Beyond Gravity: The Mechanics of Cohesive Sediment Transport

How electrochemistry, biology, and history govern the lifecycle of mud, clay, and silt

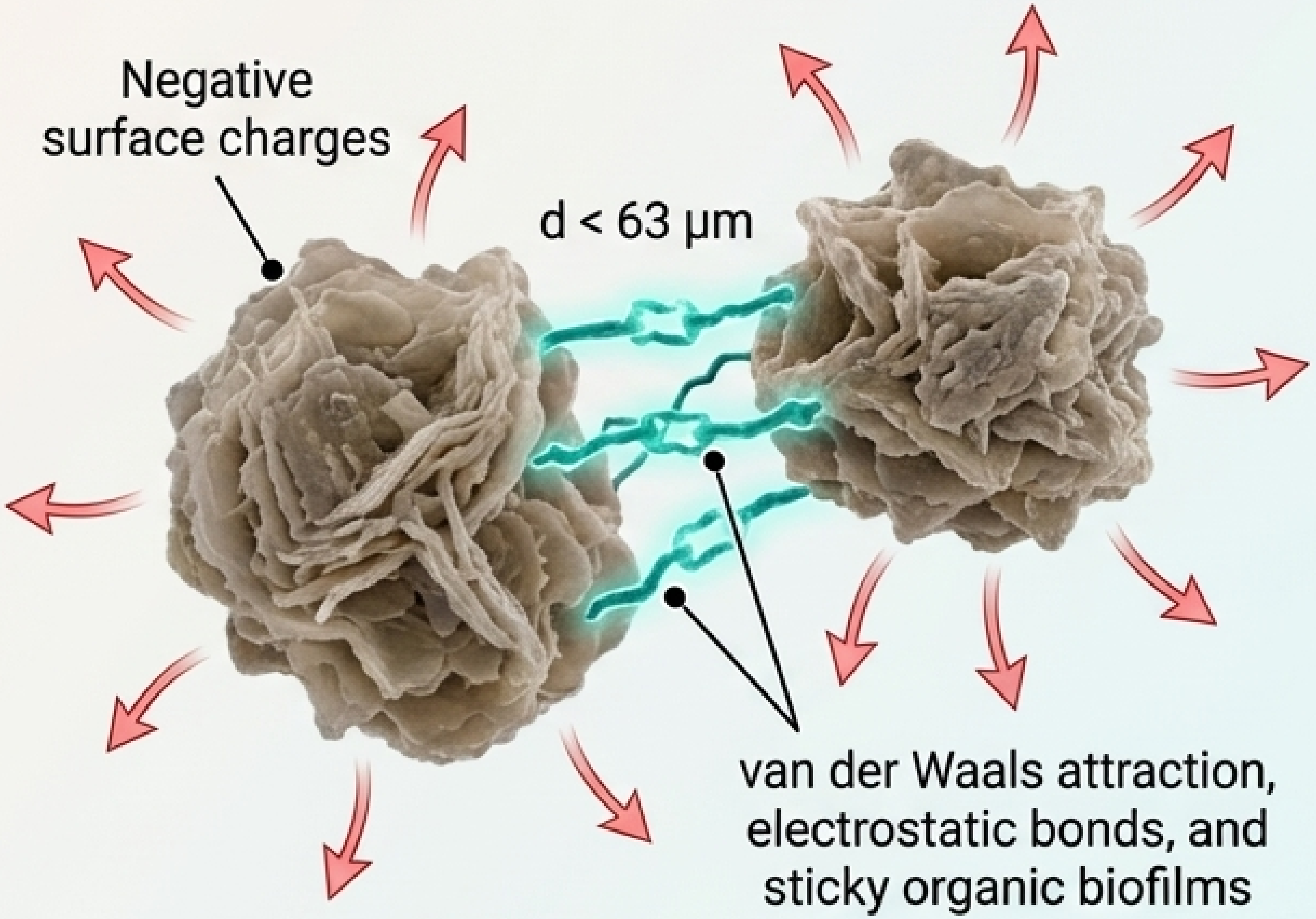
A comprehensive synthesis for engineers and hydrologists

Diagnostic Matrix

Noncohesive (Sand)	Cohesive (Clay)
Gravity vs. Fluid Shear	Electrochemical + Biological + Gravity
Independent grains	Flocs (dynamic aggregates)
Well-defined (Shields curve)	Ill-defined, history-dependent
Size only (Stokes)	Variable (flocculation, salinity, concentration)
Deterministic	Probabilistic (Krone model)
Grain Size (D50)	% Fines (> 10-20% threshold)

Rule 1: If the clay fraction exceeds 10%, gravity and fluid shear are no longer the sole actors.

