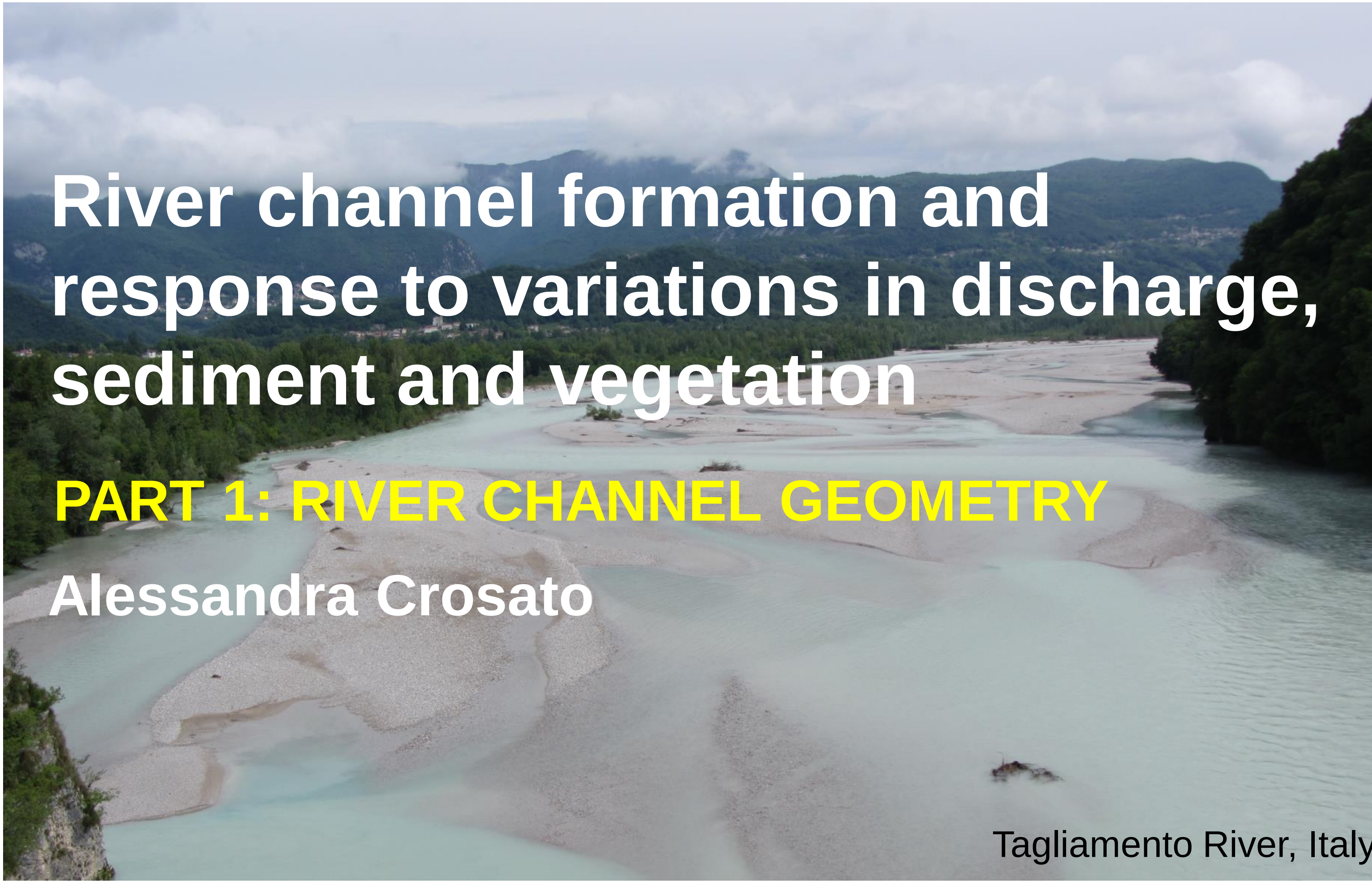
River channel formation and response to variations in discharge, sediment and vegetation

PART 1: RIVER CHANNEL GEOMETRY

Alessandra Crosato



Tagliamento River, Italy

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PART 1 RIVER CHANNEL GEOMETRY

