143SRPP
Stream Revitalization: Principles & Practices

LECTURE 4

Fluvial Geomorphology

Fluvial Processes:
Sediment Transport, Pool-riffle Maintenance

Winter 2019 Semester

14 October 2019

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Fluvial Processes: Sediment Transport

Initiation of Sediment Motion:

Critical shear stress for flow over a granular bed:

Forces acting on a non-cohesive sediment particle include:
particle weight (F_W),
bouyancy force (F_B),
lift force (F_L),
drag force (F_D),
and
resisting force (F_R).

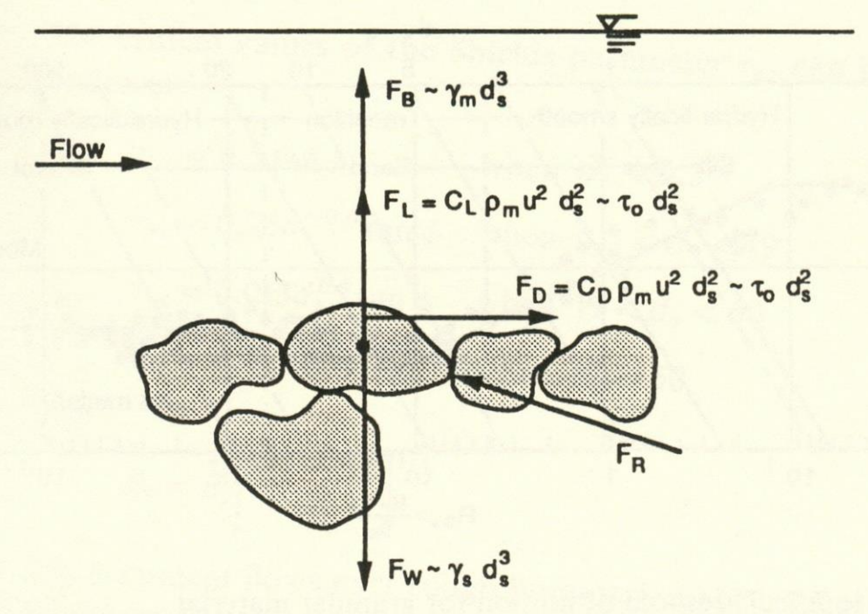


Figure 7.4. Force diagram under steady uniform flow

Julien (1998)

Fluvial Processes: Sediment Transport

The **threshold for sediment motion** is defined in terms of a critical shear stress, τ_c ; it is a function of:

$\tau_c = f_1(\gamma_s - \gamma, d_s, \rho_m, \mu)$ ***for*** $(\tau_0 = \tau_c)$ $u_{*c} = (\tau_c/\rho)^{1/2}$

Dimensional analysis leads to a solution, in which $u_{*c} = (\tau_c/\rho_m)^{1/2}$ is the critical value for shear velocity and $\nu = \mu/\rho$, yielding:

$$\frac{\tau_C}{(\gamma_S - \gamma)d_S} = f_2\left(\frac{u_{*C} d_S}{\nu}\right)$$

critical Shields parameter: →

$$\tau_{*C} = \frac{\tau_C}{(\gamma_S - \gamma)d_S}$$

critical particle Reynolds number: →

$$\mathbf{Re}_{*C} = \frac{u_{*C} d_S}{\nu}$$

Fluvial Processes: Sediment Transport

Threshold for Sediment Motion

Critical Shields parameter is defined as the ratio of the shear stress to the submerged weight of a grain per unit of surface area at critical conditions (incipient motion).

$$\tau_{*C} = \frac{\tau_C}{(\gamma_S - \gamma) d_S}$$

Critical particle Reynolds number is defined as the ratio of the grain diameter to the viscous sublayer thickness.

$$\mathbf{Re}_{*C} = \frac{u_{*C} d_S}{\nu}$$

Threshold conditions for incipient motion can be described in terms of critical shear stress τ_c or critical velocity V_c; but both are derived from experimental flume data on sediment movement, either by visual observation or measured sediment transport rates to zero – this data was used to generate the **Shields Diagram**.

Three visual classifications: 1) weak movement, motion of a few particles, 2) medium movement, many particles in motion too many to count, and 3) general movement, observed as particle motion in all areas of the bed.

Fluvial Processes: Sediment Transport

Shields Diagram: τ_{*c} versus $\mathbf{Re}_{*c}$

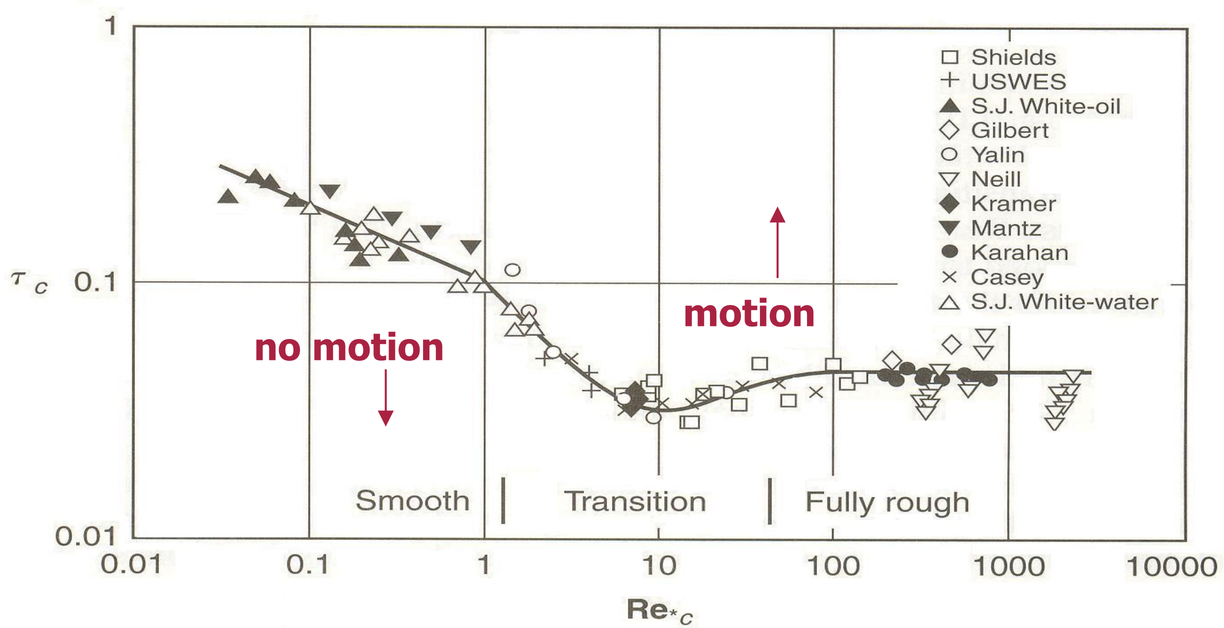


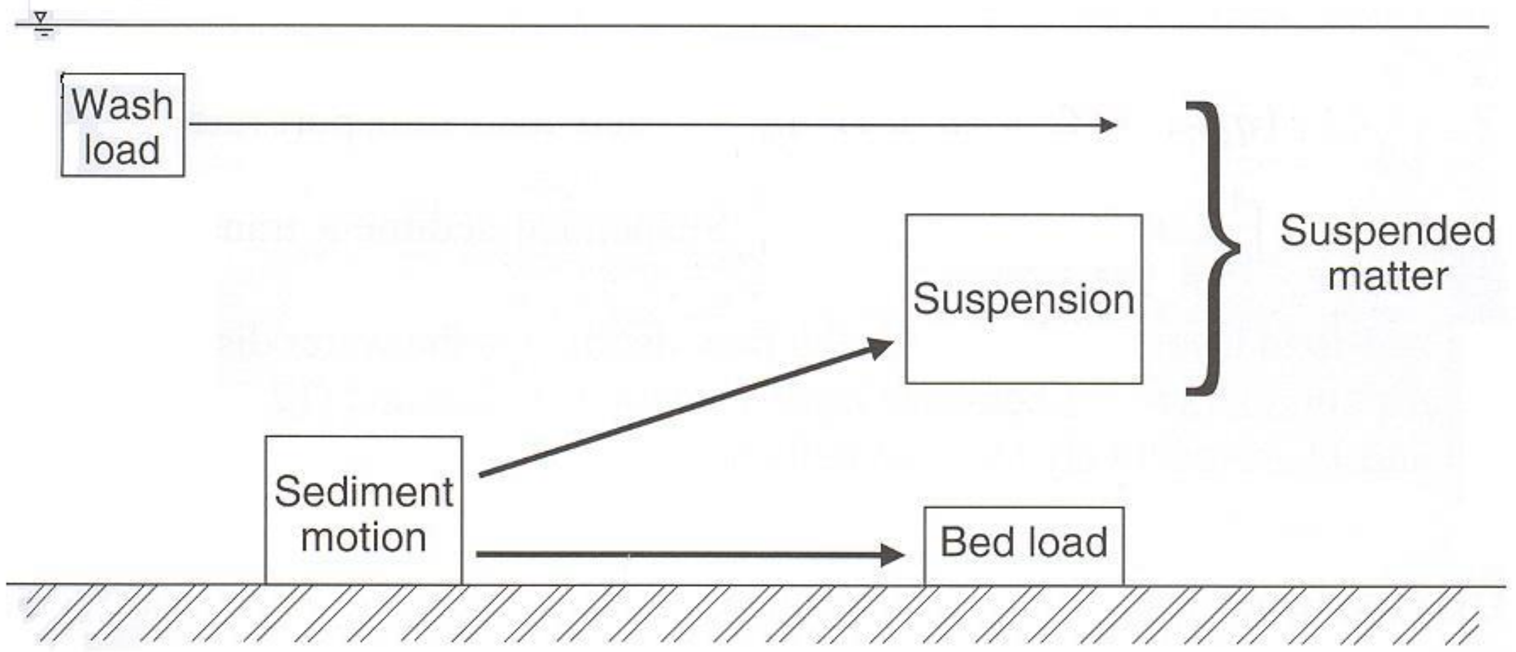
FIGURE 10.5
The Shields diagram as updated by Yalin and Karahan (1979). (*Source: M. S. Yalin and E. Karahan. "Inception of Sediment Transport," J. Hyd. Div., © 1979, ASCE. Reproduced by permission of ASCE.*)

Strum (2001)

Fluvial Processes: Sediment Transport

Sediment Transport Classification:

Sediment in motion: bed load, suspended load, wash load



Sediment transport classification.