The Cohesion Engine



Equation Block

Mohr-Coulomb Cohesion Law

$$\tau = \tau_y + \sigma \tan \phi$$

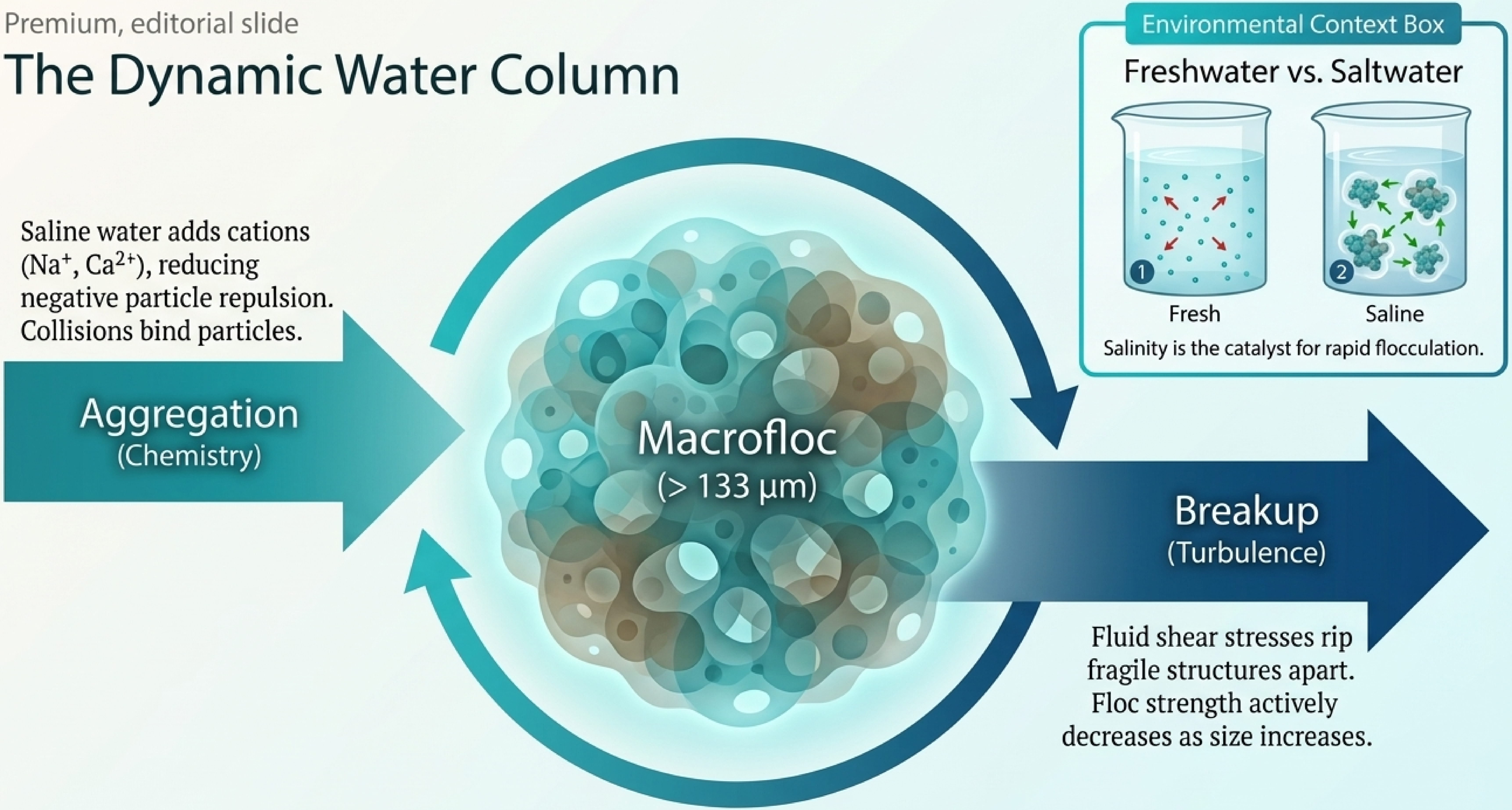
Yield Stress (Cohesion) — The critical chemical/biological baseline resistance.

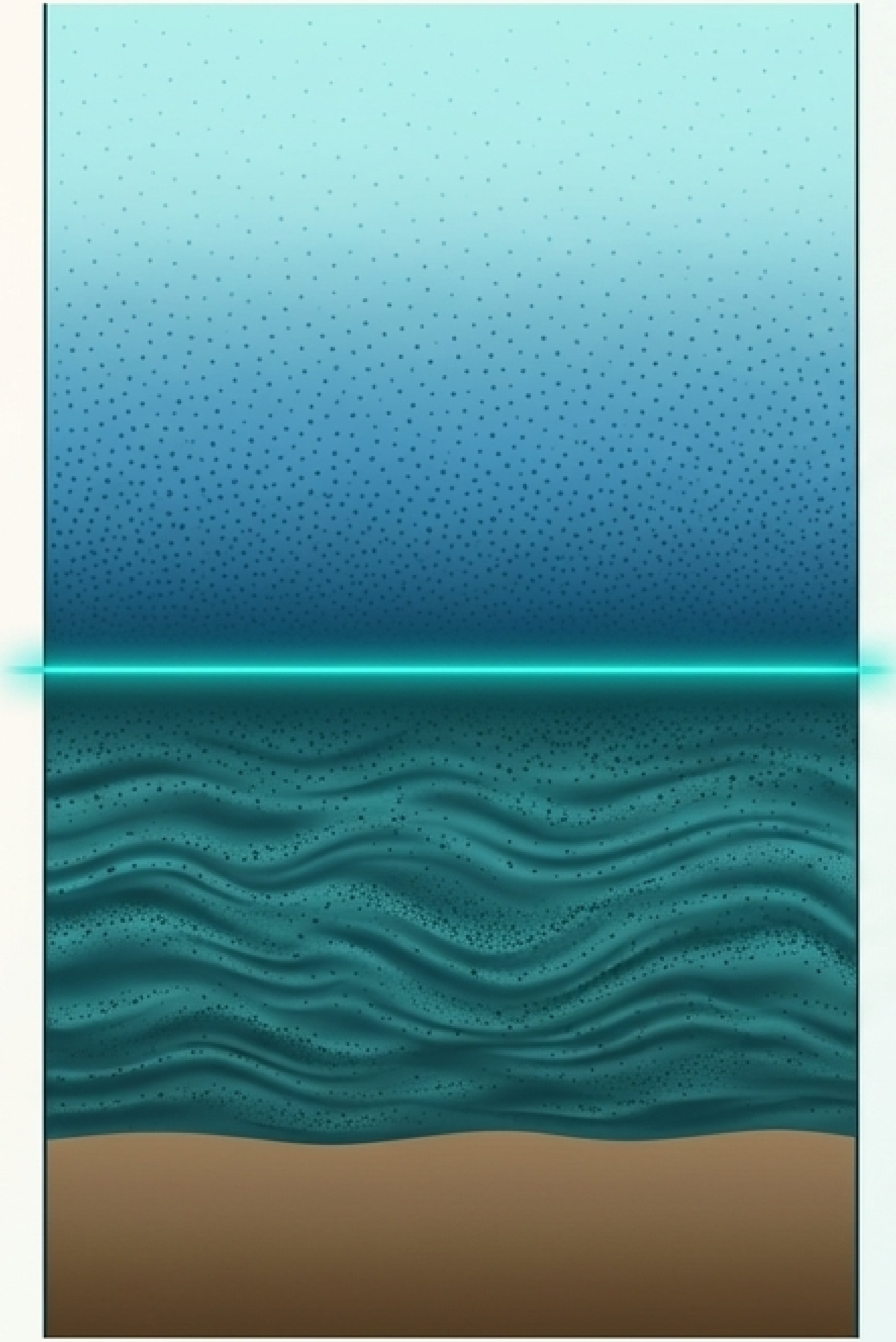
Internal Friction — standard mechanical resistance.

