

# Morphological response of rivers

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# Fluvial geomorphology

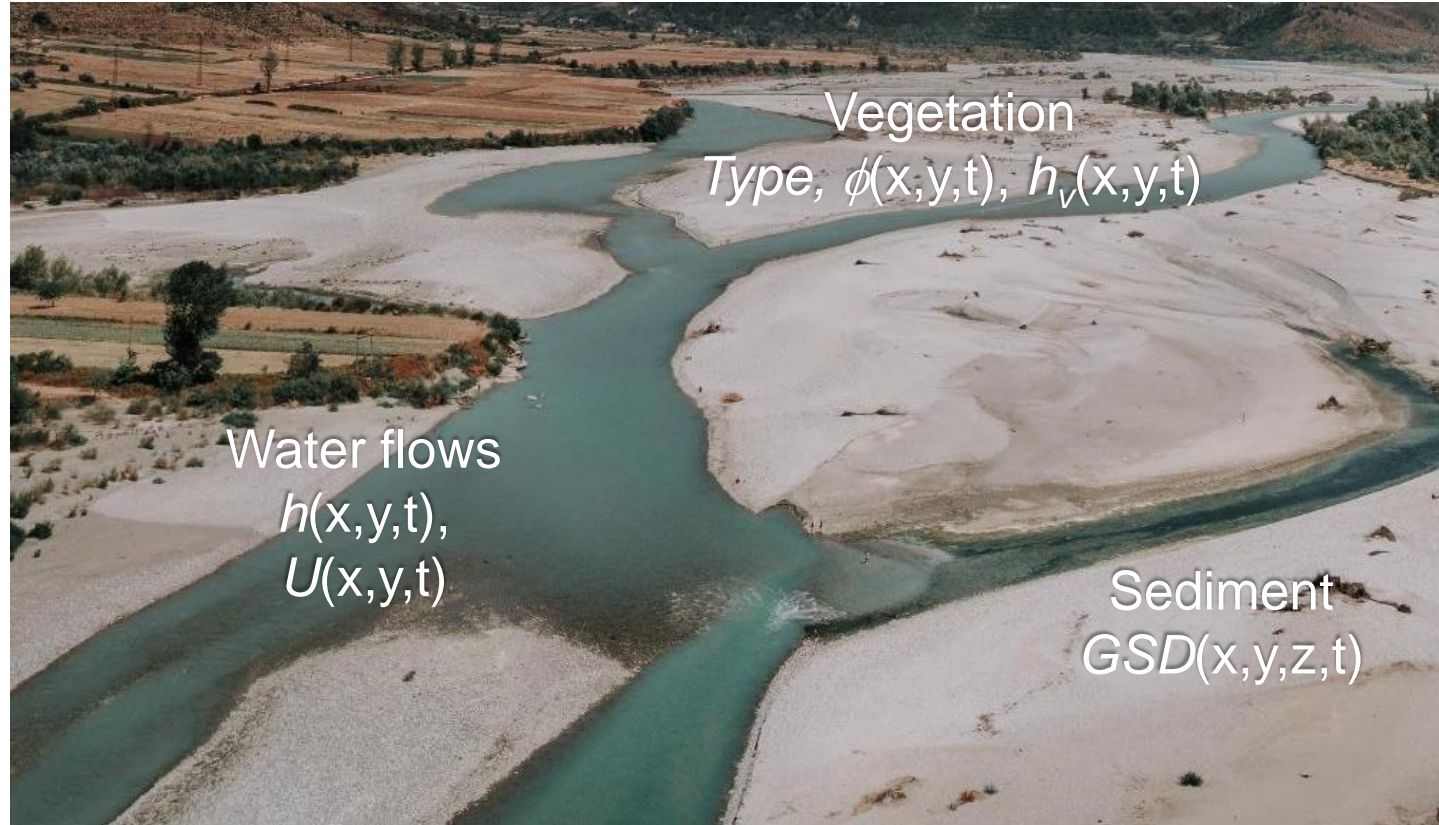
(River hydro-morphology)

Study of the physical and the resulting bedforms for a watercourse.

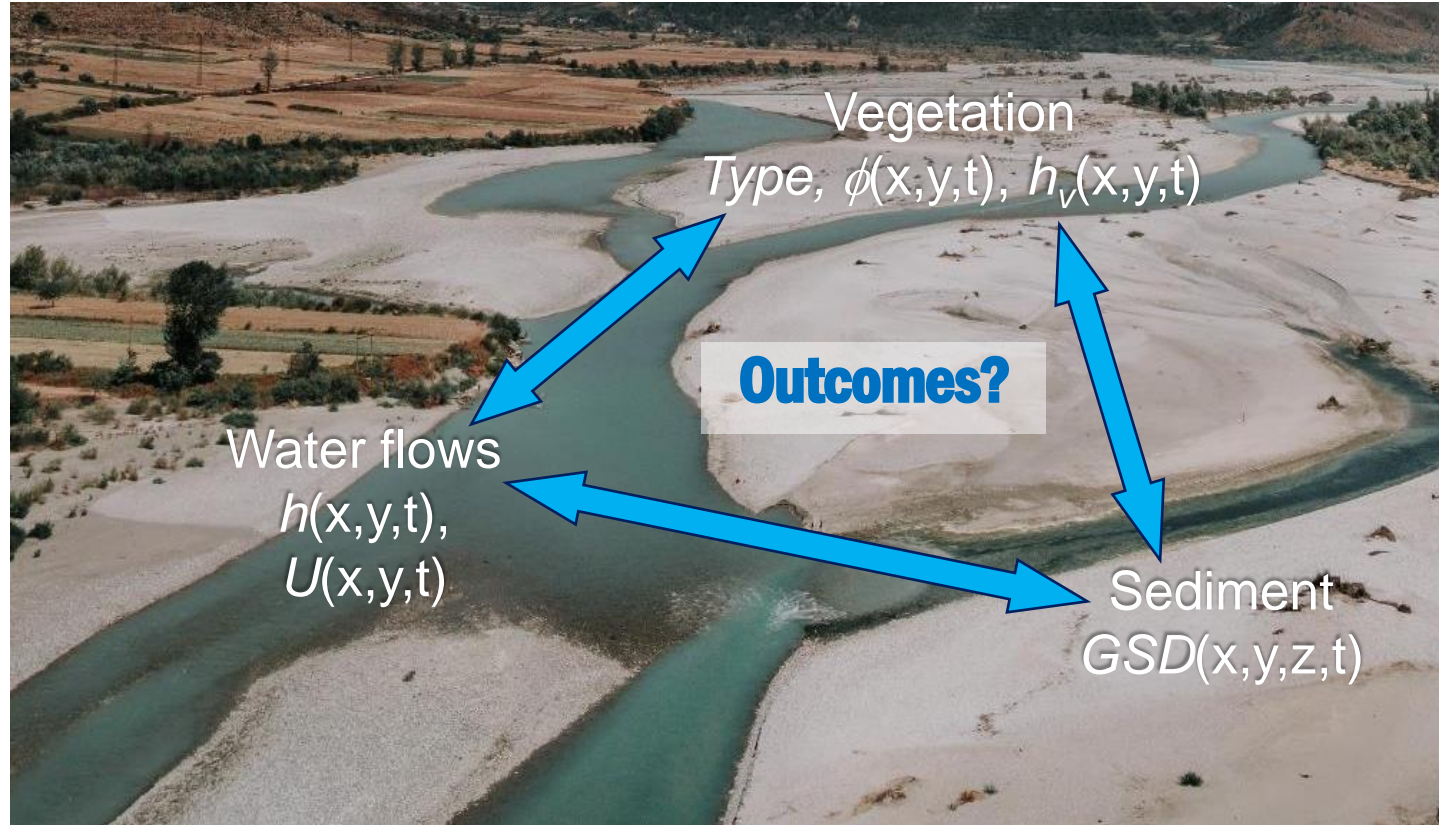
Discipline appeared in the 1940s in the United States.