Chanson (2004)

Fluvial Processes: Sediment Transport

Total Sediment Discharge:

equals bed load + suspended load

Bed Load – **sediment particles that roll, slide or saltate along the bed in a shallow zone only a few grain diameters thick once entrainment threshold has been exceeded ($\tau_b > \tau_{bc}$).**

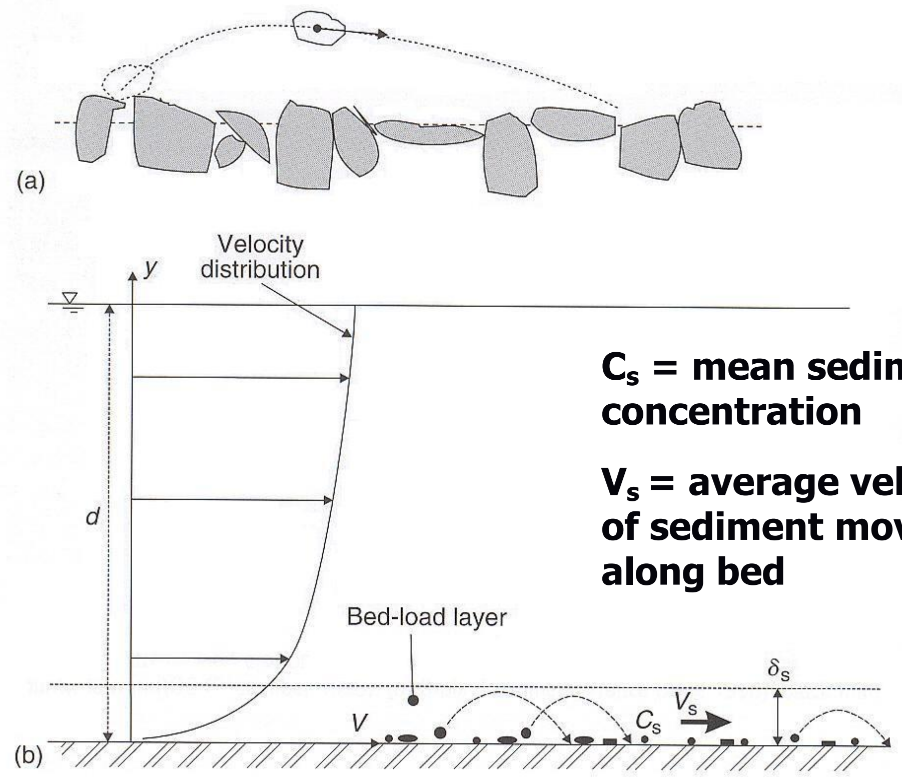
Suspended Load – **sediment particles transported within the full water column downstream, temporarily maintained in the main body of flow by turbulent mixing processes.**

Wash Load – **fine sediment delivered to the stream from upland erosion; consisting of settling velocities so low that they are transported in suspension downstream at approximately the same velocity as the flow, and only settle after instream velocities (V_O) are much reduced.**

Introduction to Bedload Discharge

Bedload Transport:
Sediment consisting of sand, gravel or larger particle size roll, slide, or saltate along the bedload layer; bedload layer thickness (δ_s) typically between 10 to 20 d_s heights.

Bedload discharge rate per unit width:
$q_s = C_s \delta_s V_s$



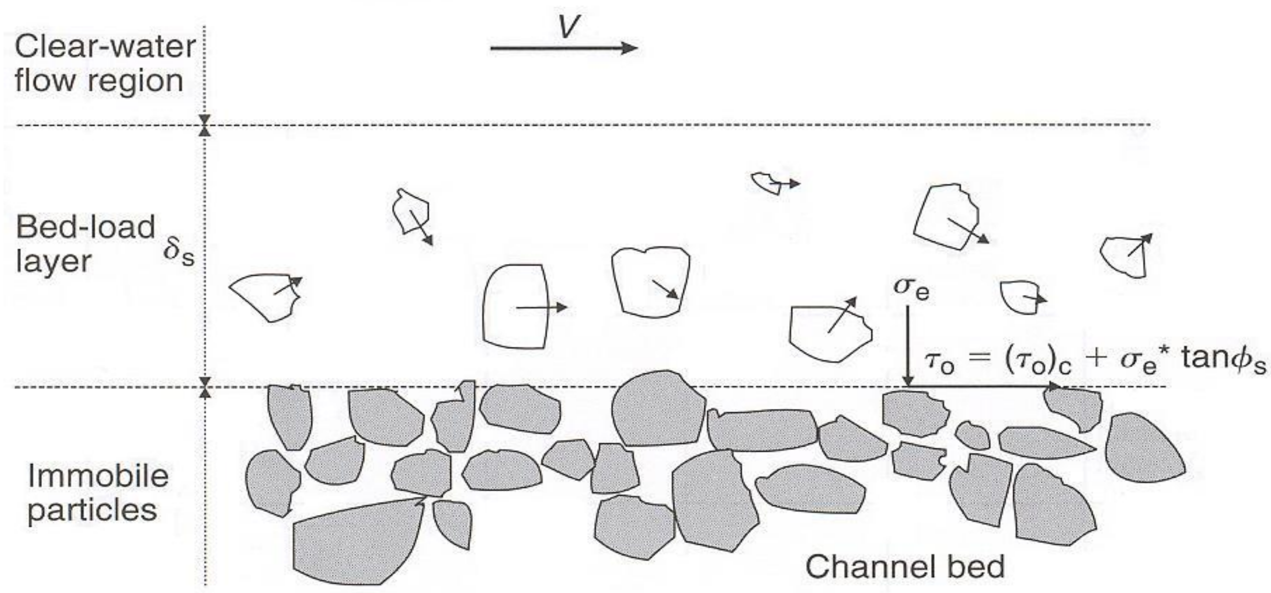
Bed-load motion: (a) sketch of saltation motion and (b) definition sketch of the bed-load layer.

C_s = mean sediment concentration

V_s = average velocity of sediment moving along bed

Bedload Motion

Bedload Motion: During bedload motion, moving grains are subjected to hydrodynamic forces, gravity force, and inter-granular forces.



Sketch of bed-load motion at equilibrium.

Bedload Motion

Boundary Bed Shear Stress:

Boundary shear stress applied to the top layer of the immobile grains become:

$$\tau_0 = \tau_c + \sigma_e \tan\phi_s$$

The submerged weight of the bedload is transferred as a normal stress to the immobile bed grains; the normal stress is called the effective stress (σ_e). Effective stress is proportional to:

$$\sigma_e \propto \rho\,(SG-1)\,g\cos\theta\,C_s\,\delta_s$$

where, ρ = fluid mass density; θ = longitudinal bed slope
τ_c = critical shear stress at the bed for incipient motion
ϕ_s = angle of repose; g = gravity
δ_s = bedload layer thickness; C_s = mean concentration

Bedload Motion

Bedload Transport:

Bedload transport occurs when the bed shear stress (τ_0) exceeds the critical shear stress for initiation of motion (τ_c), typically expressed in dimensional form using the Shields parameter (τ_*) and the critical Shields parameter (τ_{*c}).

Recall: $\tau_* = \tau_0 / (\gamma_s - \gamma) \cdot d_s = \tau_0 / [\rho \cdot (SG-1) \cdot g \cdot d_s] = \tau_0 / [\rho \cdot R \cdot g \cdot d_s]$

Prediction of Bedload Transport:

Many researchers have attempted to predict the rate of bedload transport, because of the complexity of physical processes, most transport relationships are empirically or semi-empirically based.

Alternatively, saltation models provide a deterministic approach to prediction of bedload transport mechanics.