Unlike sand, cohesive sediment maintains shear resistance (τ_y) even when effective normal stress (σ) drops to zero. The strength comes from the chemistry, not just the weight.

Premium, editorial slide

The Dynamic Water Column





Mixed Suspension Layer
Constant concentration,
minimal interaction.

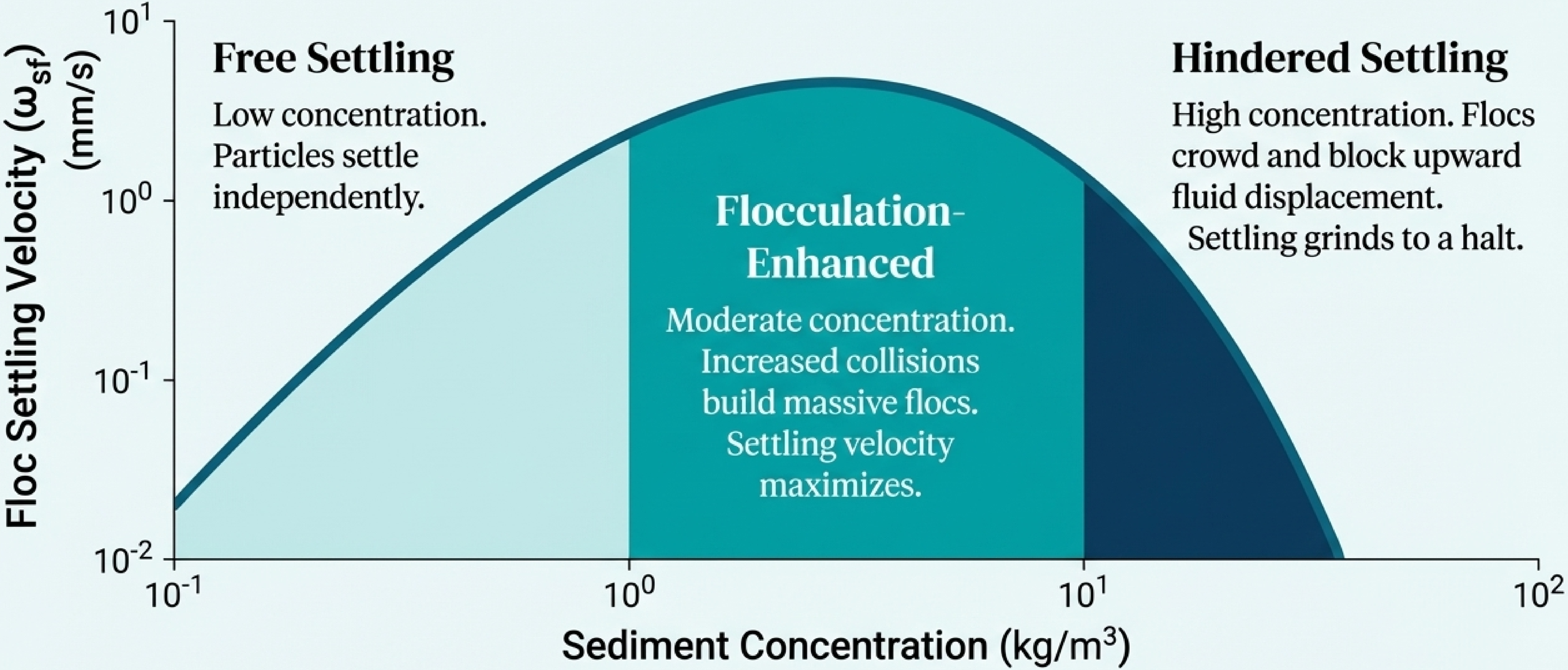
Stratified Layer
Settling begins to
outpace mixing.

The Lutocline
The critical transition zone.
A sharp gradient where sediment
concentration spikes.

Fluid Mud Layer
Behaves as a non-Newtonian fluid.
Capable of stationary entrainment.

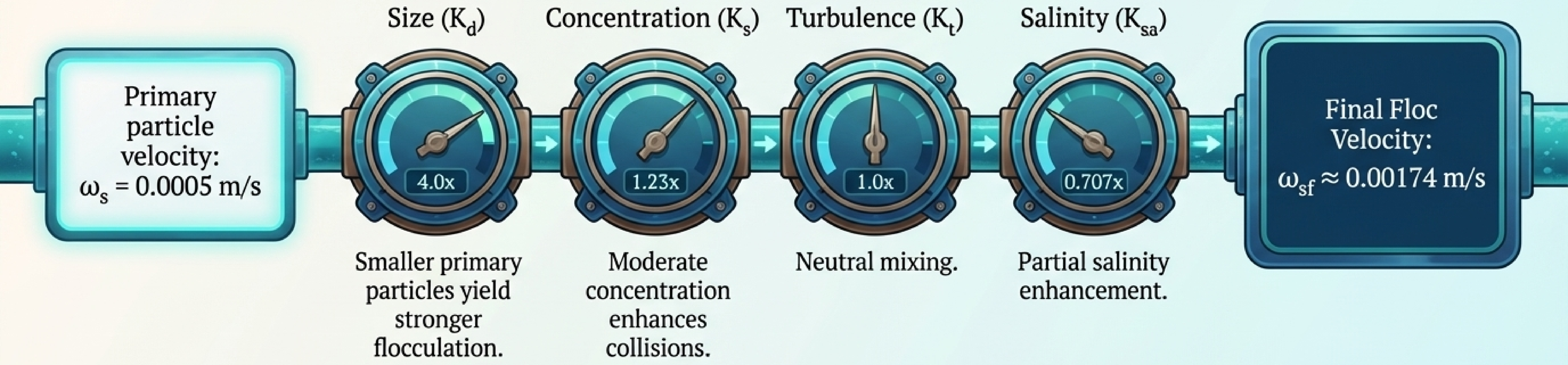
Consolidated Bed
Measurable effective stress.
History-dependent strength.

