Fluid Mechanics Principles for Sediment Transport

Executive Summary

This briefing synthesizes the foundational principles of fluid mechanics as they apply to sediment transport. The central thesis is that sediment transport is fundamentally governed by fluid mechanics, with specific hydraulic variables being of primary importance.

A critical paradigm shift is the move from emphasizing **flow velocity** to emphasizing **bed shear stress** $\tau_0$and **turbulence** as the principal drivers of sediment motion. Bed shear stress—defined as the force per unit area exerted by flowing water on the channel boundary—is obtained from a force balance in steady, uniform open-channel flow:

$$\tau_0 = \gamma RS$$

Nearly all sediment transport formulations—incipient motion, bedload, suspended load, and scour criteria—are built upon this variable.

Flow resistance provides the essential link between hydraulics and sediment movement and is quantified using either:

- Darcy–Weisbach friction factor f
- Manning's roughness coefficient n

Natural sediment-transporting rivers operate almost exclusively in **turbulent flow**. Within turbulence, the interaction between bed roughness (e.g., grain size k_s) and the viscous sublayer produces three regimes: hydraulically smooth, transitional, and hydraulically rough. The prevailing regime controls resistance behavior and therefore sediment transport.

Finally, while steady, uniform flow forms the conceptual foundation, realistic river processes require **unsteady, non-uniform flow analysis** using the Saint-Venant equations.

I. Foundational Concepts in Open-Channel Flow

Purpose and Rationale

Sediment transport theory is built directly on fluid mechanics. Key hydraulic concepts that control sediment behavior include:

- Flow resistance
- Shear stress
- Turbulence
- Flow unsteadiness

These directly govern:

- Initiation of motion
- Transport rate
- Bedforms and morphodynamics

Governing Principles

Fluid mechanics rests on three conservation laws:

1. **Mass (Continuity)**
2. **Momentum (Newton's Second Law)** → origin of bed shear stress
3. **Energy (Bernoulli)** → origin of flow resistance

Classification of Open-Channel Flow

By Time

- Steady: $\partial / \partial t = 0$
- Unsteady: $\partial / \partial t \neq 0$

By Space

- Uniform: $\partial / \partial x = 0$
- Non-uniform: $\partial / \partial x \neq 0$

Analysis begins with steady, uniform, one-dimensional flow and later extends to unsteady flow.

II. Bed Shear Stress: The Primary Driver of Sediment Motion

Central Argument

Velocity is secondary; **bed shear stress and turbulence are primary**.

Sediment motion depends on forces acting on grains, not simply bulk flow speed.

Force Balance in Uniform Flow

In steady, uniform flow:

$$\text{Driving Force} = \text{Resisting Force}$$

Driving force = downslope component of water weight
Resisting force = boundary friction

Fundamental Equation

$$\tau_0 = \gamma R S$$

Where:

- τ_0= boundary shear stress
- $\gamma = \rho g$= specific weight of water
- $R = A/P$= hydraulic radius
- S= energy slope

Derivation Assumptions

- Steady flow
- Uniform flow
- Hydrostatic pressure distribution
- Small slopes

Under these conditions, pressure forces cancel and weight balances friction.

Relevance to Sediment Transport

Bed shear stress determines:

- Incipient motion (e.g., Shields parameter)
- Bedload and suspended-load formulas
- Bedform regimes
- Channel stability and scour

III. Flow Resistance and Turbulent Regimes

Link Between Resistance and Shear Stress

Darcy–Weisbach form:

$$\tau_0 = \frac{f}{8}\rho U^2$$

Equating with $\tau_0 = \gamma RS$ links velocity, slope, and resistance.

Laminar vs. Turbulent Flow

Reynolds number:

$$Re = \frac{4UR}{\nu}$$

- $Re < 500$: Laminar
- $500 < Re < 2000$: Transitional
- $Re > 2000$: Turbulent

Natural rivers: almost always turbulent.

Structure of Turbulent Flow Near Bed

- **Viscous sublayer** (thin, smooth)
- **Fully turbulent region** (dominant)

Shear velocity:

$$u_* = \sqrt{\frac{\tau_0}{\rho}}$$

Controls turbulence intensity and sediment entrainment.

Roughness-Based Turbulent Regimes

Based on:

$$\frac{k_s u_*}{\nu}$$

Regime	Criterion	Description	f Dependency
Hydraulically smooth	< 5	Roughness buried in sublayer	Depends on Re
Transitional	5–70	Partial protrusion	Depends on Re and roughness
Hydraulically rough	> 70	Roughness fully protrudes	Depends only on R/k_s

For fully rough flow, f is independent of Reynolds number.

IV. Empirical and Practical Formulations

Manning's Equation

Discharge:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

Velocity:

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

Manning's n represents combined effects of:

- Grain size
- Bedforms
- Vegetation
- Irregularity

Important: n changes as bedforms change.

Typical Manning's n Values

Channel Type	n
Concrete	0.012–0.015
Earth, uniform	0.018–0.022
Natural, clean	0.025–0.035
Natural, winding	0.033–0.045
Floodplain, brush	0.040–0.060
Heavy timber	0.080–0.120

Hydraulic Geometry

Relationships for:

- Area $A(y)$
- Wetted perimeter $P(y)$
- Hydraulic radius $R(y)$

are required for numerical modeling.

V. Unsteady, Non-Uniform Flow Dynamics

Limitations of Uniform Flow

Uniform flow cannot represent:

- Flood waves
- Dam breaks
- Hydraulic jumps
- Long-term morphology change

Saint-Venant Equations (1-D)

Continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial (UA)}{\partial x} = 0$$

Momentum:

Accounts for acceleration, pressure, gravity, and friction.

Friction slope S_f closure via:

- Manning
- Darcy–Weisbach
- Chezy

Solved numerically.

Significance for Sediment Transport

Unsteady hydraulics controls:

- Sediment pulses
- Flood hysteresis
- Morphologic evolution
- Reservoir sedimentation
- Extreme-event scour

VI. Key Takeaways

- Bed shear stress is the primary hydraulic driver of sediment transport.
- Flow resistance links hydraulics and sediment motion.
- Roughness–sublayer interaction defines turbulent regime.
- Manning's n is not constant for mobile beds.
- Unsteady flow modeling is essential for real rivers.