system gradually seeks an equilibrium profile.

4.2 Key Concepts in Cross-Shore Transport

- **Equilibrium Wave Height (Hbe):** This is the theoretical wave height at which there is no net cross-shore transport; onshore and offshore forces are balanced. It represents a threshold between erosive and accretional conditions. Coarser-grained, steeper beaches have a larger Hbe, while fine-grained, gentler beaches have a smaller Hbe.
- **Depth of Closure (h_c):** The water depth beyond which there is no significant cross-shore sediment exchange under the prevailing wave climate. It marks the seaward limit of the active beach profile.

4.3 Modeling Cross-Shore Transport

Simple empirical formulas for cross-shore transport are uncommon and unreliable because the process is inherently unsteady, non-linear, and site-specific. Instead, modern practice relies on more sophisticated approaches.

Type	Common Formula / Models	Usefulness
Empirical (simple)	$Q_x = K_x * (H_\beta^2 - H_{\beta e}^2)$	Rough qualitative estimates (storm vs. fair weather).
Energetics-based (semi-empirical)	Bailard (1981), Dally & Dean (1986)	Good for research and profile evolution models. Rooted in physical reasoning.
Process-based (numerical)	SBEACH, XBeach, Delft3D, CSHORE	Standard in modern coastal engineering practice. Explicitly simulates wave-current-sediment interactions.

5. Longshore Sediment Transport and Shoreline Evolution

Longshore transport, also known as littoral drift, is the movement of sediment parallel to the shoreline and is the primary mechanism for large-scale, long-term coastal change.

5.1 Mechanism and Governing Formula

When waves approach the shore at an angle, they generate a longshore current that carries sediment. The transport rate depends on wave energy and the angle of approach. The total longshore transport rate (Q) is often estimated using the CERC formula: $Q = K * H_\beta^{2.5} * \sin(2\alpha_\beta)$ Where:

- **Q**: Longshore sediment transport rate.
- **K**: Empirical coefficient depending on sediment properties.
- **H_β**: Breaking wave height.
- **α_β**: Breaker angle (angle between wave crests and the shoreline).

5.2 Case Study: Littoral Drift Along the New Jersey Shore

The New Jersey coast provides a clear example of longshore transport patterns, featuring a distinct nodal zone where the dominant drift direction reverses.

- **Nodal Zone:** Located roughly between Ocean and Mammoth counties, this transition area separates northward and southward drift.
- **Northern New Jersey:** Sediment transport is predominantly northward, moving sand from the Manasquan area towards the spit of Sandy Hook. Evidence includes sand accumulation on the south side of structures like the Manasquan Inlet jetties.
- **Southern New Jersey:** The drift is predominantly southward, carrying sand towards Cape May. Evidence includes sediment buildup on the north side of structures at Holgate and the Cape May Passage.

6. Human Influences and Morphodynamics

Coastal morphology is the result of the interaction between hydrodynamics and sediment transport, creating features like beaches, dunes, and inlets. This natural system is often altered by human activities.

- **Bed Forms:** The interaction between flow and sediment creates bedforms like ripples (under oscillatory flow) and dunes (under steady currents), which in turn influence flow resistance and energy dissipation.
- **Coastal Structures:** Groins, jetties, seawalls, and breakwaters are built to stabilize shorelines or maintain navigation channels but inevitably alter natural sediment pathways, often causing erosion downdrift.
- **Dredging and Nourishment:** Artificial methods used to manage sediment, such as deepening channels or replenishing eroded beaches.
- **Coastal Management:** The practice of balancing human needs with natural processes to achieve goals like erosion control, habitat preservation, and coastal resilience.

7. Conclusion and Key Takeaways

Coastal processes create a dynamic equilibrium among energy, sediment, and morphology. A thorough understanding of these interactions is fundamental for predicting shoreline changes, designing effective and resilient coastal infrastructure, and managing coastal zones sustainably.

- Sediment motion is initiated when hydrodynamic forces from waves and currents exceed a critical threshold defined by the Shields criterion.
- Cross-shore transport, driven by wave asymmetry and undertow, governs the beach profile's response to storms and calm periods.
- Longshore transport, driven by obliquely breaking waves, governs the long-term evolution of the shoreline's planform.
- Proficient coastal engineering and management depend on accurately assessing these distinct but interconnected transport processes.