Sediment behavior is fundamentally distinct in each vertical layer. A particle's dynamics change as it descends through the Lutocline.



More sediment does not mean faster deposition. The system chokes itself at high concentrations.

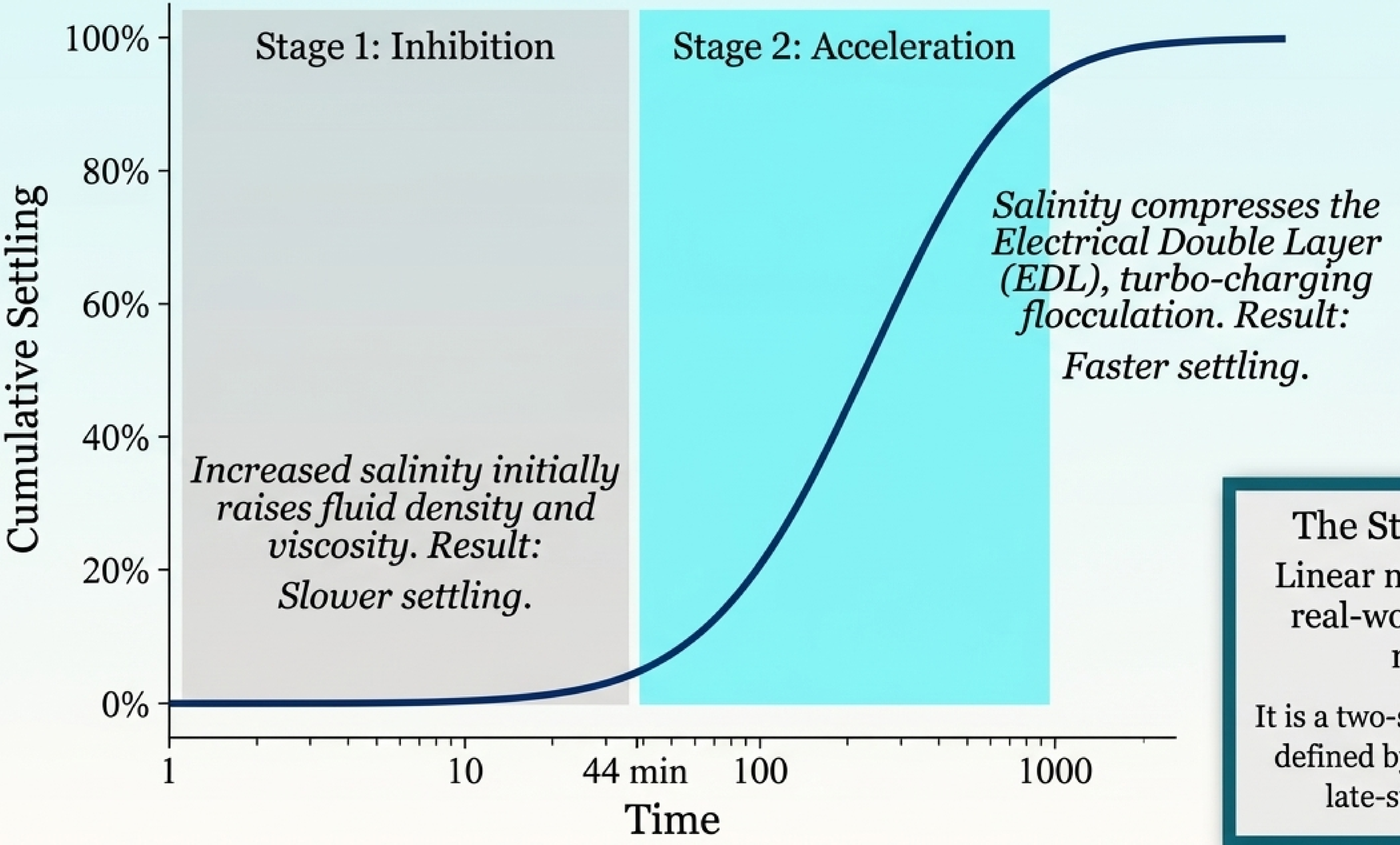
Pipeline Flowchart



$$\omega_{sf} = K_d K_s K_t K_{sa} \omega_s$$

The Flocculation Multiplier: In this real-world example, dynamic interactions cause the sediment to settle ~3.5x faster than gravity alone would predict.

Based on Li et al. (2025).



The Stokes-Law Trap:

Linear models fail because real-world settling is not monotonic.

It is a two-stage temporal process defined by early inhibition and late-stage acceleration.

Low Suspended Sediment Concentration (SSC)

When sediment concentration is low, Salinity drives the system.

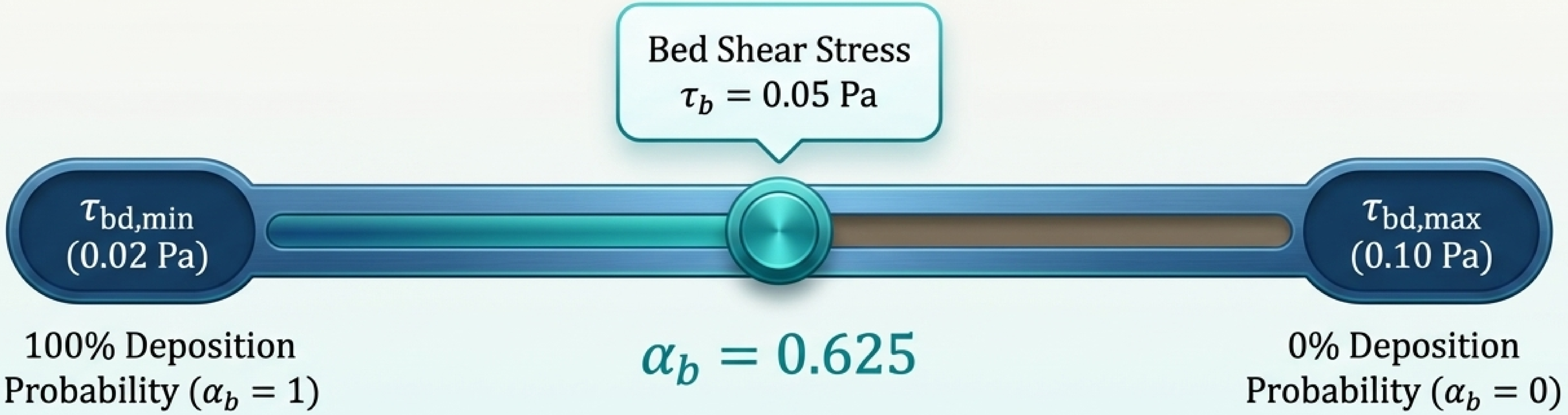
It dictates floc size by reducing electrostatic repulsion.