Nowadays it gained importance for the design of effective renaturalization and restoration projects.

# What are we dealing with ?



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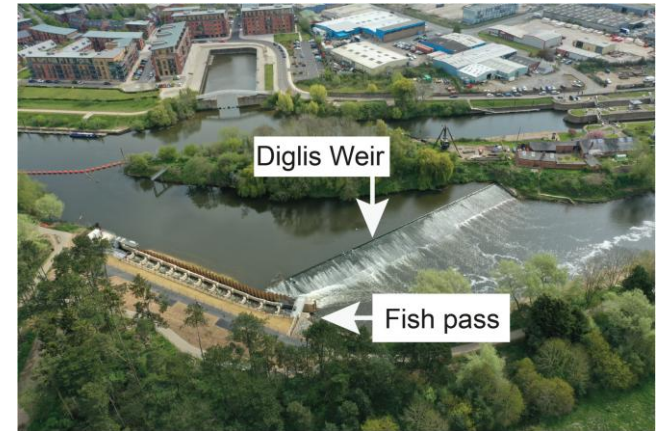


# What are we dealing with ?

Other factors

Animals

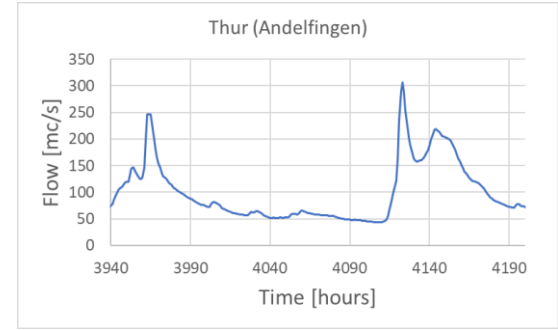
Human activities



# Flow discharge

## Temporal variability

- $Q = Q(t)$

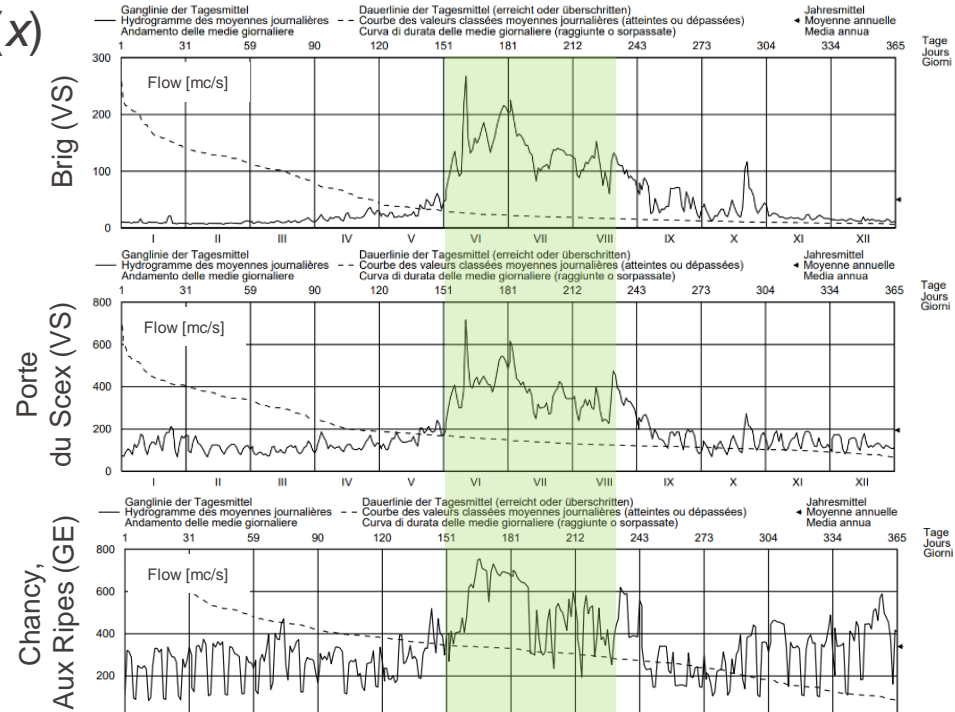


## Variables

- Climate
  - Precipitations: types and amount
  - Seasonality
- Soil
  - Type (permeability)
  - Saturation
- Human activities (e.g., regulation by dams)

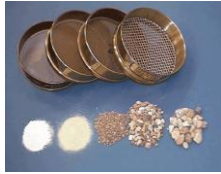
## Spatial variability

- $Q = Q(x)$

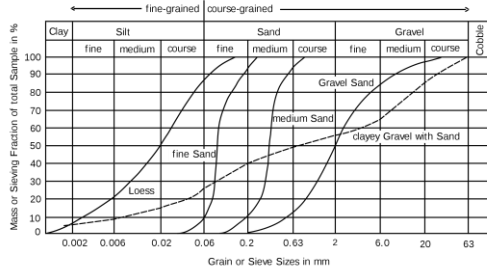


# Sediment

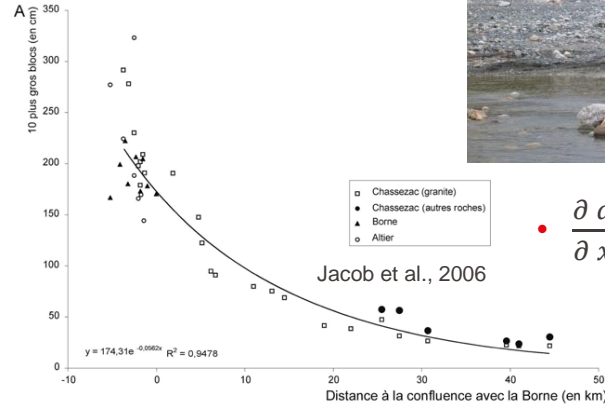
## Particle size (d)



- Gravel bed rivers
- Sand bed rivers



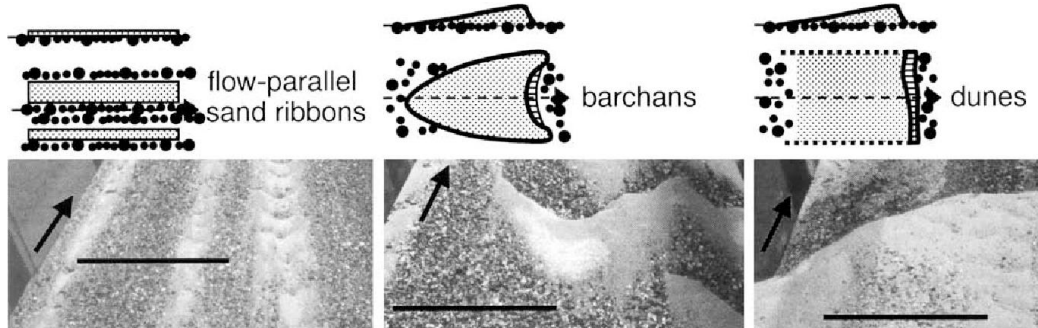
- inside the channel: riverbed
- outside the channel: bank erosion, landslide (eventually with organic material)
- $d=d(x,y,z,t)$  but usually  $d=d(x,z)$