Bedload Discharge Equations

Deboy's Equation:

Based on the concept that sediment moves in thin layers along the bed. The applied bed shear stress τ_0 must exceed the critical shear stress τ_C to initiate motion.

$$q_b = \frac{0.173}{d_{50}^{0.75}} \tau_0 (\tau_0 - \tau_C)$$

where,

$$\tau_C = 0.025 + 0.019 d_{50}$$

q_b = ft^2/s

τ_0 and τ_C are in lbs/ft^2

d_{50} is in mm

Bedload Discharge Equations

Meyer-Peter and Müller's Equation:
Based on laboratory experiments for sediment sizes from 5 to 28.6 mm, and developed in a Deboys-type formula in that $\tau_0 > \tau_C$ to initiate motion, where the critical Shields parameter τ_{*C} is estimated as 0.047 assuming fully rough flow.

$$\phi_b = \frac{q_b}{\sqrt{Rgd_s^3}} = 8.0(\tau_* - 0.047)^{1.5}$$

q_b = ft²/s, m²/s
τ_* is the Shields parameter
$d_s = d_{50}$ (in ft, m); R = submerged specific gravity (sg-1)

Bedload Discharge Equations

Meyer-Peter and Müller's Equation:

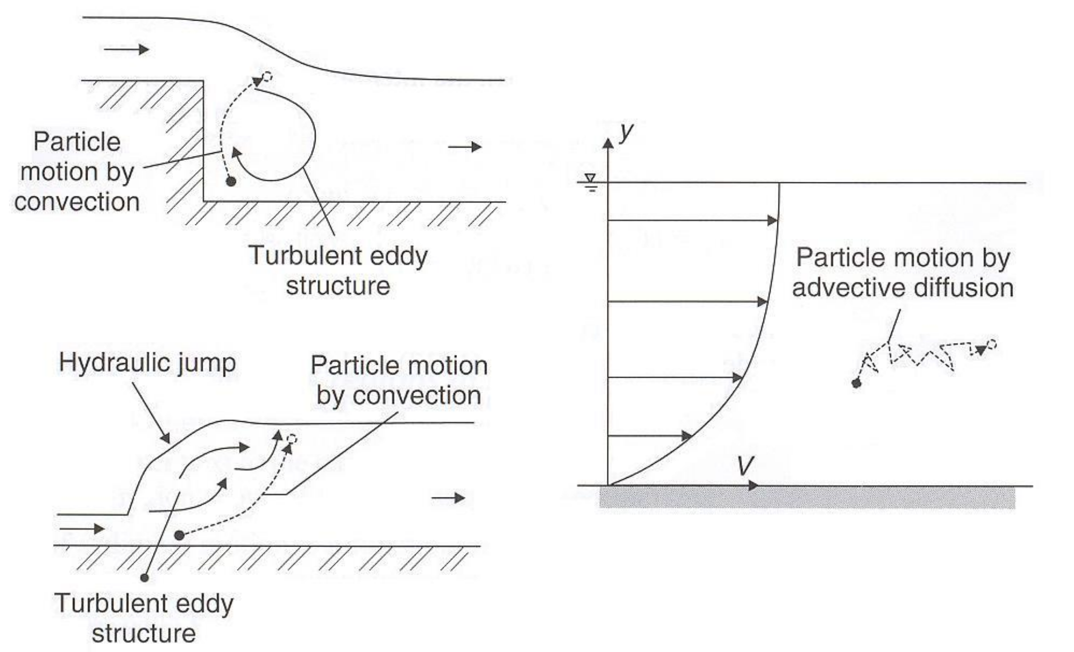
Example Application:
$Q = 530\ m^3/s$, $y_0 = 4.27\ m$, $S_0 = 0.0011$, $d_{50} = 0.012\ m$

$$\phi_b = \frac{q_b}{\sqrt{Rgd_s^3}} = 8.0(\tau_* - 0.047)^{1.5}$$

$q_b = ft^2/s,\ m^2/s$
τ_* is the Shields parameter
$d_s = d_{50}$ (in ft, m); R = submerged specific gravity (sg-1)

Introduction to Suspended Sediment

Suspended Load – finer sediment particles brought into suspension when turbulent velocity fluctuations are sufficiently large to maintain the particles within the full water column without frequent contact with the bed, and transported downstream.



Suspended-sediment motion by convection and diffusion processes.

Suspended Sediment Discharge

Suspended Sediment Discharge:

In steady, uniform turbulent flow in a stream, turbulent velocity fluctuations in the *vertical direction* transport sediment particles upward.

The mean turbulent flux of sediment per unit area expressed as

$\overline{w'c'}$, where

w′ is the vertical velocity fluctuation and c′ is the turbulent fluctuation in concentration, which are assumed to be positively correlated in space.

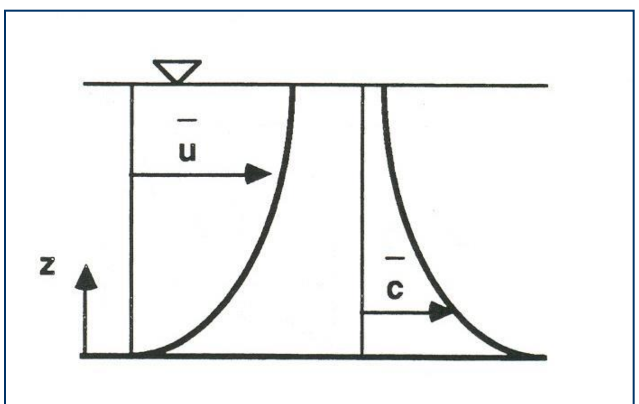
The positive correlation results from the positive (upward) values of w′ bringing parcels of fluid with higher sediment concentration (+c′).

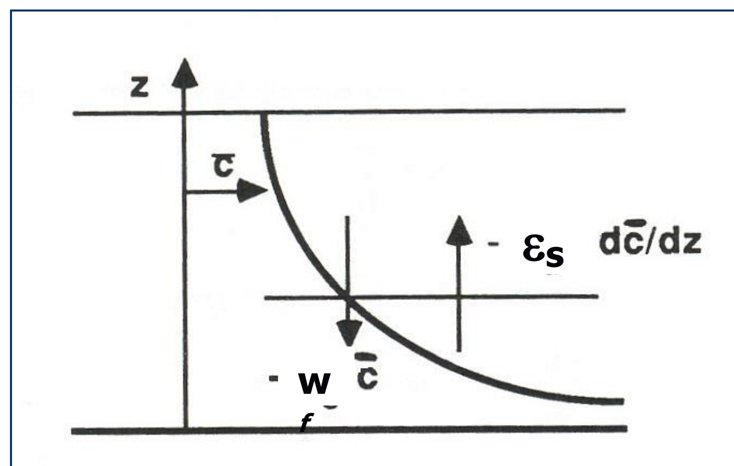
Suspended Sediment Discharge

Suspended Sediment Discharge:
Mass sediment fluxes are balanced between upward turbulent mixing and downward gravitational settling, expressed as:

$$\overline{w'c'} = -\varepsilon_s \frac{dC}{dz}$$

where ε_s is the turbulent sediment diffusion coefficient



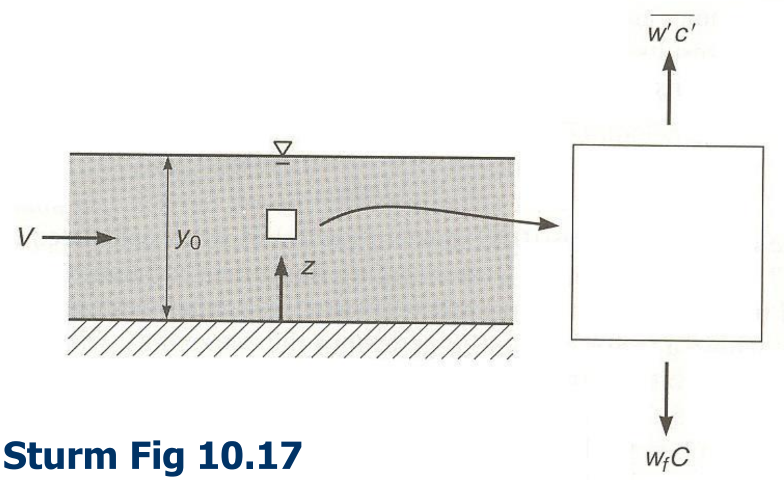


Suspended Sediment Discharge

Suspended Sediment Discharge:
The suspended sediment concentration decreases in the upward direction in the water column; *it is mass flux balanced* by gravitational settling of the sediment particles given by $w_f C$ for a unit area, assuming the balance is an equilibrium state in which sediment concentration in the *vertical* has no changes in the flow direction.