High Suspended Sediment Concentration (SSC)

When concentration is extremely high (>1200 NTU), the Salinity effect vanishes.

Physical particle collisions overwhelm chemical bonds.

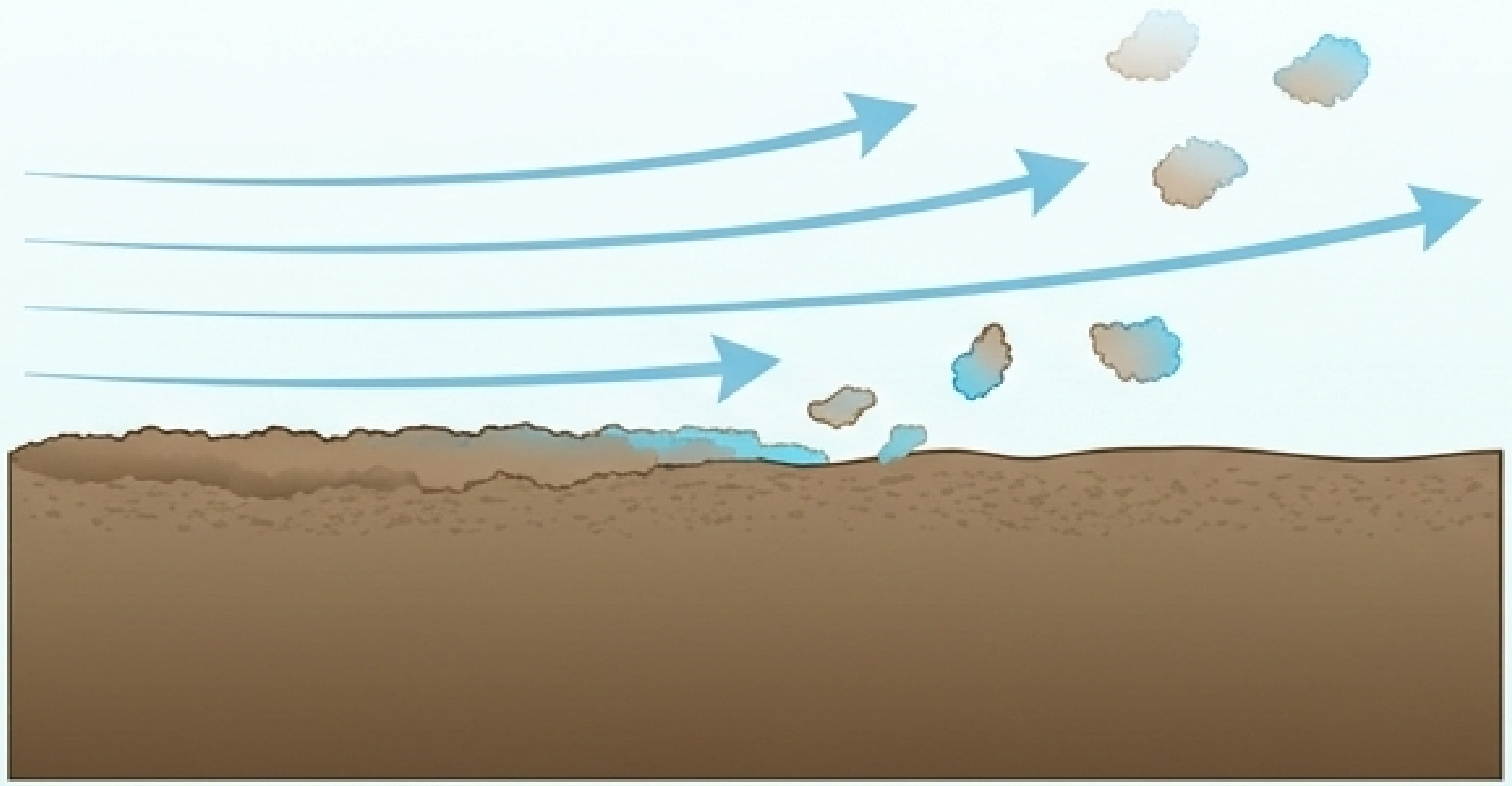
The Synergistic Trap: You cannot model salinity or concentration in isolation. The impact of water chemistry scales inversely with the volume of mud in suspension.



$$D_b = \alpha_b \omega_{sf} C$$

Unlike sand, which drops deterministically when flow slows, mud deposition is governed by a sliding probability (α_b) calculated between critical thresholds.

Mode 1: Surface Floc Erosion



Gradual shearing of surface aggregates.