•  $\frac{\partial d}{\partial x} < 0$  downstream fining

## Availability of bed material

Supply limited  
(usually in bedrock rivers)  
vs.  
Transport capacity limited

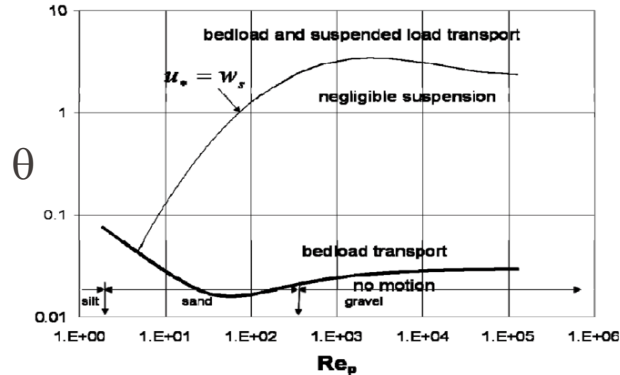


# Sediment transport rate

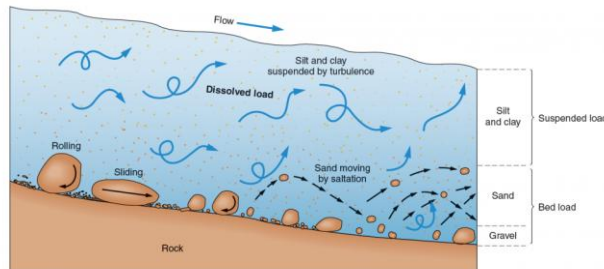
Transport capacity

$$q_s = q_s(q(x,t), D_{50})$$

$$q_s = q_s(\theta(x,t), Re_p)$$



Several relationships depending on transport mechanism



Real sediment transport rate

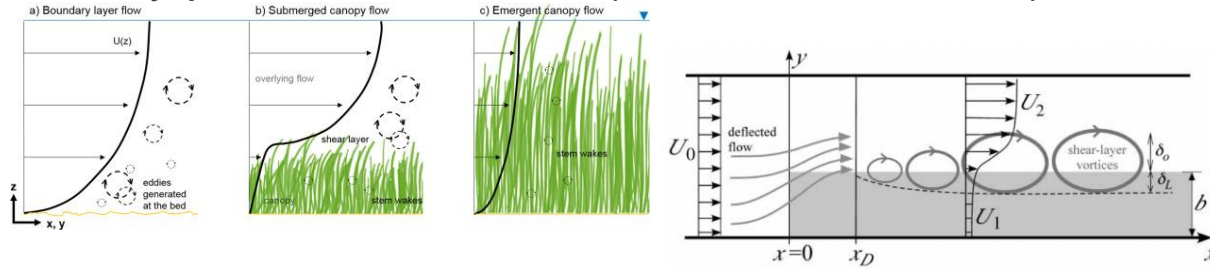
- Bedload measurements with Helley-Smith sampler



- Suspended load measured through vertical integrated samplings



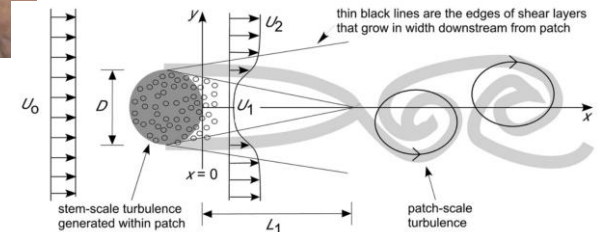
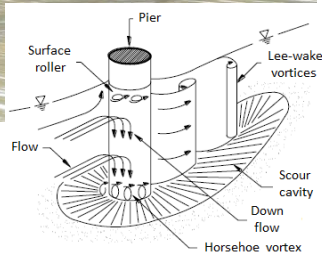
## Velocity profile and vortices (turbulent structures)



## Bank protection



## Local patterns of erosion/deposition





# Morphological response

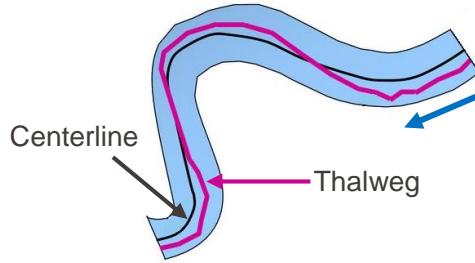
Longitudinal profile

Cross-section geometry

Planimetric configuration

# Longitudinal profile

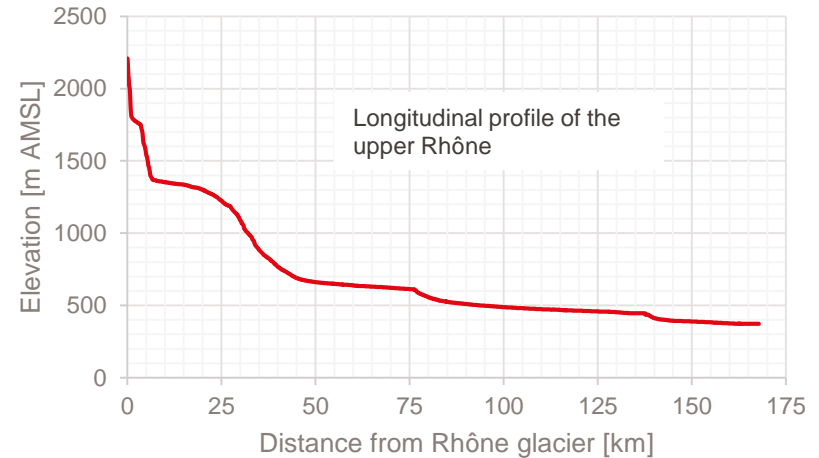
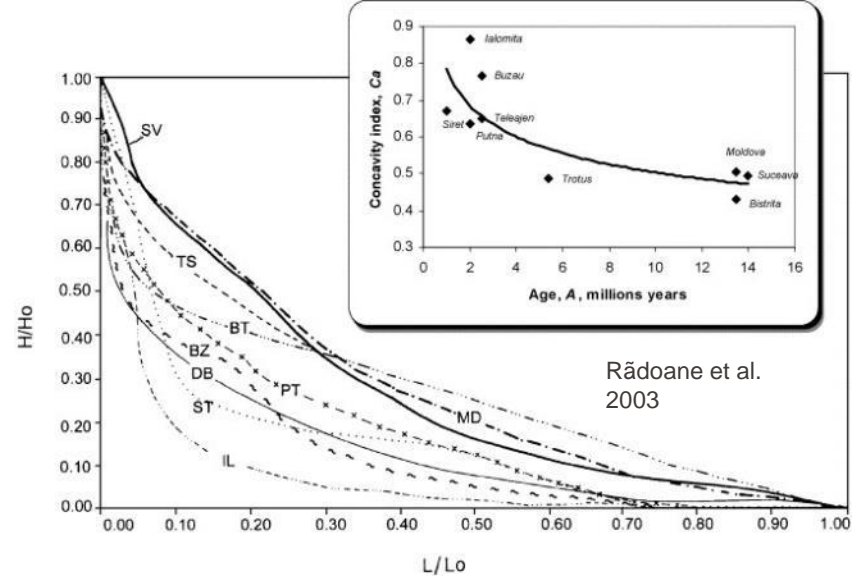
## Elevation of the thalweg



## Common characteristics among rivers

- Progressive decrease of bed slope
- Concave shape
- Smoothing over time

The longitudinal profile appears to follow a sort of «universal law»