C = time-averaged concentration at a point in the vertical

w_f = sediment fall velocity



Sturm Fig 10.17

Suspended Sediment Discharge

Model Derivation of Suspended Sediment Discharge:

Because gravitational settling is assumed in balance with mean turbulent flux in the upwards direction; $w_f C$ can be substituted for w′c′ into the vertical mass balance relationship:

$$\overline{w'c'} = -\varepsilon_s \frac{dC}{dz} \Longrightarrow \varepsilon_s \frac{dC}{dz} + w_f C = 0$$

Julien Eq. 10.16

and integrated, solved as:

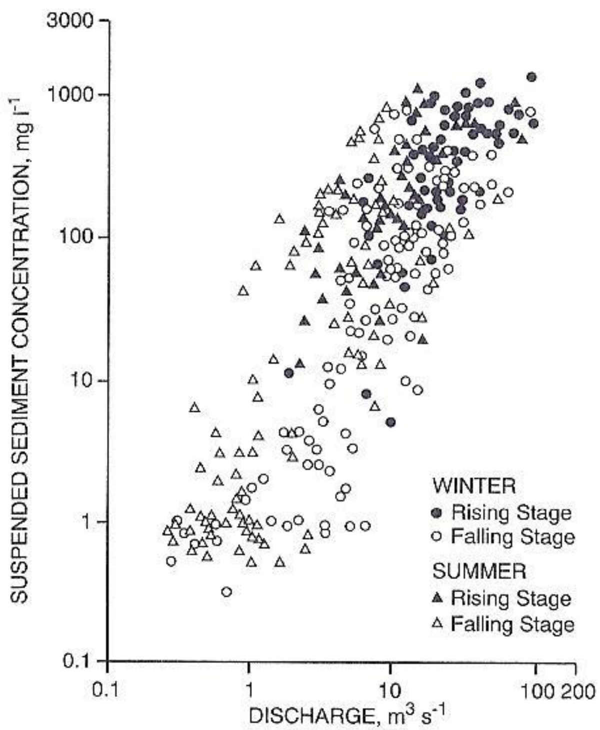
$$\frac{C}{C_a} = e^{\left[-\frac{w_f}{\varepsilon_s}(z-a)\right]}$$

Sturm Eq. 10.60

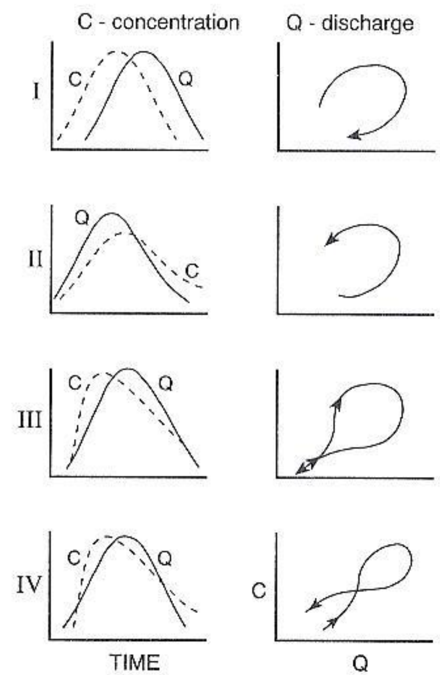
C_a is the sediment concentration at z = a

Fluvial Processes: Sediment Transport

Suspended sediment (ss) discharge variation per season



Types of hysteretic loops in ss concentration/discharge relationships



Characteristic is a function of sediment supply rate, and upstream distance to source(s).
I = small basin
II = large basin

[River Creedy, UK]; Knighton (1998)

Total Load Transport Rates

Prediction of Total Load Transport Rates:
Existing sediment transport formulas can be classified into several categories according to their basic approach; formulations include:

1. derivation based on advection-diffusion principles
2. derivation based on energy concepts, in which the rate of work done for transporting sediment particles in turbulent flow is related to the energy expenditure rate
3. development based on empirical equations based on regression analysis and graphical methods

Fluvial Processes: Sediment Deposition

Sediment deposition can be equally important to that of bed and bank erosion in determining channel form.

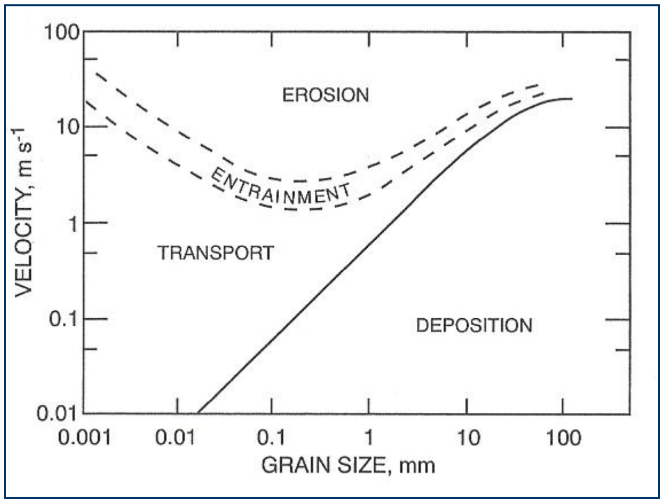
Sediment deposition is a function of settling velocity (w_f); therefore is a function of particle properties (size, density, and drag), and temperature-dependent fluid properties (viscosity and density):

$$w_f = [4/3(\gamma_s/\gamma - 1)g \cdot d/C_D]^{1/2}$$

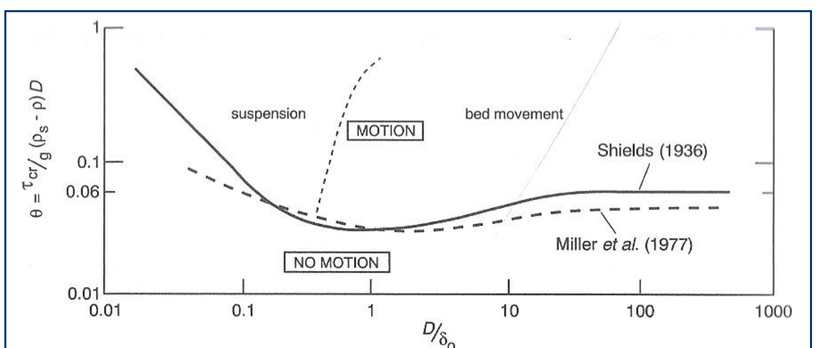
settling velocity of a particle

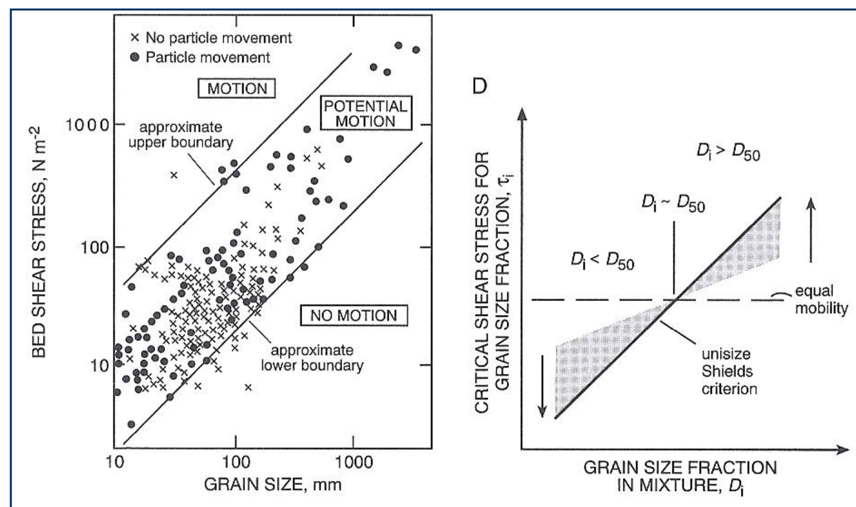
Fluvial Processes: Sediment Deposition

Sediment Transport: Erosion vs Deposition



Knighton (1998)

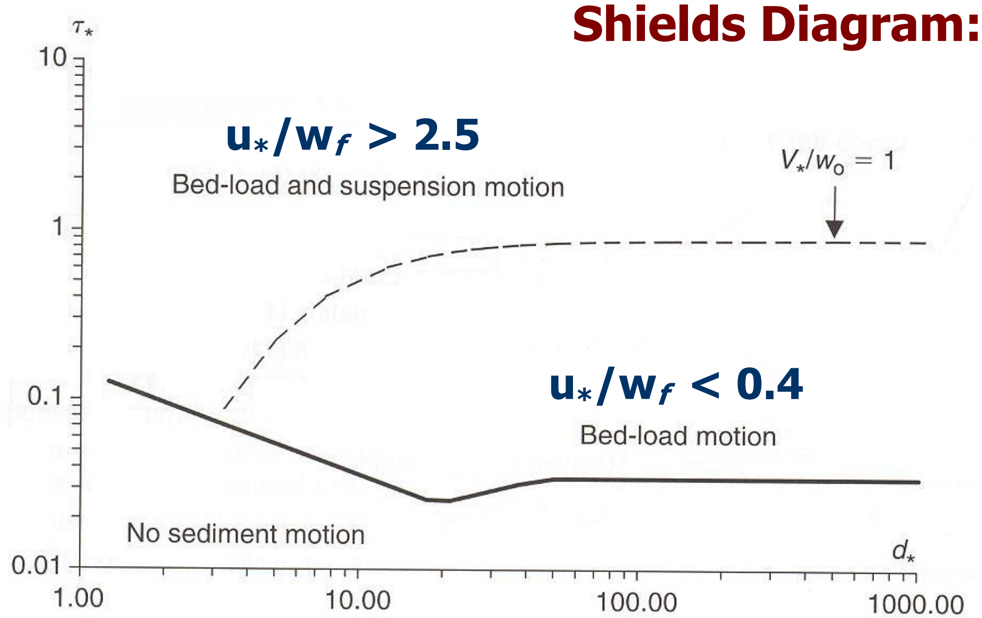




Fluvial Processes: Sediment Deposition

Sediment Transport: opposing forces of turbulent suspension and gravity are reflected by the dimensional ratio u_*/w_f, defining dominant ranges for **bed load & suspended load transport**

Shields Diagram: τ_* vs d_*



Threshold of sediment motion (bed-load and suspension): Shields parameter $\tau_* = \tau_0/(\rho g(\mathbf{s} - 1)d_s)$ as a function of the dimensionless particle parameter $d_* = d_s \sqrt[3]{(\mathbf{s} - 1)g/\nu^2}$ (for water at 20°C and $\mathbf{s}$ = 2.69).