PART 1

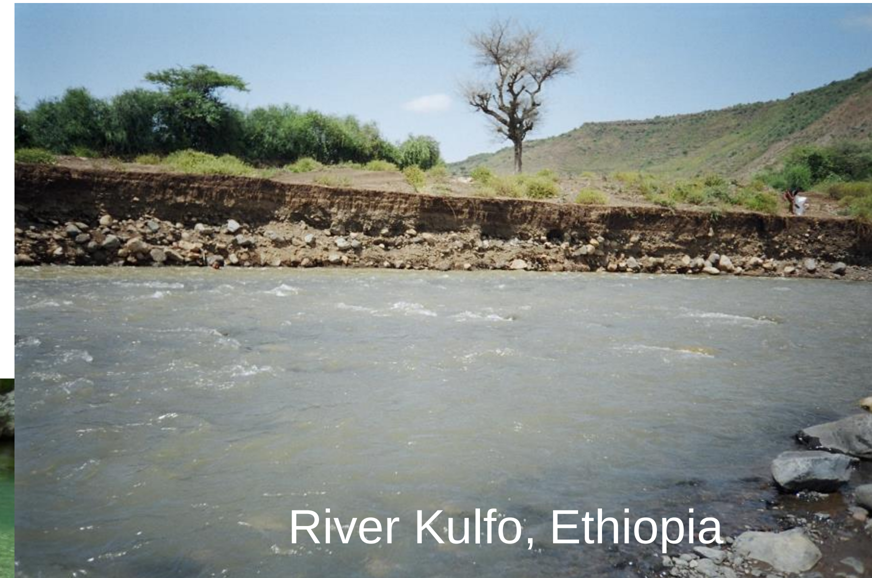
1. Alluvial rivers
2. Factors governing the channel slope and depth
3. Comparison with empirical relations
4. Factors governing the channel width
5. Effects of discharge, sediment, vegetation