# Longitudinal profile

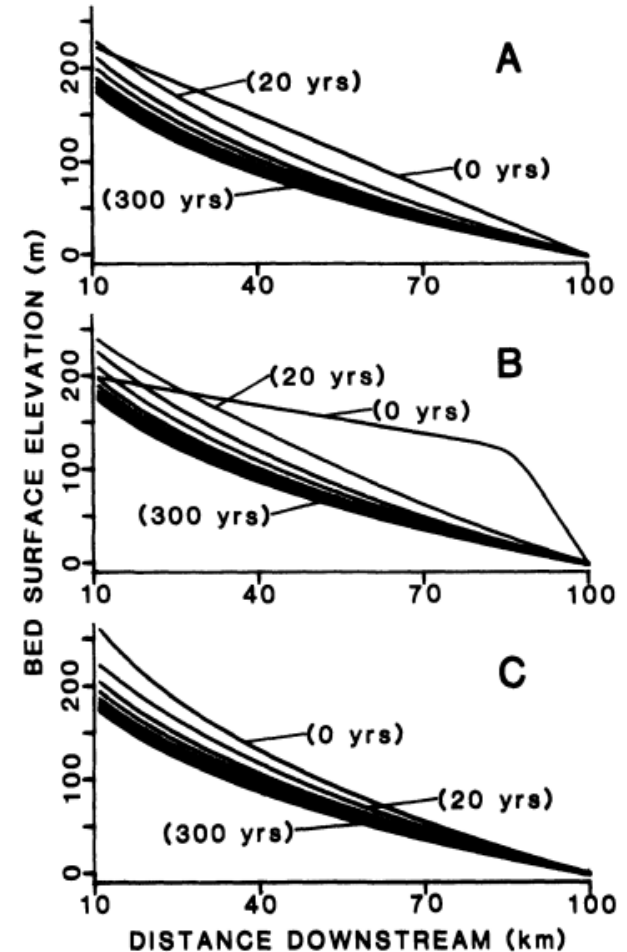
Achievement of an equilibrium profile

Continuous adjustments between erosion and deposition processes

Long-term evolution predicted by numerical models (e.g., Snow and Slingerland, 1987)

Temporal space between profiles = 20y

Different initial bed profile (different concavity) → information on the IC is lost just after the first timestep (t=20y)

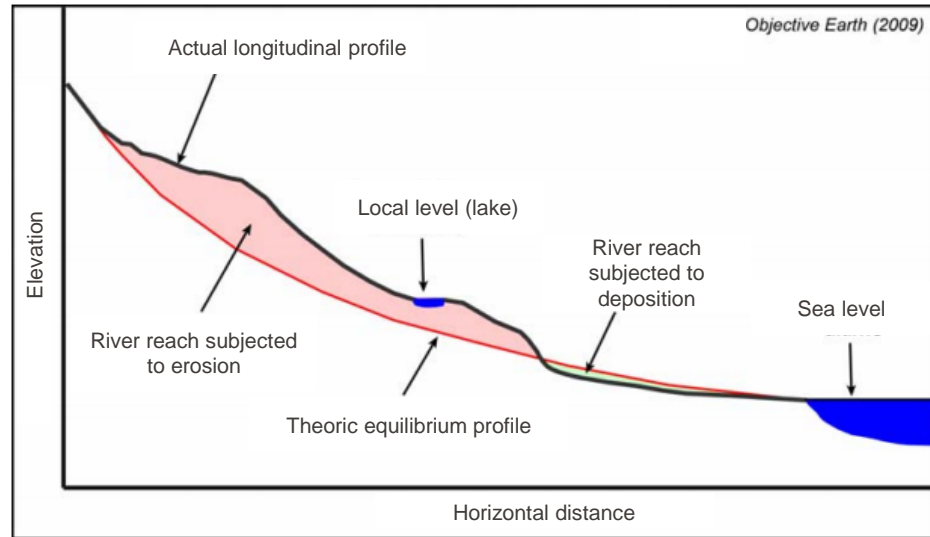


Downstream control on the profiles

Usually the BC is defined by the sea level

Local/Temporal BC:

- a lake
- an alluvial fan
- channel narrowing/widening
- bed material composition



Société Suisse de Géomorphologie (SSGm) – Schweizerische Geomorphologische Gesellschaft Fiches – Géomorphologie de la montagne – Août 2009

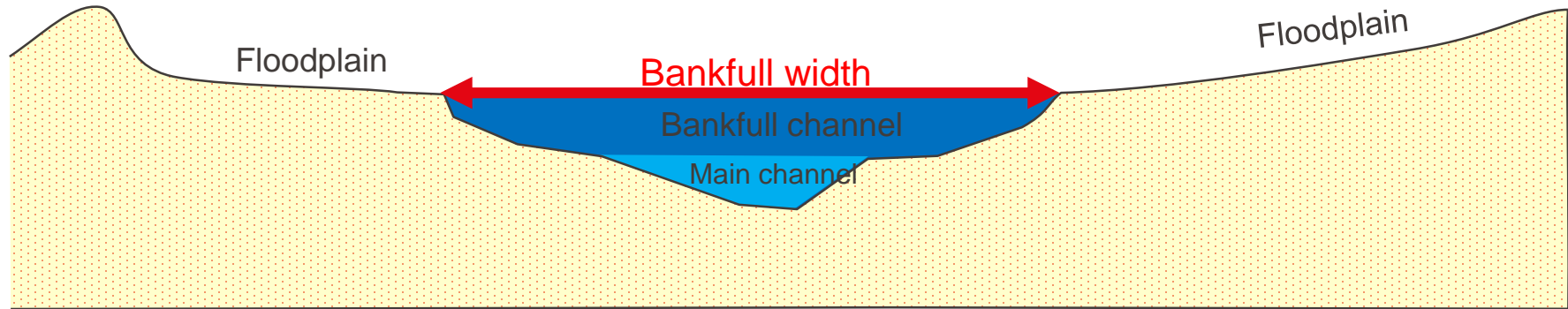
# Transversal profile (cross section geometry)

Bed decomposition

- Main channel, corresponding to low water flows  $\rightarrow Q < \text{mean}(Q)$
- Bankfull channel
- Floodplain

Relationships between bankfull channel and...

offshore discharge, vegetation, catchment area, grain size  
(Schumm, 1960; Hey and Thorne, 1986; Parker et al., 2007)



Assuming rectangular cross-section:

$$Q = A \cdot \bar{v} = B \cdot h \cdot \bar{v}$$

- $B = a Q^b$  (bankfull)
- $h = c Q^f$  (water depth)
- $\bar{v} = k Q^m$  (mean flow velocity)

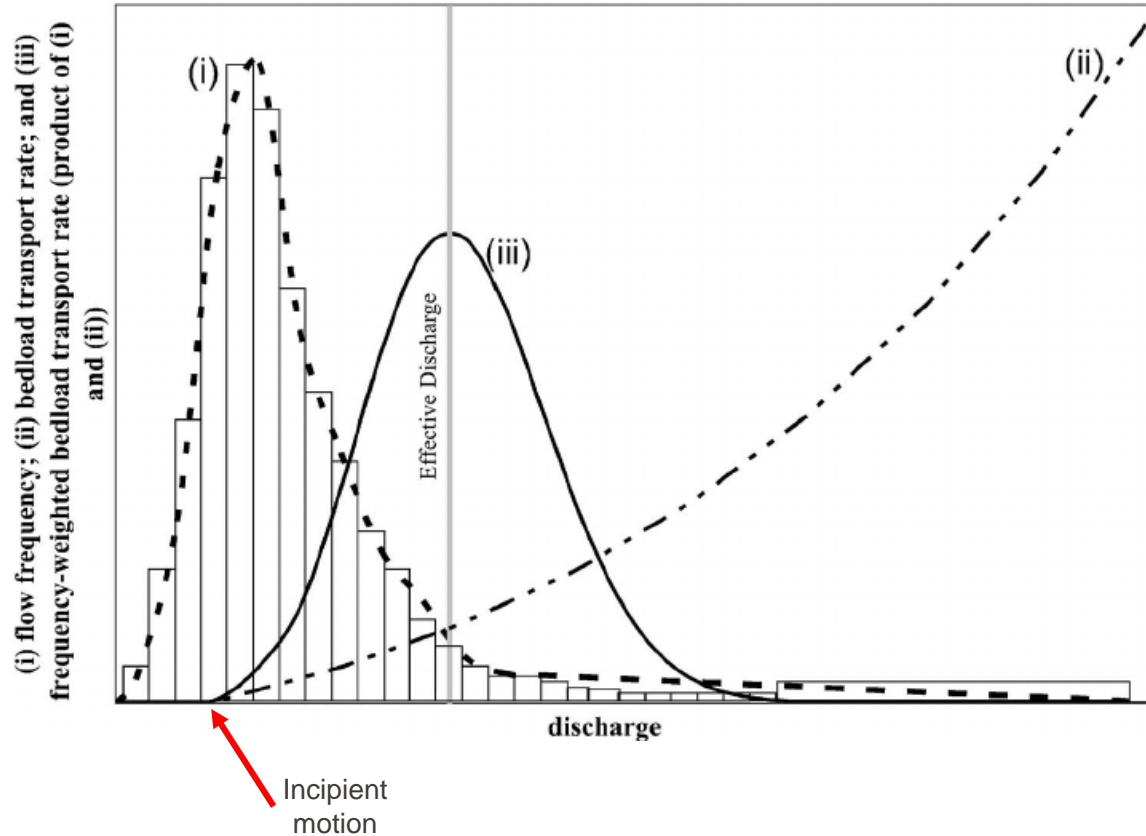
According to the literature:

- $b, f$  and  $m > 0$  usually,  $b \cong 0.6$ ,  $f \cong 0.3$  and  $m \cong 0.1$
- $a, c$  and  $k$  depend on watershed properties (e.g., catchment area, land use)

Can all flow rates lead to an adjustment of the hydraulic geometry?

# Transversal profile (cross section geometry)

Barry et al. (2008)



Formative discharge

$$Q_f = Q_{bf}$$

(bankfull discharge)

$$Q_f = Q(\text{Tr}=2-5 \text{ years})$$

# Planimetric configuration



Tilt River, Scotland



Green River, US



Columbia River, Canada



1985

Upper Amazon River, Brazil



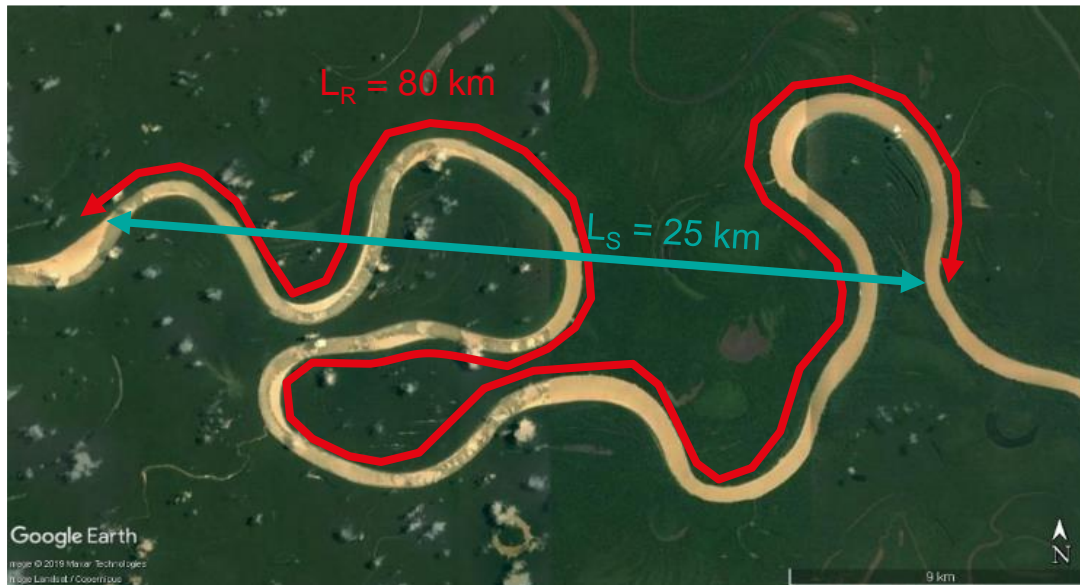
Waimakariri River, New Zealand

# Planimetric configuration

Planform configuration =  $f(x,t)$

$$\frac{\partial f(x,t)}{\partial t} \approx \frac{f(x,t)}{T}$$

with  $T$  the timescale of planform evolution ( $1 \text{ y} < T < \sim 10^5 \text{ y}$ )



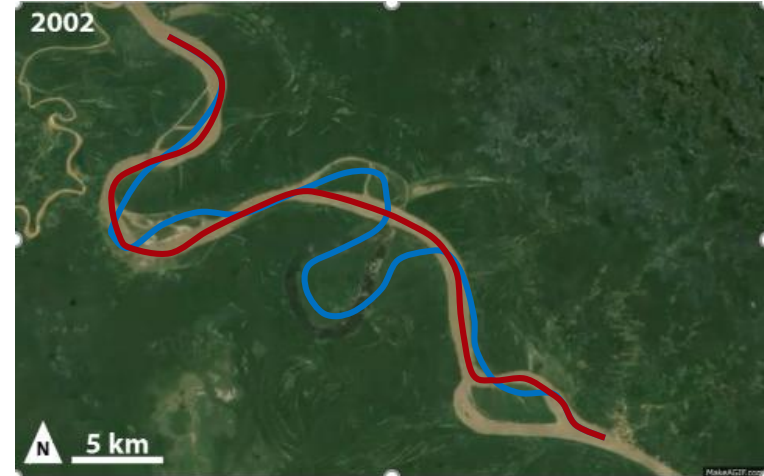
- Length as the crow flies (i.e. straight line between two points =  $L_S$ )
- Length along the water course (i.e. actual river length =  $L_R$ )
- Sinuosity Index  $I_S = L_R / L_S$  (e.g.,  $I_S = 80 \text{ km} / 25 \text{ km} = 3.2$ )

# Planimetric configuration

Classification based on  $I_S$

- $I_S < 1.05 \Leftrightarrow$  rectilinear
- $1.05 < I_S < 1.25 \Leftrightarrow$  sinuous
- $1.25 < I_S < 1.5 \Leftrightarrow$  very sinuous
- $1.5 < I_S \Leftrightarrow$  meandering