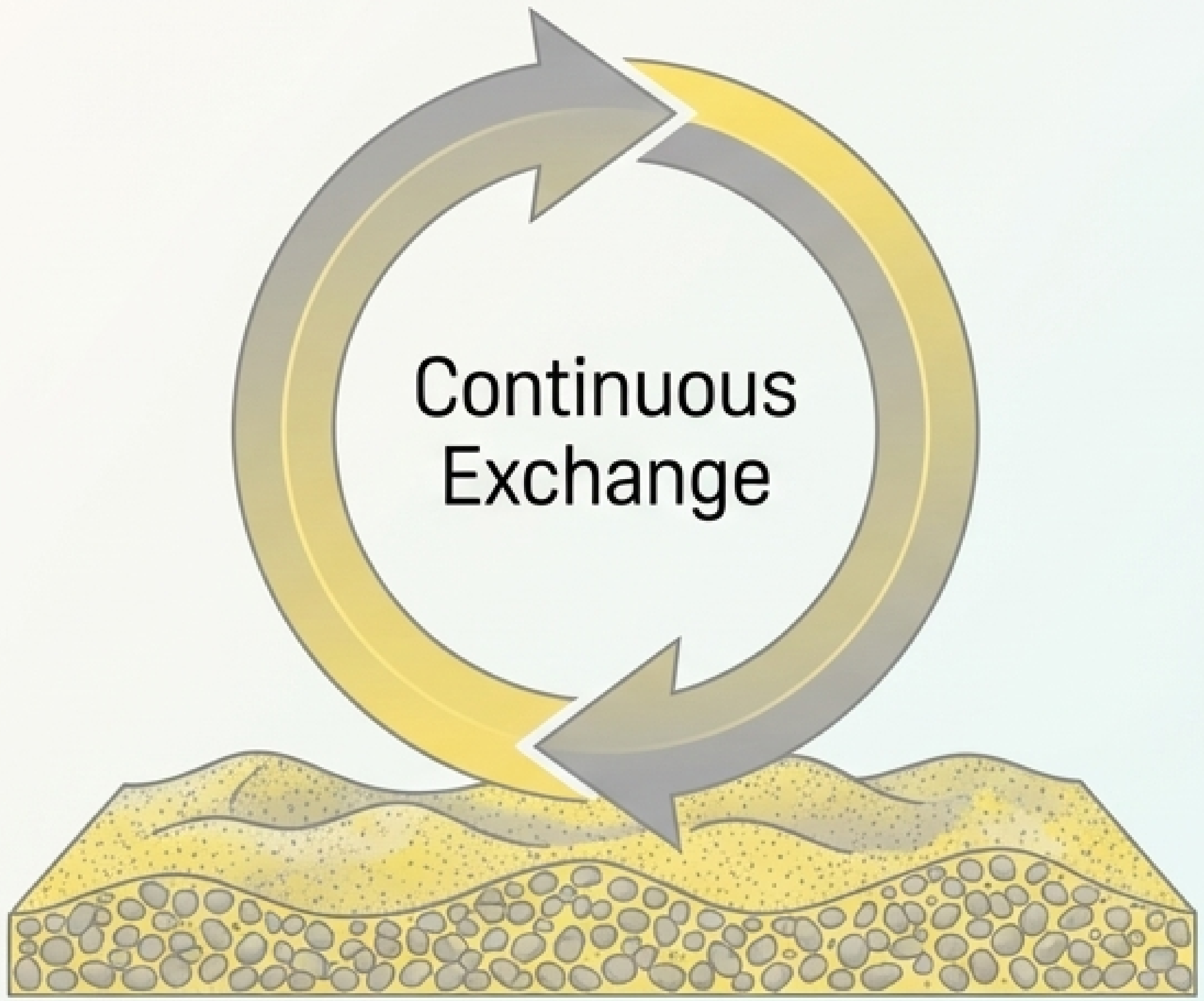
Mode 2: Mass Erosion

Catastrophic chunk failure when bed strength is fundamentally exceeded ($\tau_{\mathrm{cm}} \approx 2\text{-}5\ \tau_{\mathrm{ce}}$).

$$E_b = M\left(\frac{\tau_b}{\tau_{ce}} - 1\right)$$

Erosion (E_b) is a linear function of "Excess Shear"—how far the actual force pushes past the bed's specific threshold (τ_{ce}).

Noncohesive (Sand)

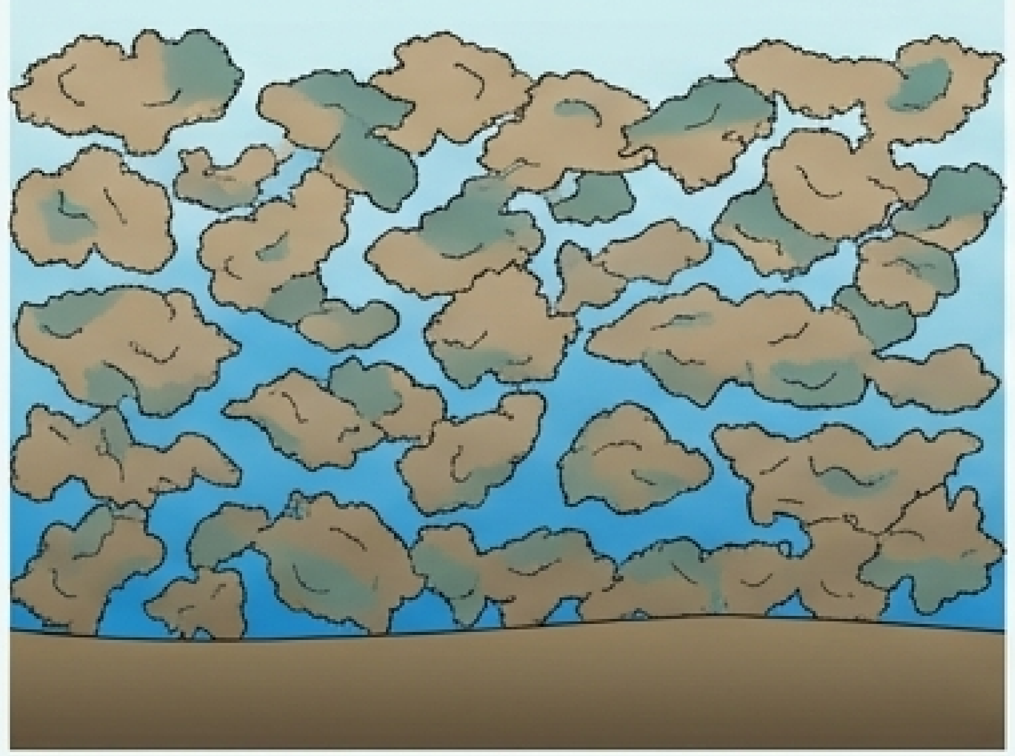


Erosion and deposition happen simultaneously and constantly. The bed is in dynamic equilibrium.