1 Alluvial rivers

River channels are excavated by water flowing on erodible soils

River Cellina, Italy

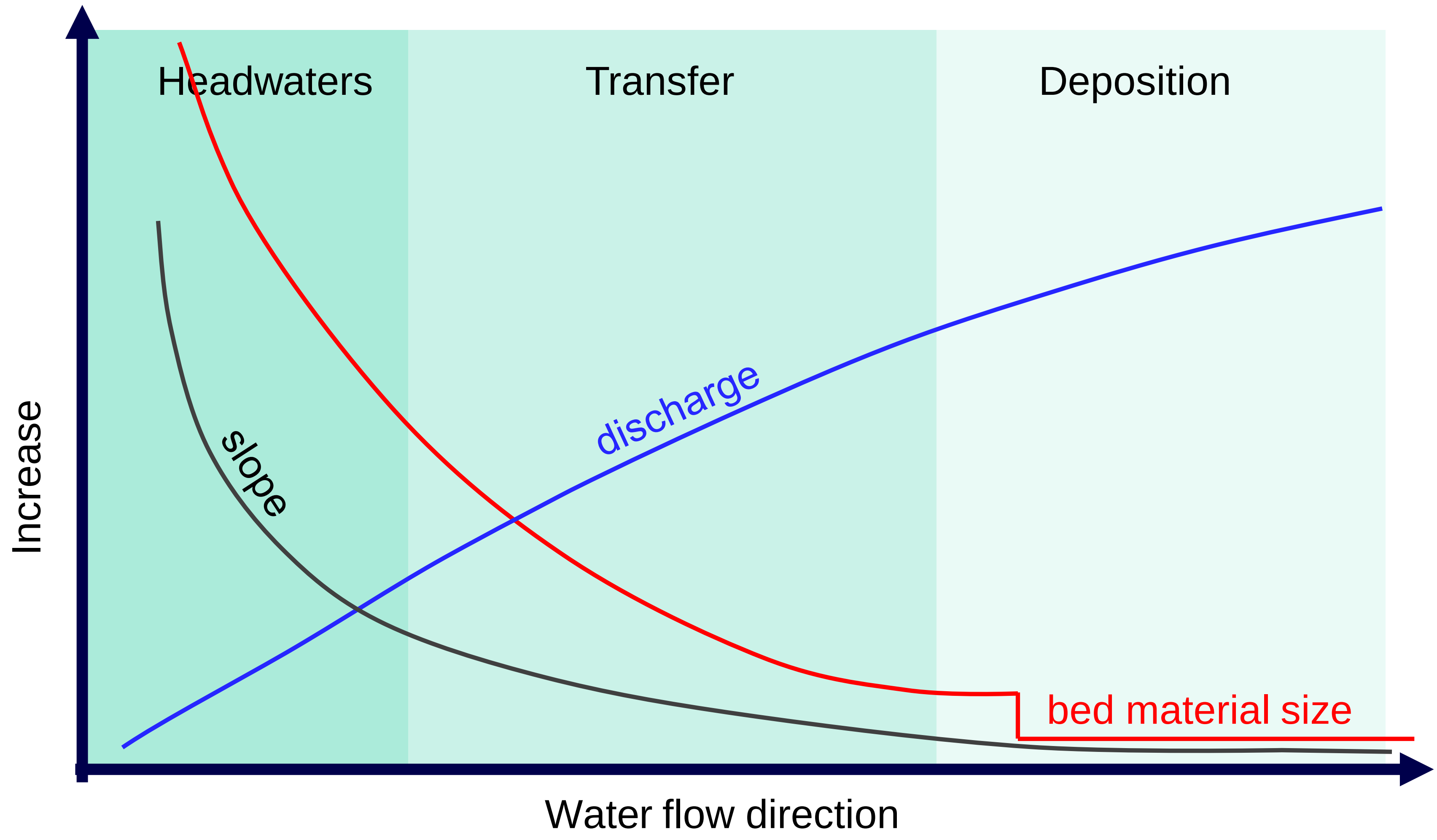
Definition of alluvial river



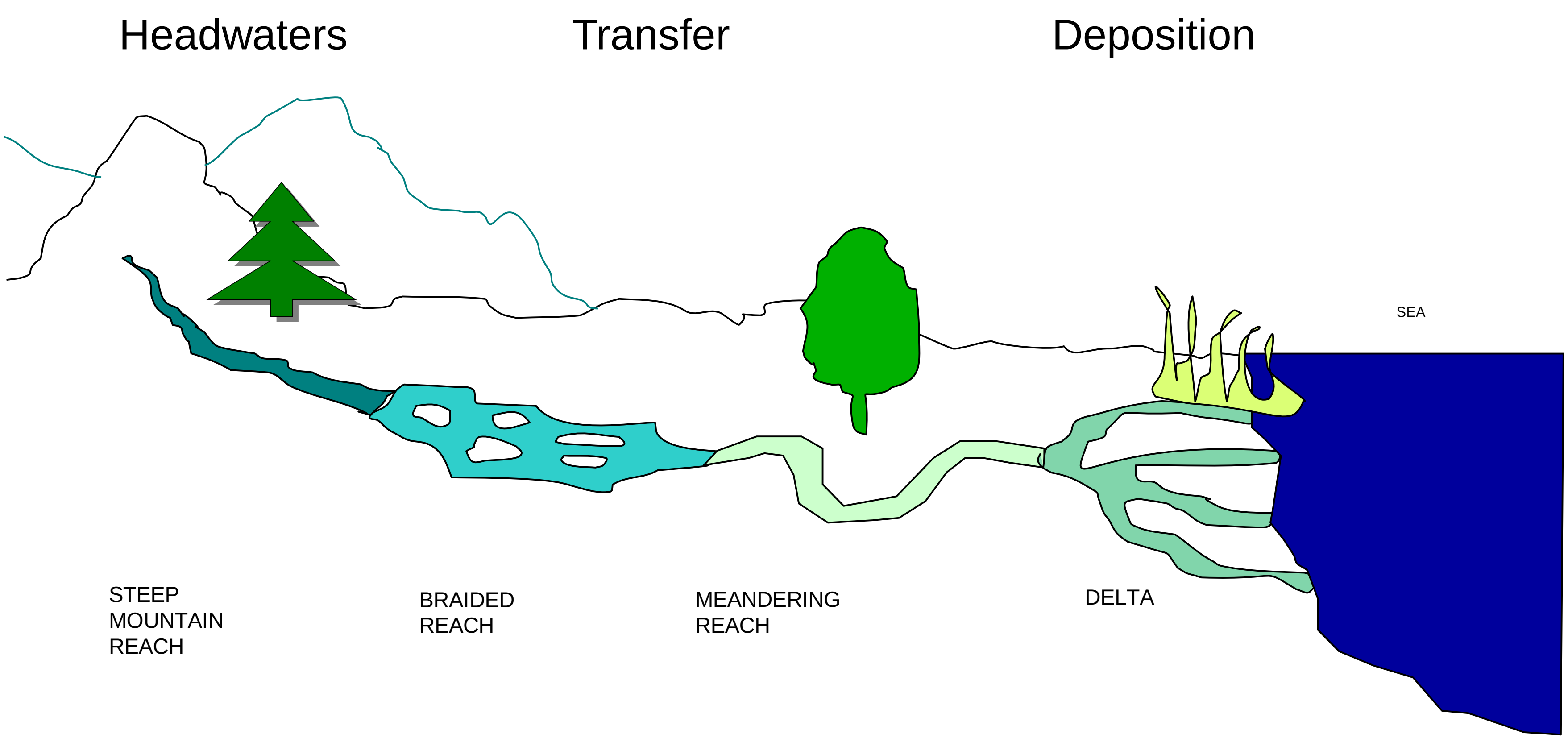
Alluvial river:
bed made of sediment captured and transported by water flow