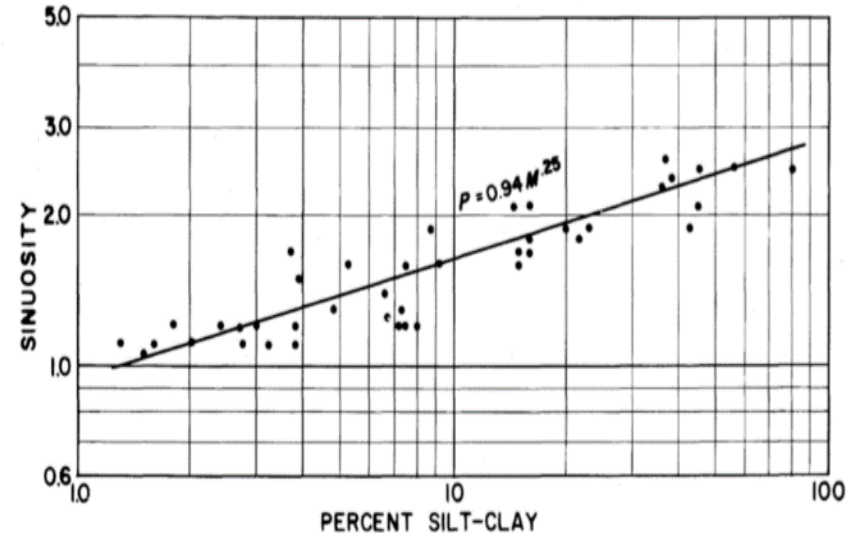
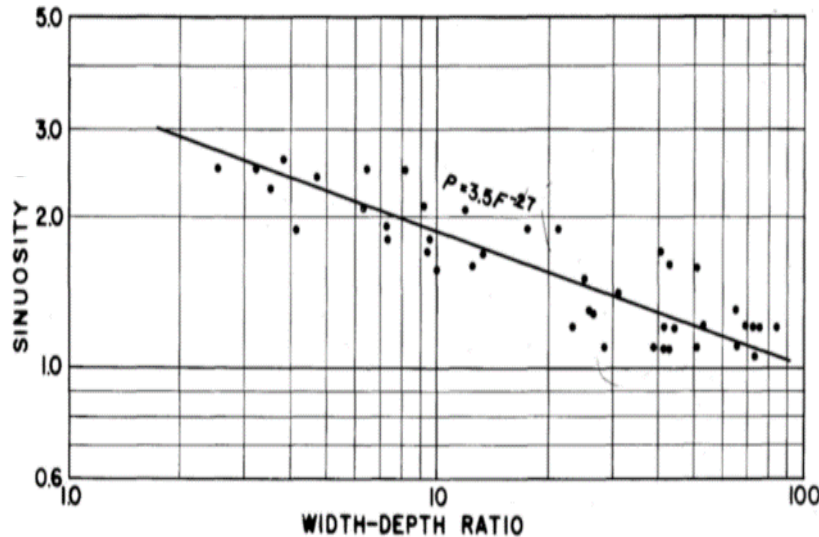
$I_S = I_S(t)$  particularly for highly active meandering rivers







# Planimetric configuration

Schumm (1963): correlation between sinuosity index and...

- Width-to-depth ratio (i.e. aspect ratio)
- Bed slope
- Bank composition (with particular regards to silt and clay fractions)



# Planimetric configuration

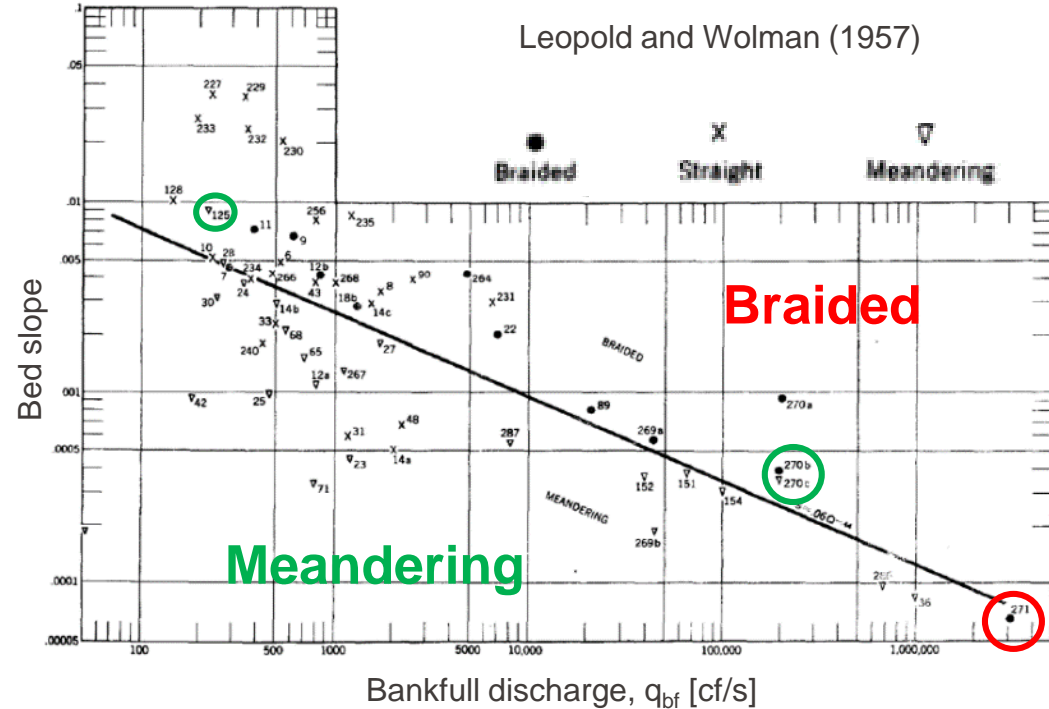
		Number of channels, N	
		N=1 → Single-thread channel	N>1 → Multiple channels
Index of sinuosity, $I_s$	$I_s < 1.05 - 1.25$	 <p><b>RECTILINEAR (straight)</b></p>	 <p><b>BRAIDED</b></p>
	$I_s > 1.25$	 <p><b>MEANDERING</b></p>	 <p><b>ANASTOMOSED ANABRANCHING</b></p>

Relationship between bankfull discharge and bed slope

Empirical relationship based on field studies

$$s [^\circ/\infty] = 0.013 q_{bf}^{-0.44} [\text{m}^3 \text{s}^{-1}]$$

With some exceptions...

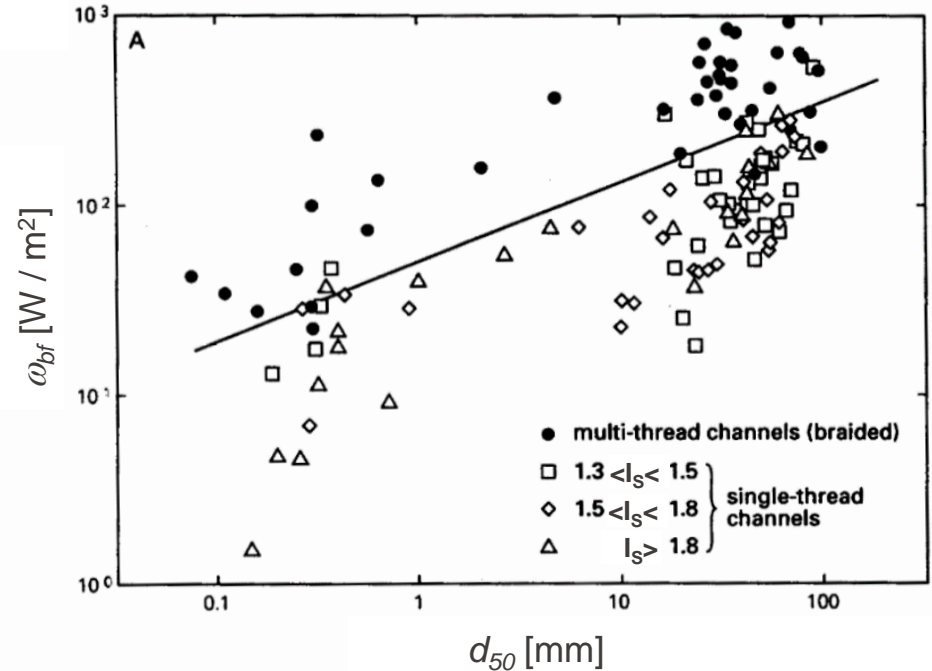


Empirical relationship between bankfull discharge, bankfull width, bed slope and bed material (Ferguson, 1987)

$$\omega_{bf} = \rho g \frac{q_{bf}}{W_{bf}} s$$

$\omega_{bf}$  = bankfull stream-power  
per unit-width [W / m<sup>2</sup>]