Chanson (2004)

Fluvial Processes: Sediment Deposition

Characteristics of River Depositions: *examples*

Alluvial bars: point bars consisting of lateral deposits on the inner bank bed of a meander; mid-channel bar forming a island of course sediments; and.

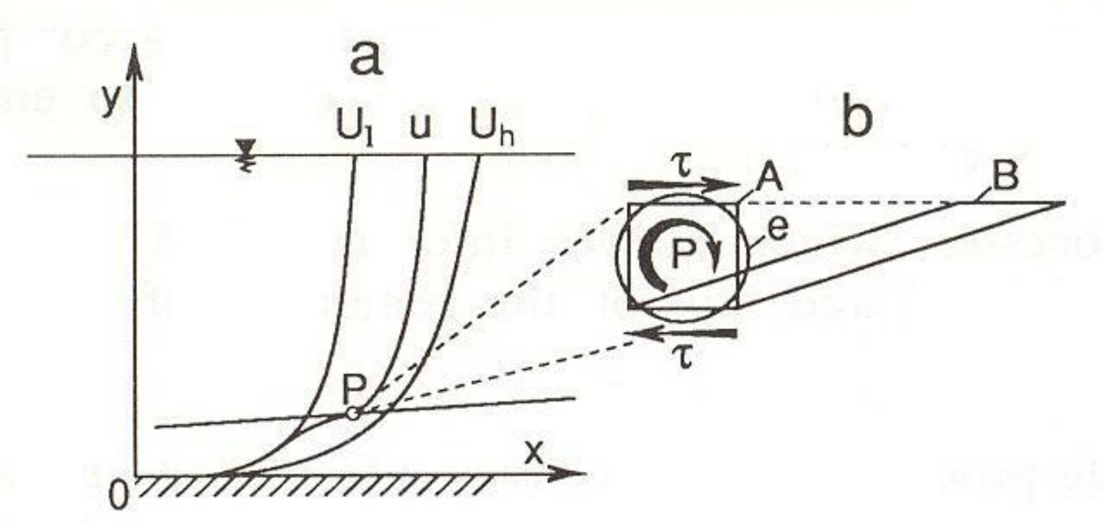
Channel Fills: fills accumulating sediment in abandoned or aggrading channel reaches

Floodplain: lateral accretion depositions of fine grained material from suspended load adjacent to point bars; general depositions of fine-grained suspended material depositing on the floodplain – can form levees, and splays.

Bed Configuration: Initiation of Pool-Riffle Sequences

Turbulence structure and the initiation of pool-riffle sequences: differential shear stress (τ) occurs at some fluid element and becomes "overstressed", and begins to roll-up into an eddy (e).

Helmholz instability



(Yalin 1992)

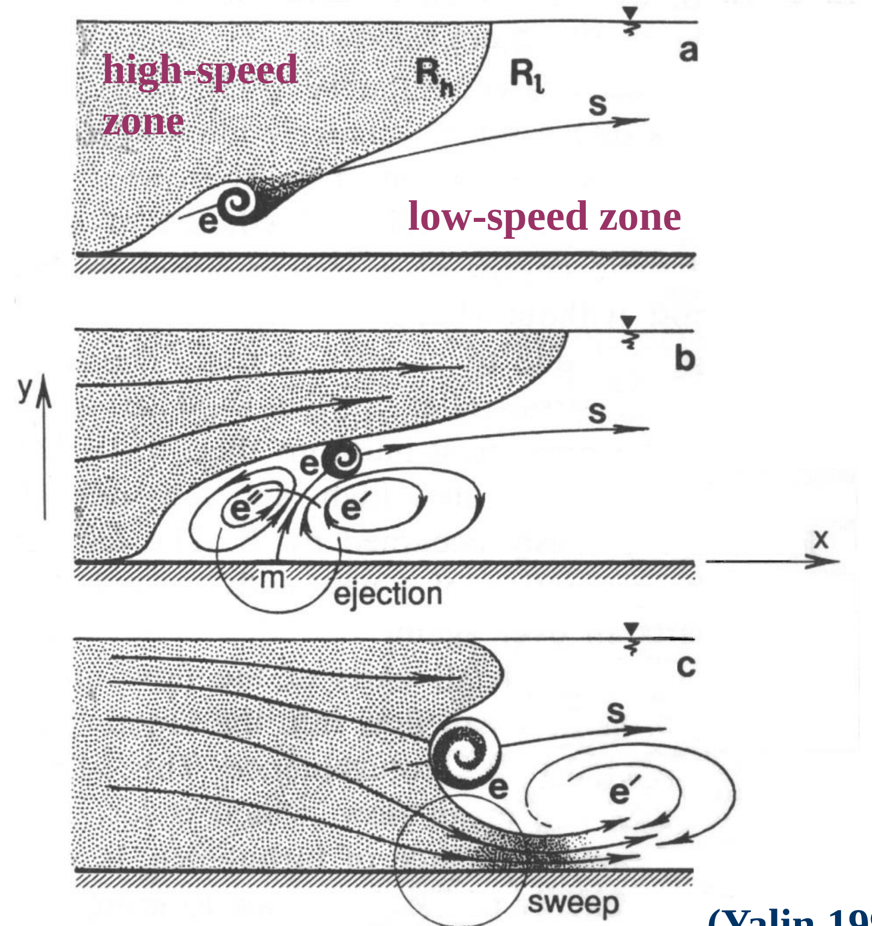
Bed Configuration: Initiation of Pool-Riffle Sequences

Sequence of events during a burst cycle:

a.) eddy forms at interface of high- and low speed fluid regions along a pathway (s) in the low-speed zone;

b.) movement of the eddy (e) along s generates circulatory motion e' in the low-speed region, which motion forms an ejection vector of fluid from m; making space for high-speed fluid; and

c.) high-speed fluid mass overtakes ejection fluid mass form a sweep and strong downward velocity vectors.

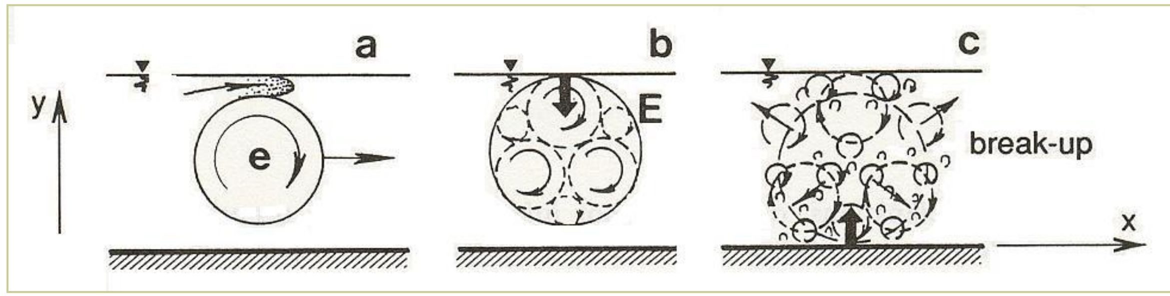


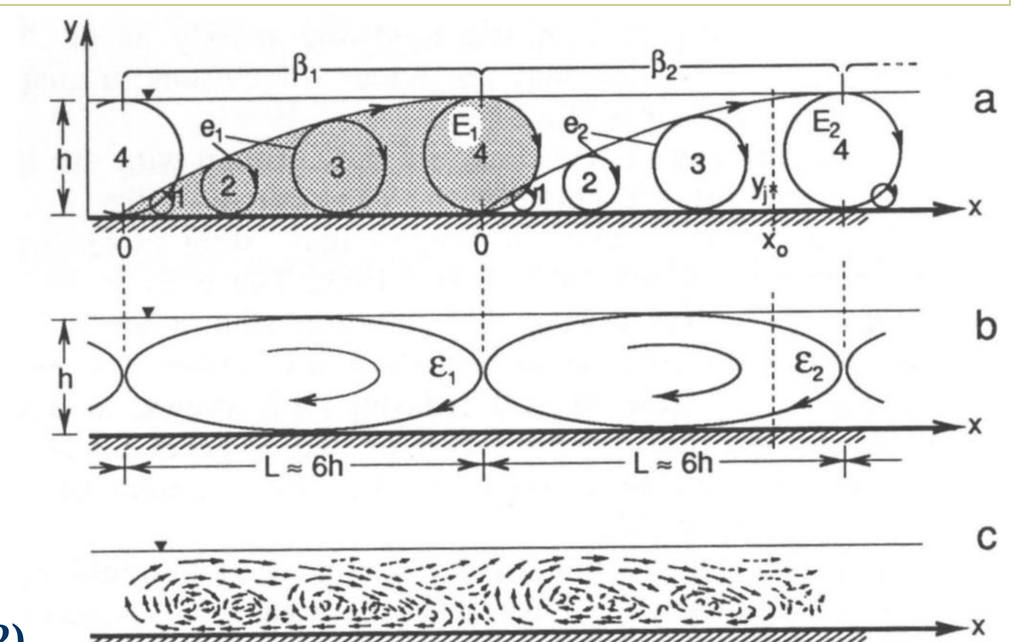
(Yalin 1992)