Erosion and accretion are the main processes that shape alluvial rivers

Discharge, slope, sediment



River planform



Mountain reaches

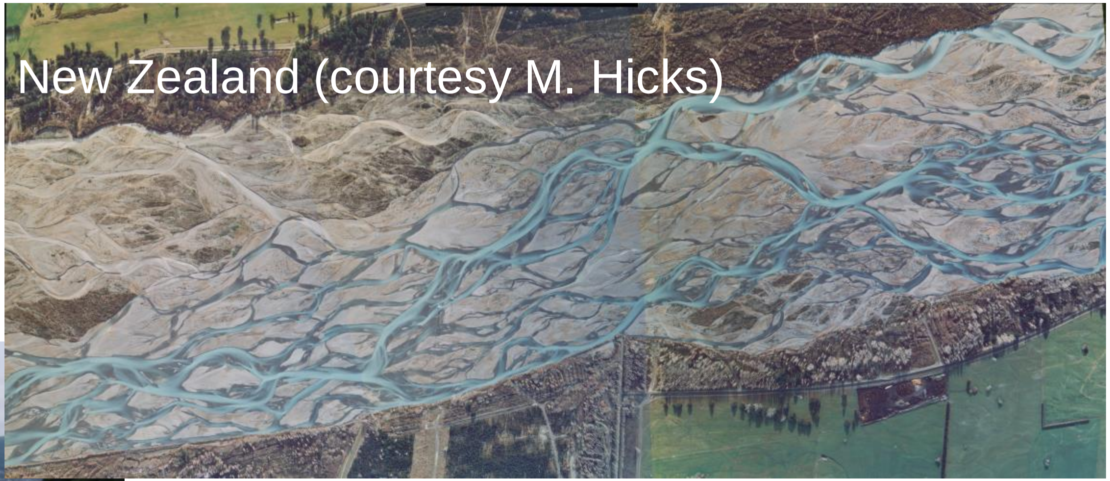
River Soča, Slovenia

River Mow, Bhutan

Steep, laterally limited by rocks, flash floods, large sediment sizes.

Braided reaches

Waimakariri River New Zealand (courtesy M. Hicks)



TYPICAL OF PIED-MONT AREAS
Channels separated by multiple bars emerging during low flow.
Flash floods, gravel bed, large sediment inputs.
Dominated by erosive processes.

Tagliamento River, Italy

Transition reaches

River Allier, France (Google Earth image)

McLeod River, Canada (courtesy J. Slaney)

TYPICAL OF PIEDMONT AREAS AND VALLEYS
Central bars and side channels.
Rather sinuous course.

Meandering reaches

River Mara, Tanzania

River Geul, the Netherlands

TYPICAL OF WIDE VALLEYS
Sand-bed and cohesive banks.
Balanced bank accretion and erosion leading to transverse channel shift and bend growth.