$$\omega_{bf} = 900 \cdot d_{50}^{0.42}$$



# Planimetric configuration

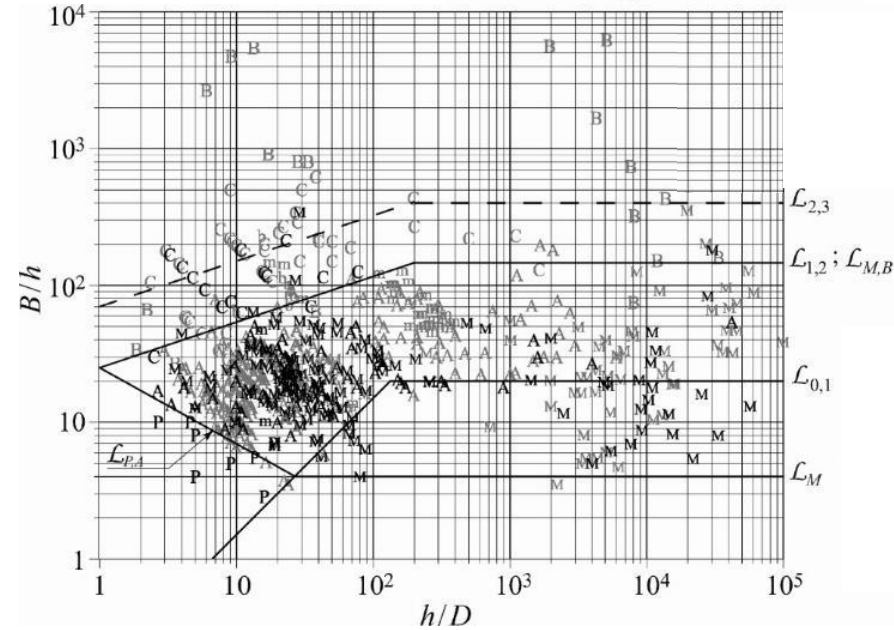
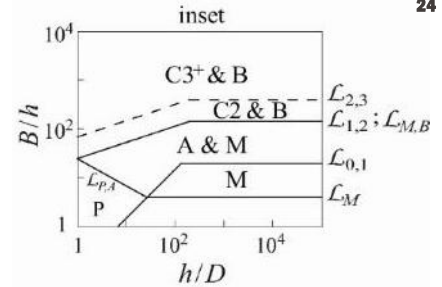
Classification based on the width, and the water depth in bankfull conditions and a characteristic grain size,  $d_m$  (usually  $d_m \rightarrow d_{50}$ ).

- Empirical formulations based on real rivers and flume experiments
- Presence of bars (bedforms)

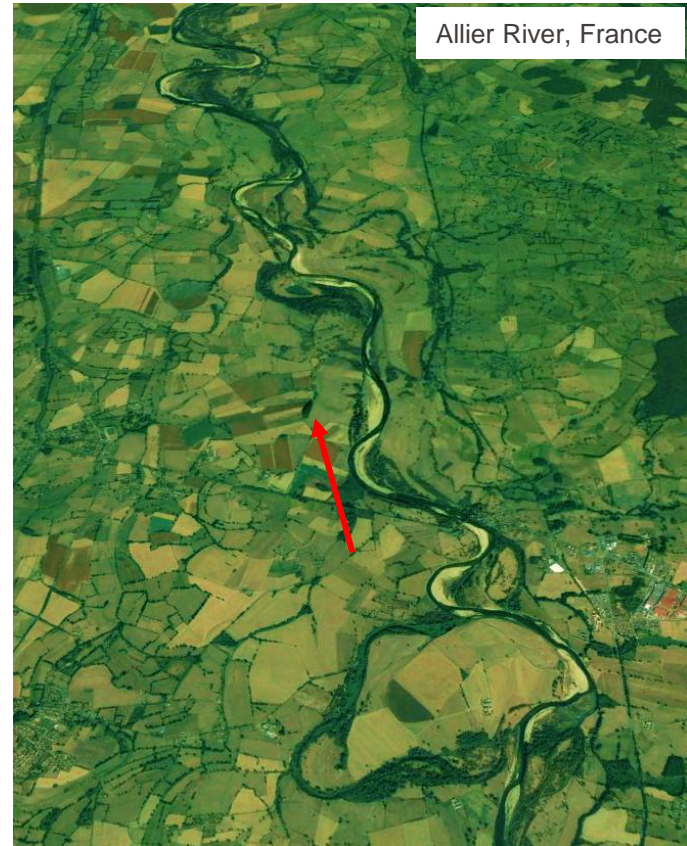


Ahamri and da Silva (2001)

A - Alternate bars  
 C - Multiple bars  
 M - Meandering rivers  
 m - Meandering lab. channel  
 B - Braiding rivers  
 b - Braiding lab. channels  
 P - Plane Bed



# Meandering rivers

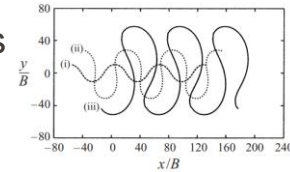
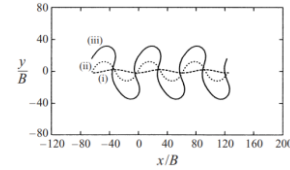




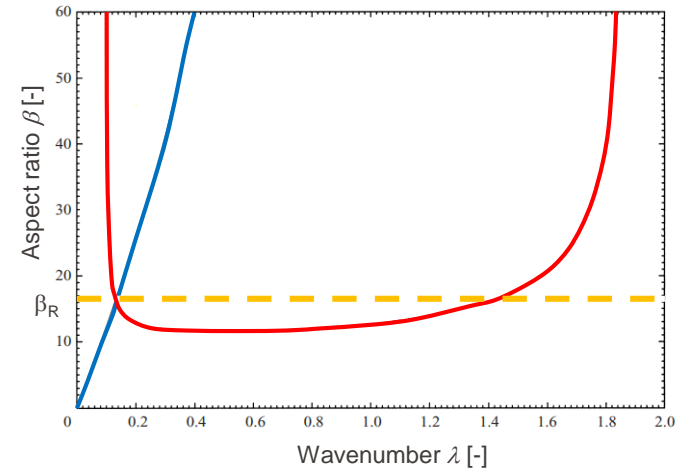
## Meander skewness

- depends on aspect and resonant conditions
- $\beta < \beta_R$  (sub-resonant)  $\rightarrow$  upstream skewness (more common, with regular meanders)
- $\beta > \beta_R$  (super-resonant)  $\rightarrow$  downstream skewness (less common, multi loops)

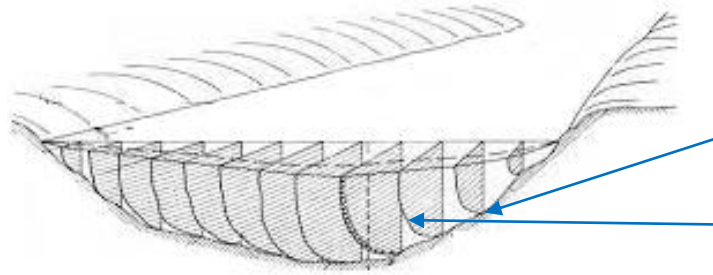
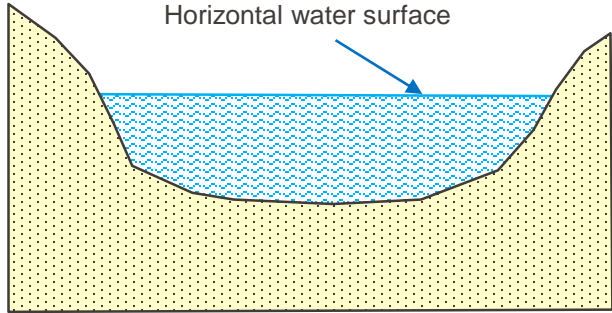
Seminara et al., 2000