Bed Configuration: Initiation of Pool-Riffle Sequences

Burst Cycle:

Sequence of burst cycle results in the break-up of the eddy, then the cycle repeats; cycle length along a channel (L) **scales** to **flow depth** (h); which approximately equals: $L \approx 6h$; matches typically-found pool spacings





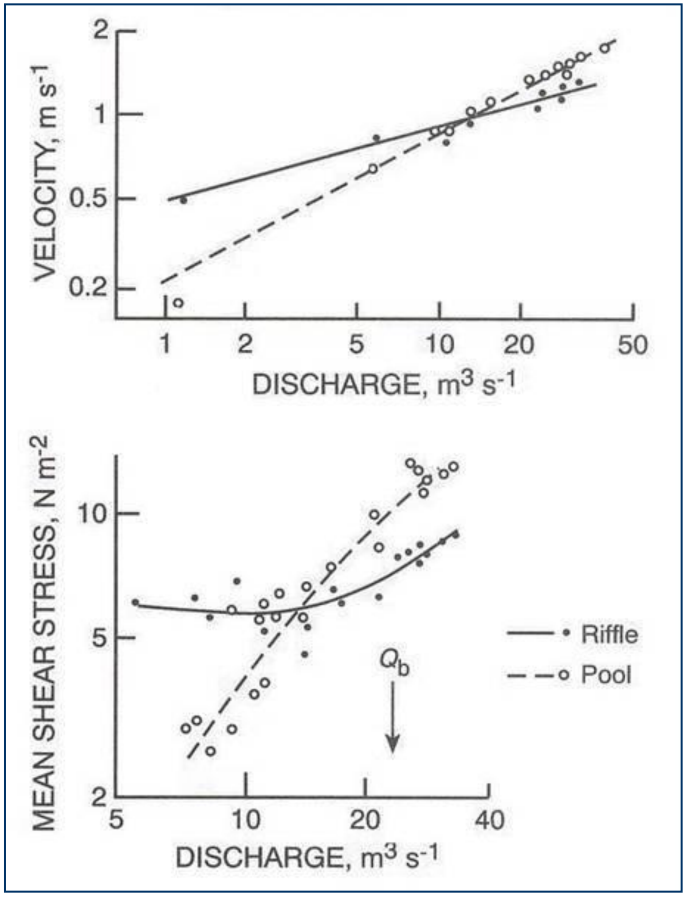
(Yalin 1992)

Bed Configuration: Riffle-pool Sequences

In general, **riffle-pool sequences occur with bed slopes < 2%, and step-pool sequences occur with bed slopes > 5%.**

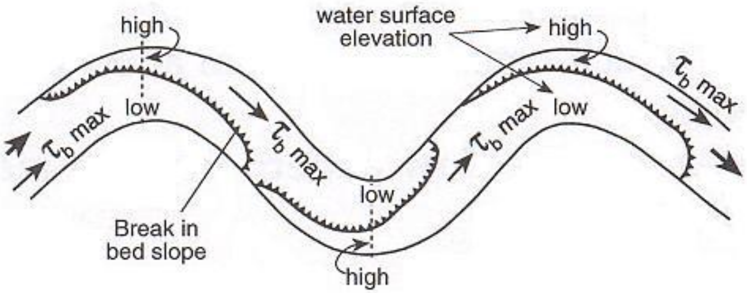
Riffle-Pool Spacing:
Average 5-7 channel unit widths from a range of 1.5 to 23.3 channel unit widths.

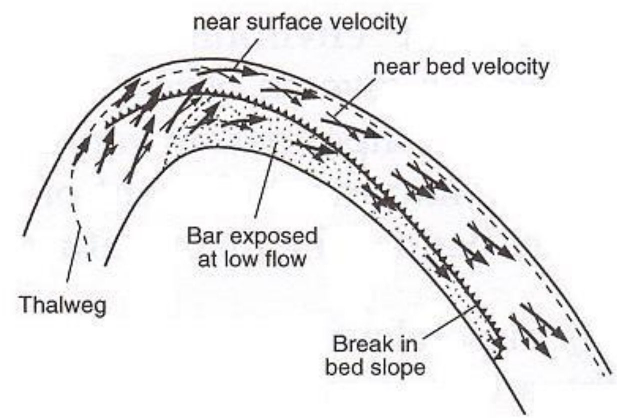
Velocity- and shear-reversal hypothesis:

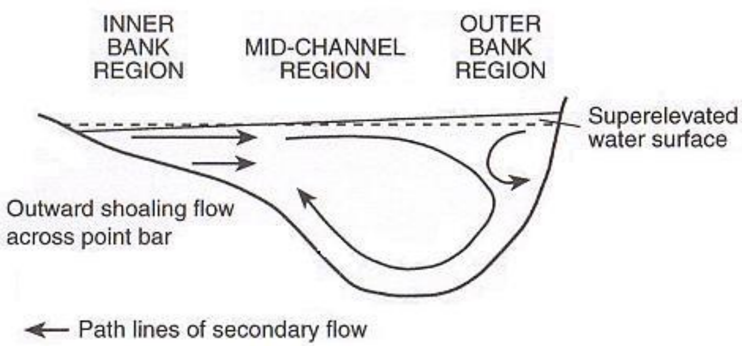


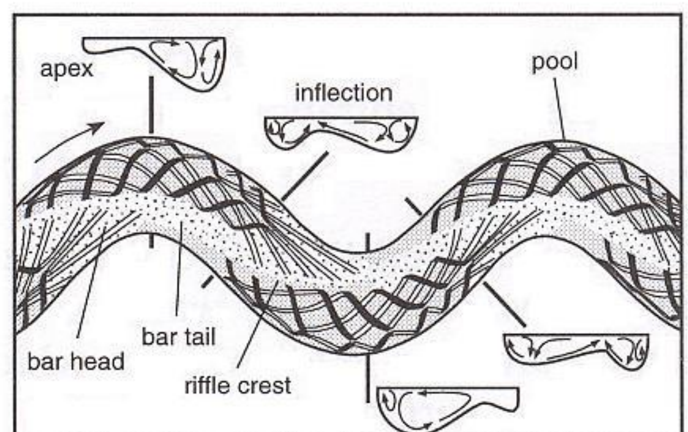
Knighton (1998)

Planforms: Bar Unit - Meander Flow Patterns





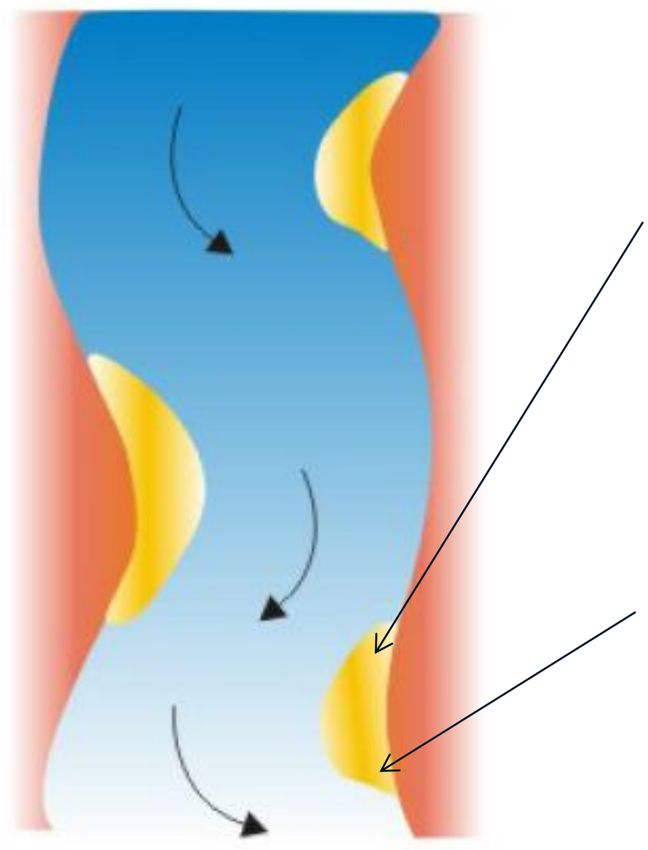




Dietrich (1987)