Anabranched reaches

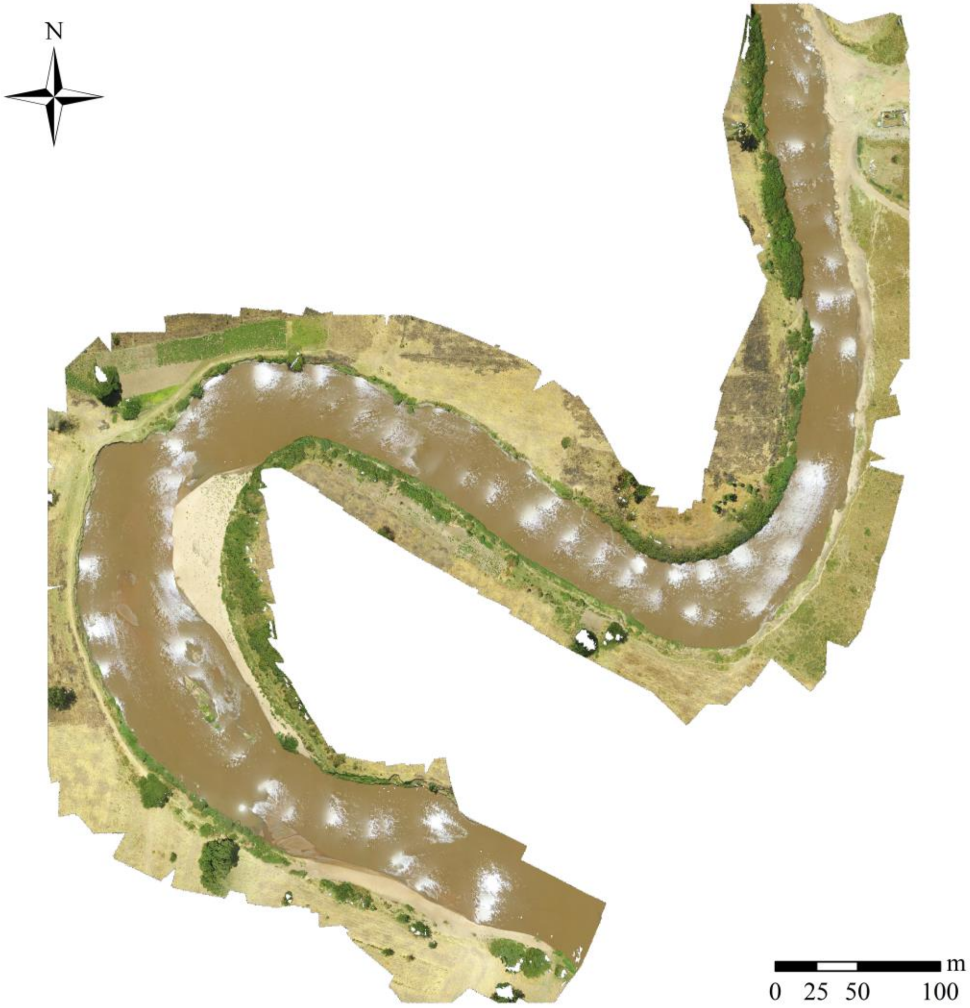
Zambezi River, Zambia (courtesy E. Mwelwa Mutekenya)

Amazon River, Peru (courtesy E. Mosselman)

TYPICAL OF LARGE RIVERS IN WIDE VALLEYS
Multiple channels separated by wide vegetated islands.

Why do rivers change their slope, size and shape from the mountains to the sea?

Focus on river reach characteristics

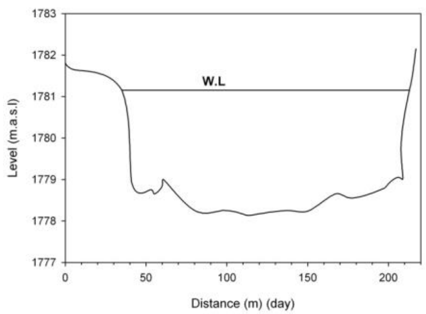


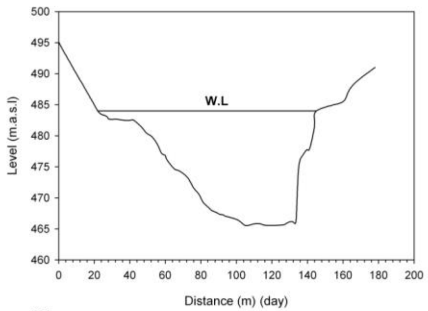
River reach characteristics:

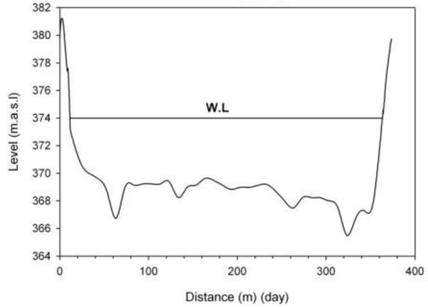
- longitudinal bed slope
- average width
- avegage depth
- planform

Mara River, Tanzania
(courtesy F. Bregoli)

Attention also to cross-section characteristics







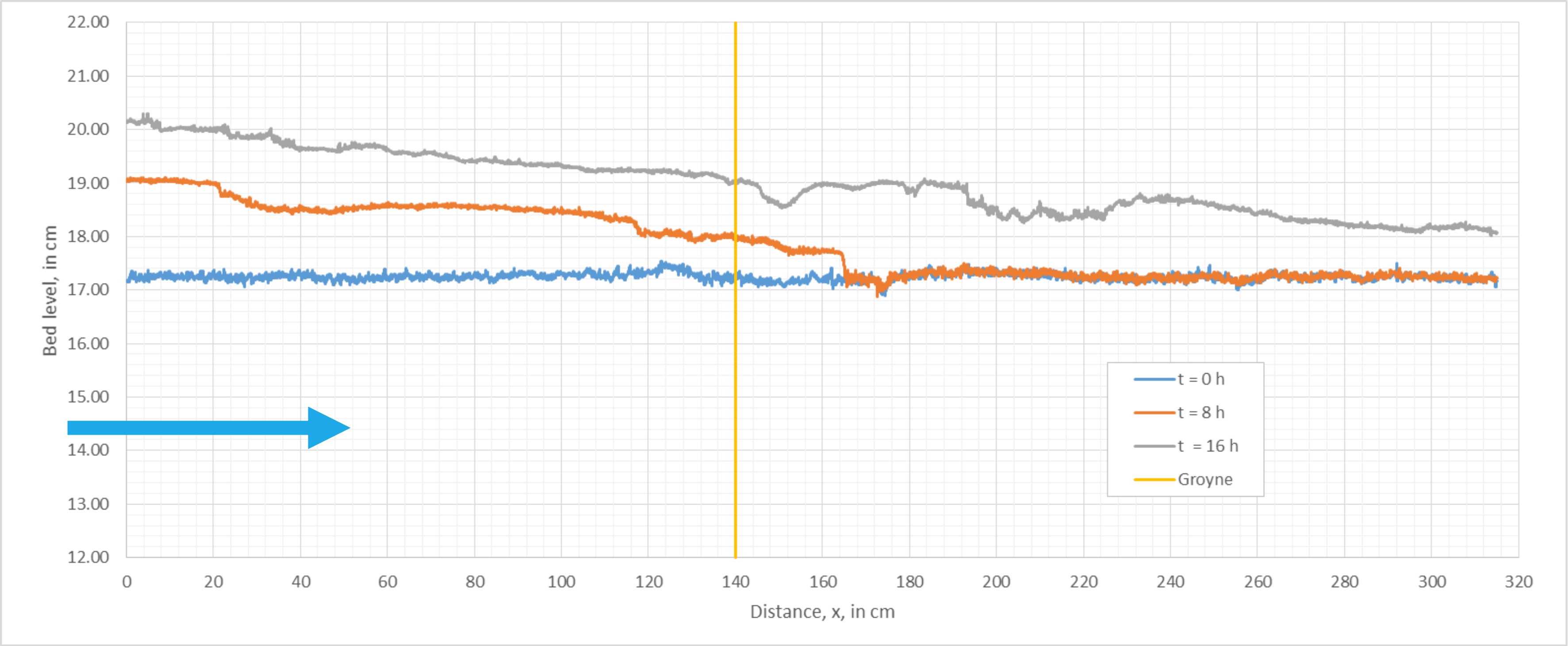
Characteristics of river cross-sections: width, depth, bed topography (bars)

Blue Nile, Sudan (courtesy Y. Ali)

River Mara, Tanzani (courtesy F. Bregoli)

2 Factors governing the channel slope and depth

(flume experiments by Crosato, Bonilla-Porras et al. 2018)