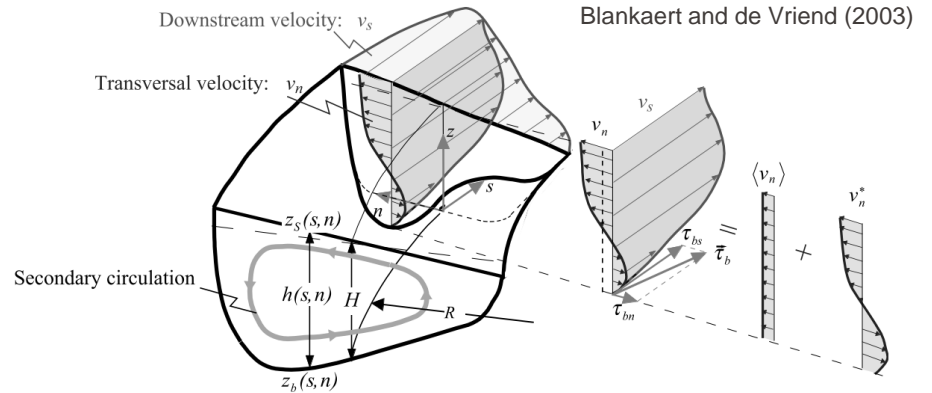
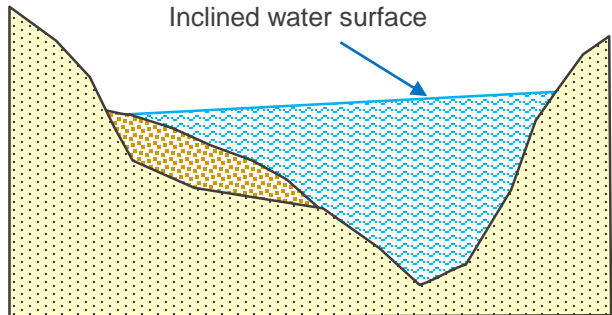
Zolezzi and Seminara (2000)

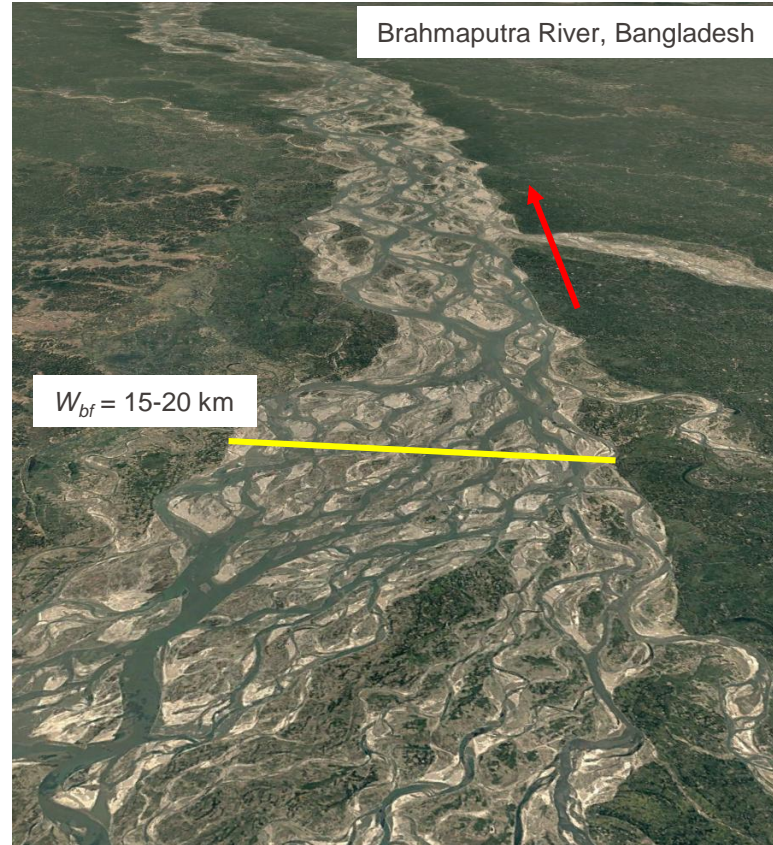
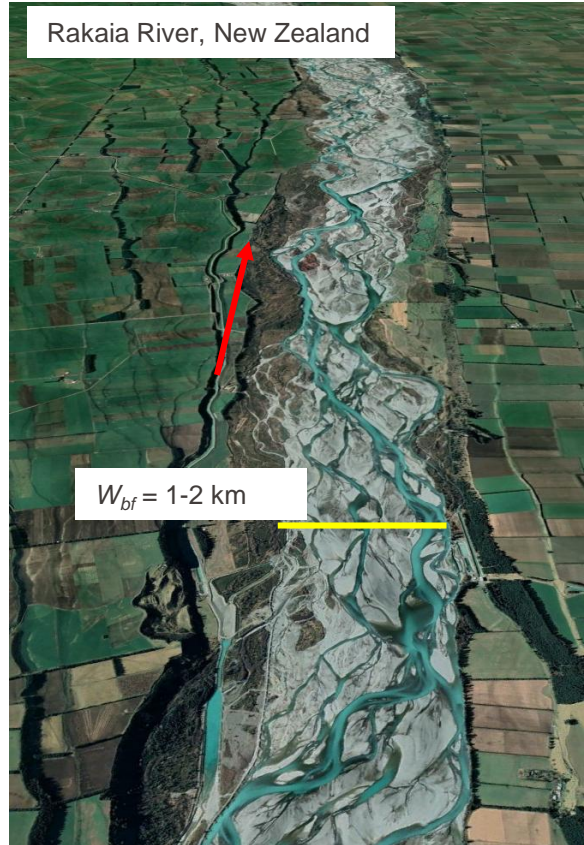


## Average velocity profile in straight channel



## Secondary current in river bends



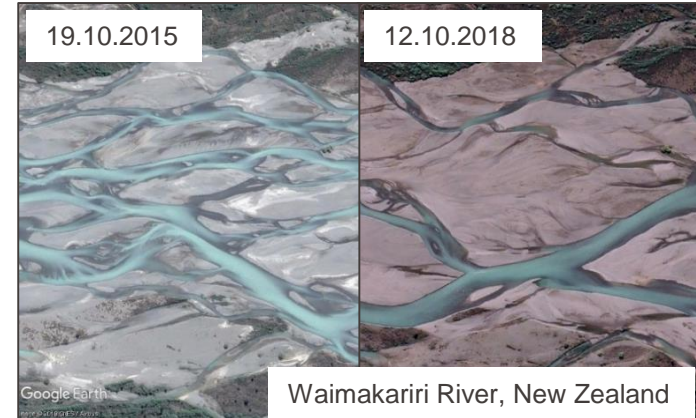




- Secondary channels have  $I_S < 1.5$
- Braiding Index  $I_B$  - Number of active channels
  - $q=0 \rightarrow I_B = 0$
  - $q > q_{bf} \rightarrow I_B = 1$
  - $0 < q < q_{bf} \rightarrow I_B > 1$
  - $I_B = I_B(x,t)$

### Main characteristics

- Rivers with the largest sediment transport and lateral mobility in short temporal scales
- One or two main channels
- Number of secondary channels depending on  $q$
- Multiple channels separated by alluvial deposits, sometimes vegetated (no islands)
- Main channel is almost rectilinear ( $I_S < 1.1$ )
- If  $I_S > 1.1$ , planform configuration is «wandering»



# Braided-Meandering comparison



## Braided rivers

- Usually located in the upstream part of the water basin (NZ rivers!)
- High bed slope
- Coarser bed material (gravel, sand)
- High stream power per unit width
- Low sinuosity (almost rectilinear)
- High bankfull discharge

## Meandering rivers

- Located in the downstream part of the water basin
- Lower bed slope
- Finer bed materials (sand, silt, clay)
- Low stream power per unit width
- High to very-high sinuosity
- Low bankfull discharge