Planforms: Bar Unit - Meander Flow Patterns

Point Bar Sediment Sorting



Course Sediment
Gravel-sand mixture

↓

Fining of sediment particle size

↓

Fine Sediment
Sand

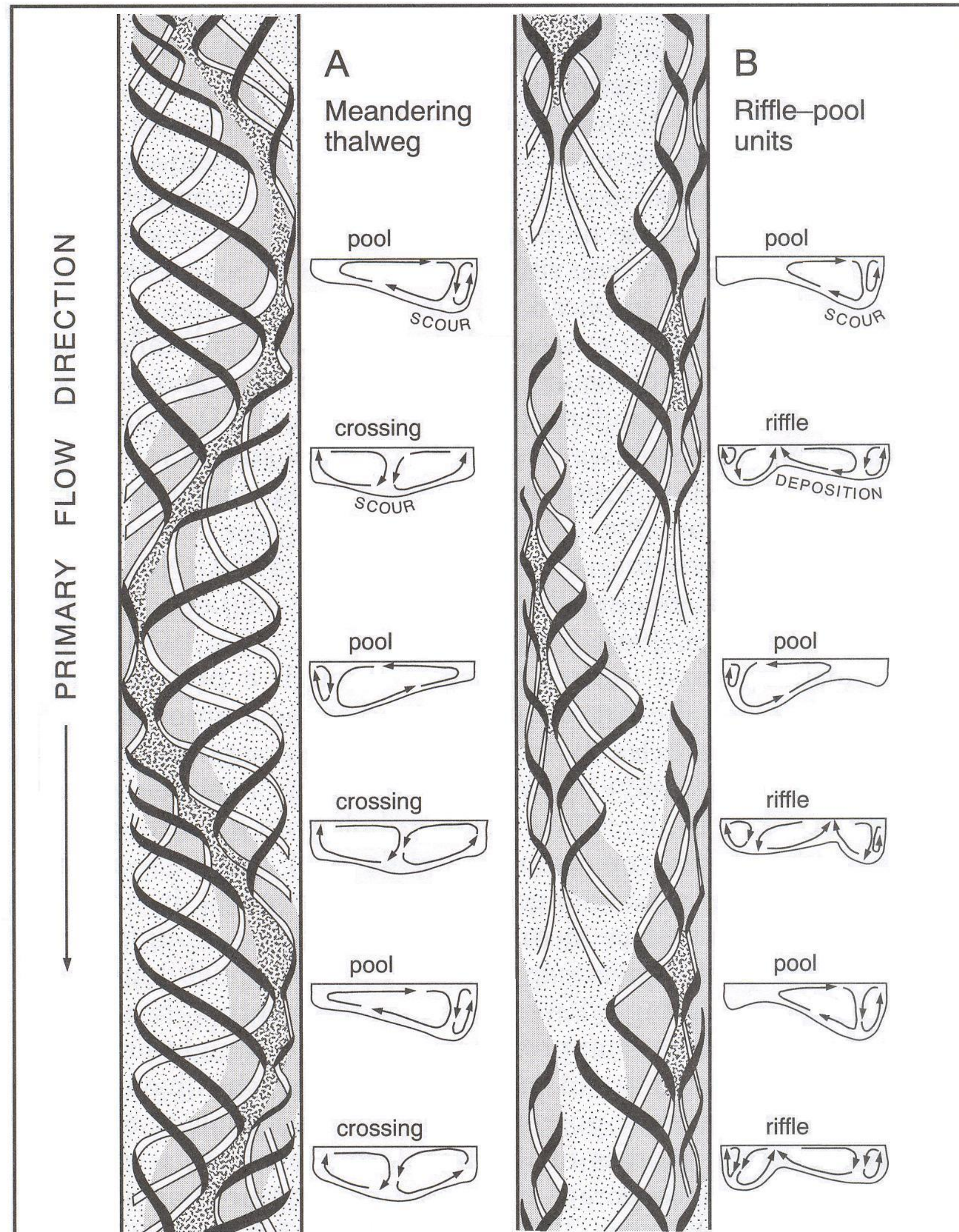
(Dietrich 1987; Sears 1996)

Bar-bend Theory

Riffle-Pool Hydraulics:

Models of flow structure in a straight channel for:
A.) twin periodically reversing surface-convergent helical cells; *and*

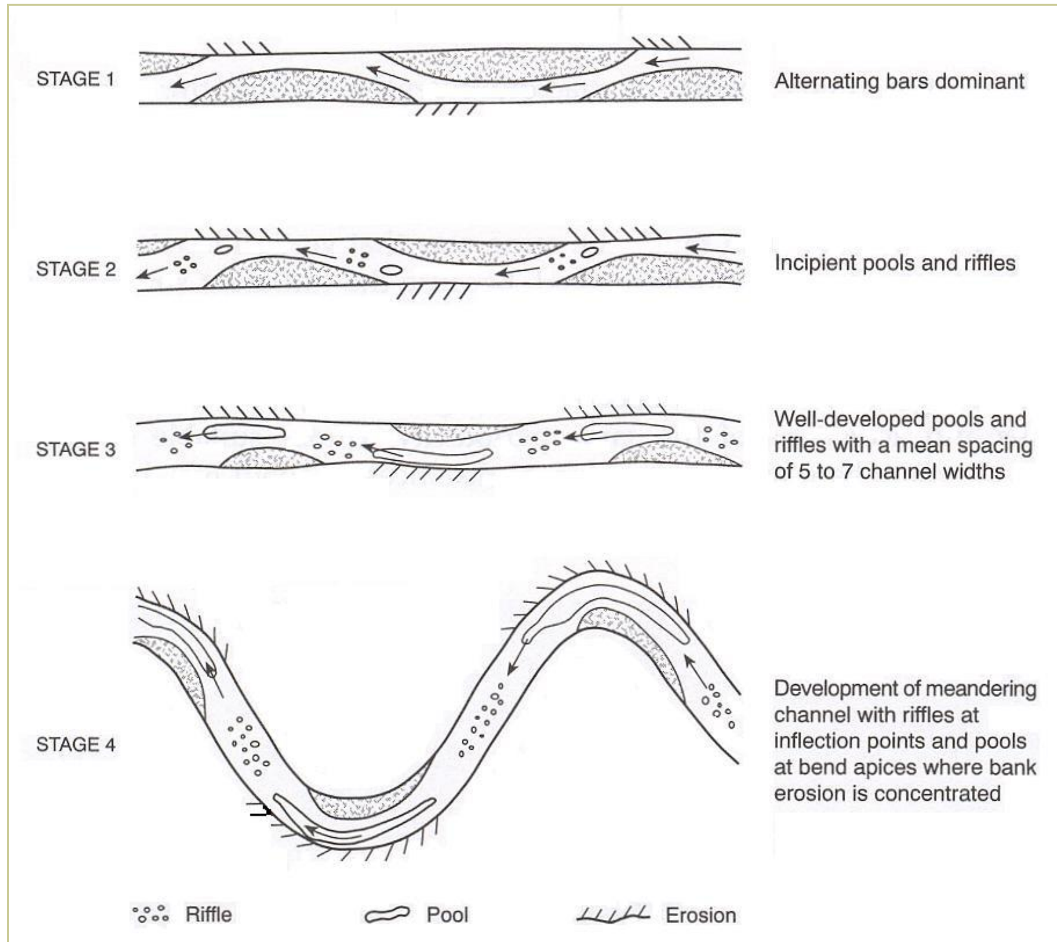
B.) surface-convergent flow produced by interactions between the flow and a mobile bed, creating riffle-pool sequences.



(Rhoads & Welford 1991)

Planforms Dynamics: Bar-bend Theory

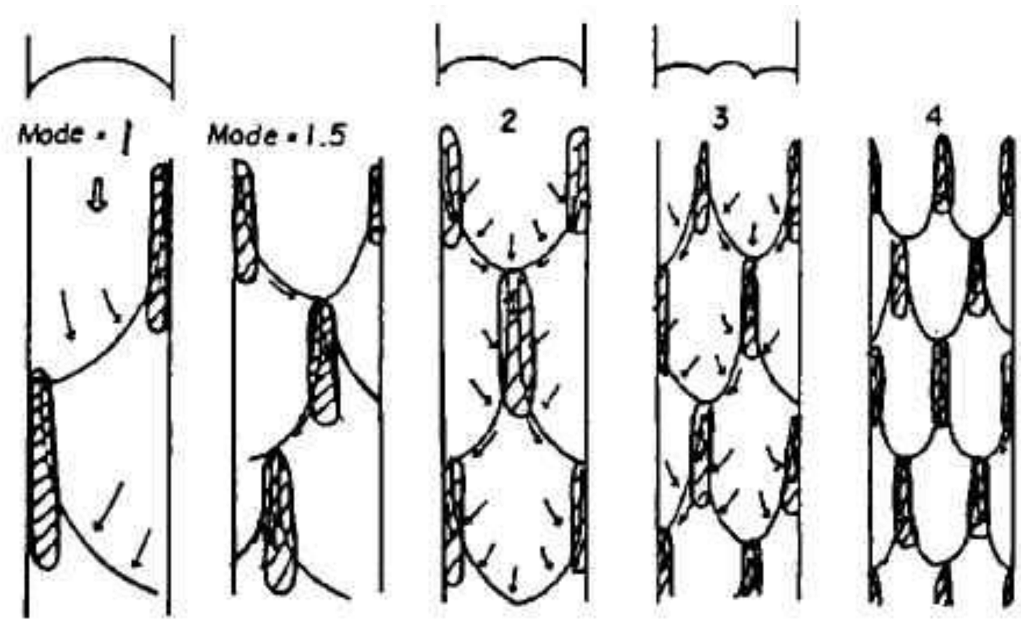
Bar-bend Theory:
Initiation of meanders



Keller (1972)
Rhoads & Welford (1991)