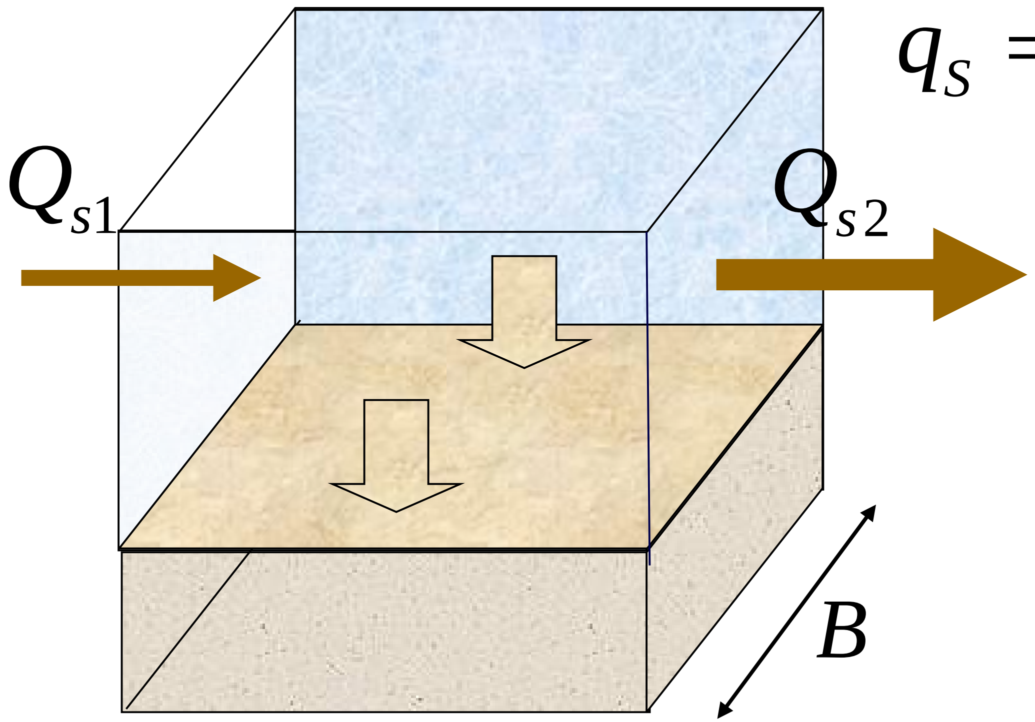


Slope adaptation to boundary conditions by sedimentation front propagation
Different slope is obtained with different roughness

Morphological changes occur if sediment input ≠ sediment output

$$Q_S = Bq_S$$

$$q_S = M(u - u_c)^b$$



$$Q_{S1} = Q_{S2} \text{ if } u_1 = u_2$$

(Exner approach)

Morphodynamic equilibrium: uniform sediment transport ↔ uniform flow

1) $u = C\sqrt{hi}$ — Chézy equation for large and shallow rivers: momentum equation

2) $Q_W = uBh$ — continuity equation for water

3) $q_S = M(u - u_c)^b$ — sediment transport capacity formula (replaces momentum equation for sediment)

4) $Q_S = Bq_S$ — continuity equation for sediment (sediment balance)

ASSUMPTIONS:

Q_W = formative discharge

$u_c \approx 0$ (sand)

Combination of 1 to 4 leads to:

channel depth

$$h = \frac{M^{1/b} Q_W}{Q_S^{1/b} B^{(1-1/b)}}$$

channel slope

$$i = \frac{Q_S^{3/b} B^{(1-3/b)}}{M^{3/b} Q_W C^2}$$

(morphodynamic equilibrium)

According to Engelund & Hansen (1967) $b = 5$, $u_c = 0$ (sand-bed rivers) and

$$M = K \frac{1}{C^3 \Delta^2 D_{50} \sqrt{g}}$$

$$i = \frac{Q_S^{3/b} B^{(1-3/b)}}{M^{3/b} Q_W C^2}$$

$$i = K' \left(\frac{1}{Q_W} \right) \left(\frac{D_{50}{}^3 Q_S^3 B^2}{C} \right)^{1/5}$$

(with K' = constant)

Response of channel slope to variations of..

The channel slope i increases with

$$i \sim \left(\frac{1}{Q_W}\right)\left(\frac{D_{50}{}^3 Q_S^3 B^2}{C}\right)^{1/5}$$

- Sediment transport: Q_S
- Sediment size: D_{50}
- Channel width: B
- Bed roughness: $1/C$

The channel slope i decreases with

- Discharge Q_W

Response of channel depth to variations of..