Cohesive (Clay)

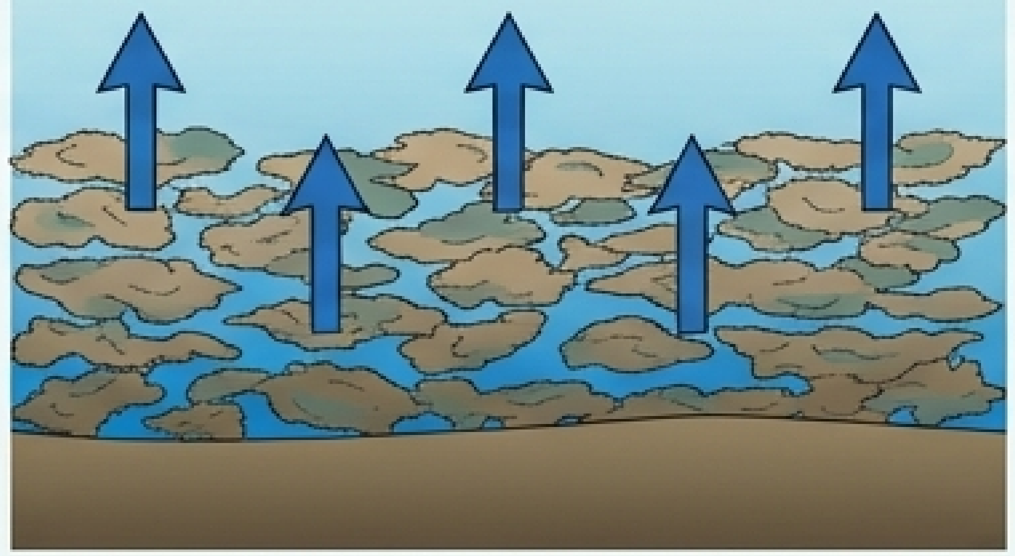
Erosion and deposition rarely occur at the same time. The system exists in discrete, mutually exclusive phases based on shear stress thresholds.

Stage 1: Fresh Deposit (Time = 0)



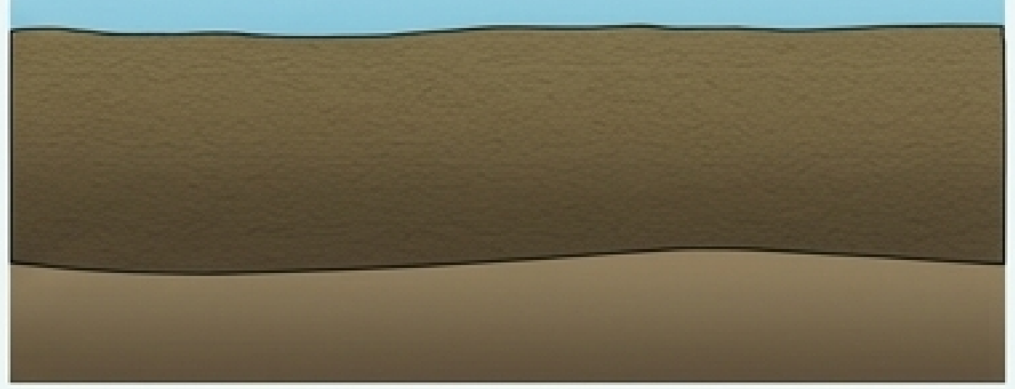
High water content.
Easily eroded fluff layer.
Low τ_{ce}.

Stage 2: Deforming Bed (Time = Hours/Days)



Weight of new sediment forces pore water out.
Density increases.

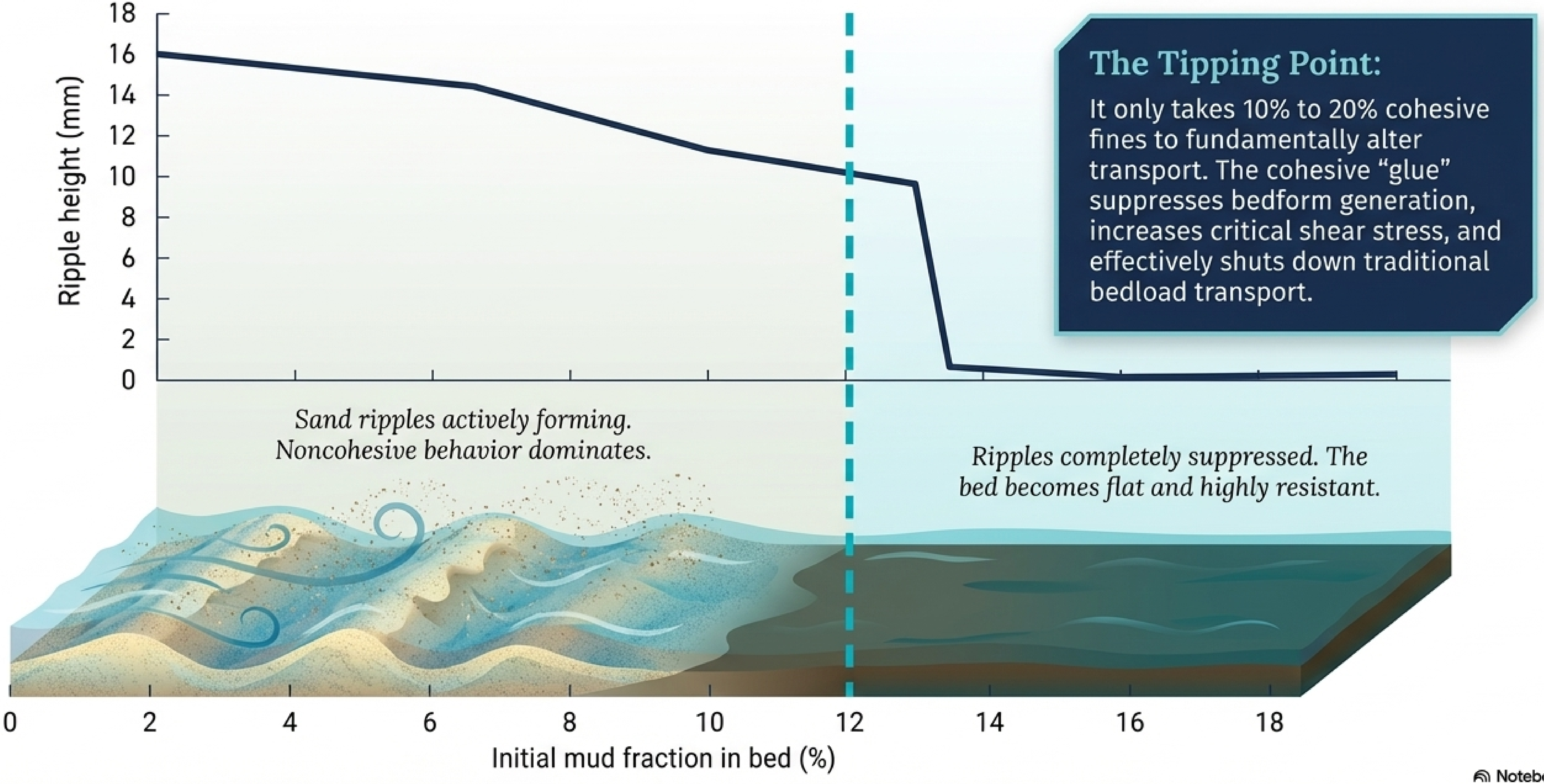
Stage 3: Consolidated Bed (Time = Weeks)