Planform Dynamics: Bar Units

Bar-bend theory expanded to braided channels:

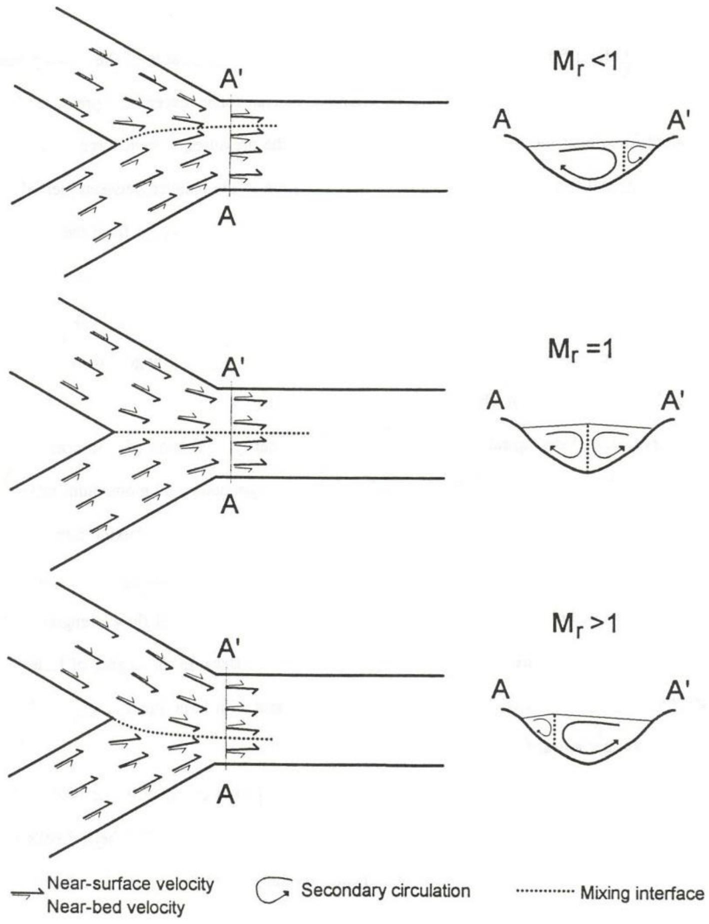


Schematic sketches of bar modes and arrangement of scour holes.

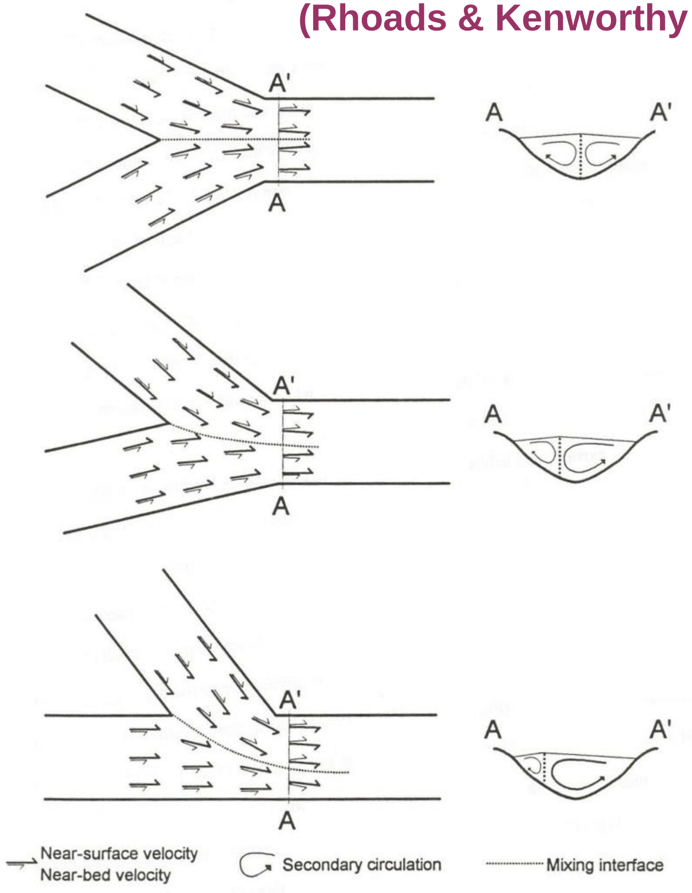
Fujita (1989) AGU Monograph

Planforms: Confluences

(Rhoads & Kenworthy 1995)

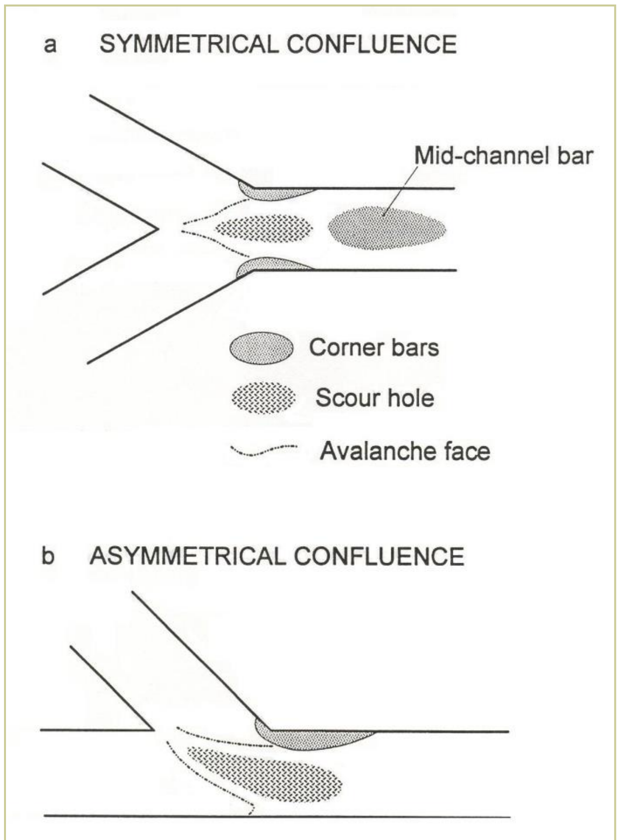


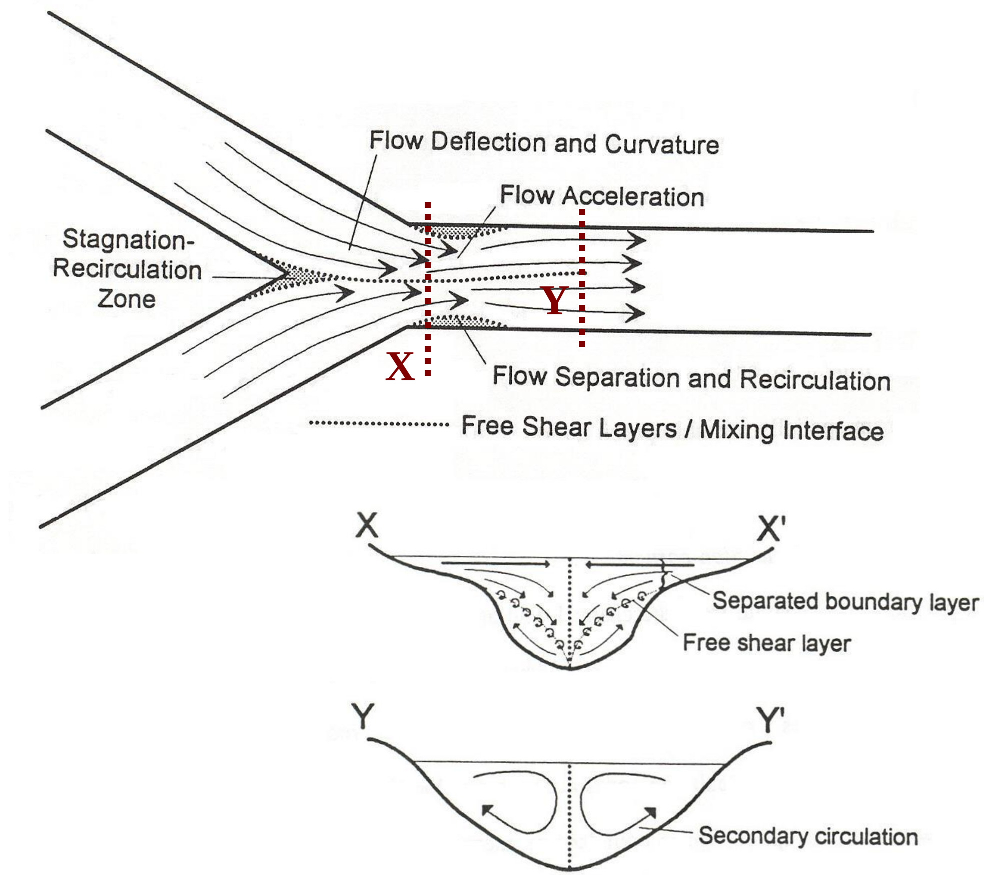
tributary size varies; trib. angle same



tributary angle varies; trib. size same

Planforms: Bar Unit - Confluences





(Rhoads & Kenworthy 1995)