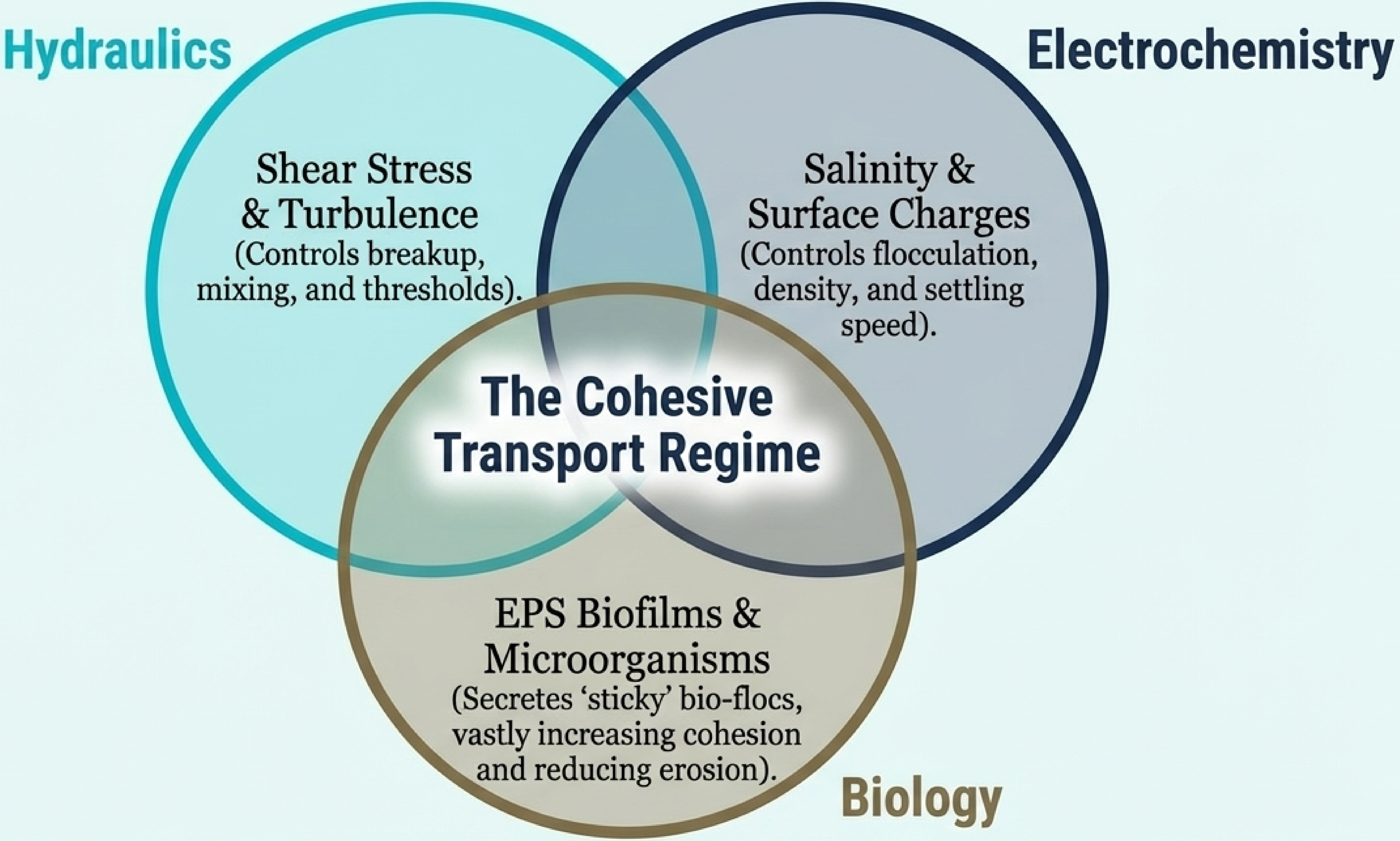


High density.
High structural strength.
Massively increased erosion threshold (τ_{ce}).

**Key Takeaway: Erodibility is an artifact of time.
The longer cohesive sediment sits, the harder it is to move.**

SEDIMENT BED DYNAMICS: RIPPLE HEIGHT VS. MUD FRACTION





Sand is driven by physics. Mud is a holistic, multi-physics ecosystem where engineering models must account for chemical bonds and biological timeframes.