The channel depth h increases with

$$h \sim (Q_W)\left(\frac{1}{B^4 C^3 D_{50} Q_S}\right)^{1/5}$$

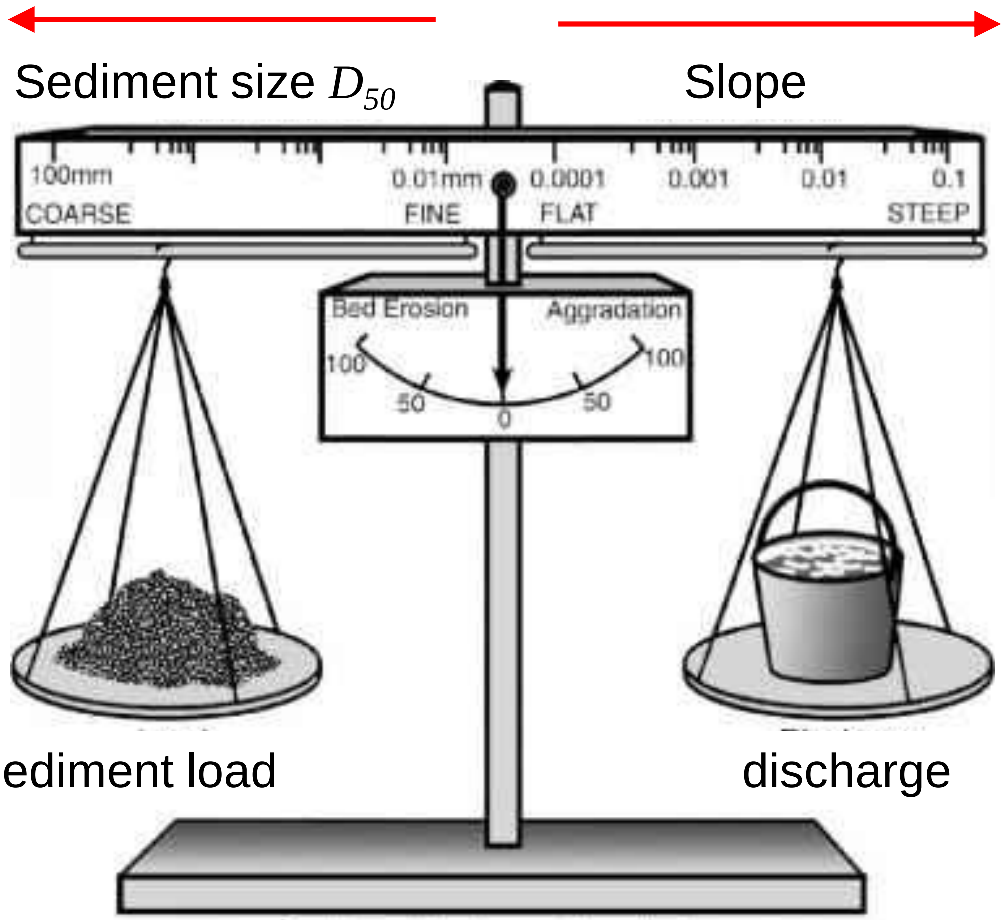
- Discharge Q_W
- Bed roughness $1/C$

The channel depth h decreases with

- Channel width: B
- Sediment size: D_{50}
- Sediment load: Q_S

3 Comparison with empirical relations

(Lane's balance adapted from Brierley and Fryirs 2005)



Lane's (1955) balance:

$$Q_S D_{50} \sim i Q_W$$

$$i \sim \frac{Q_S D_{50}}{Q_W}$$

Leopold and Maddock (1953)

$$i = \alpha_i \left(\frac{1}{Q_{bf}} \right)^{\beta_i}$$

Parker et al. (2007)

$$i = 0.101 \left(\frac{D_{50}^2 \sqrt{g \Delta D_{50}}}{Q_{bf}} \right)^{0.344}$$

Q_{bf} (bankfull discharge) assumed as formative

Derived equilibrium law

$$i \sim \left(\frac{1}{Q_W} \right) \left(\frac{{D_{50}}^3 Q_S^3 B^2}{C} \right)^{1/5}$$

Major difference: includes width, assumed as known, and bed roughness

Factors governing the channel slope and depth

Discharge

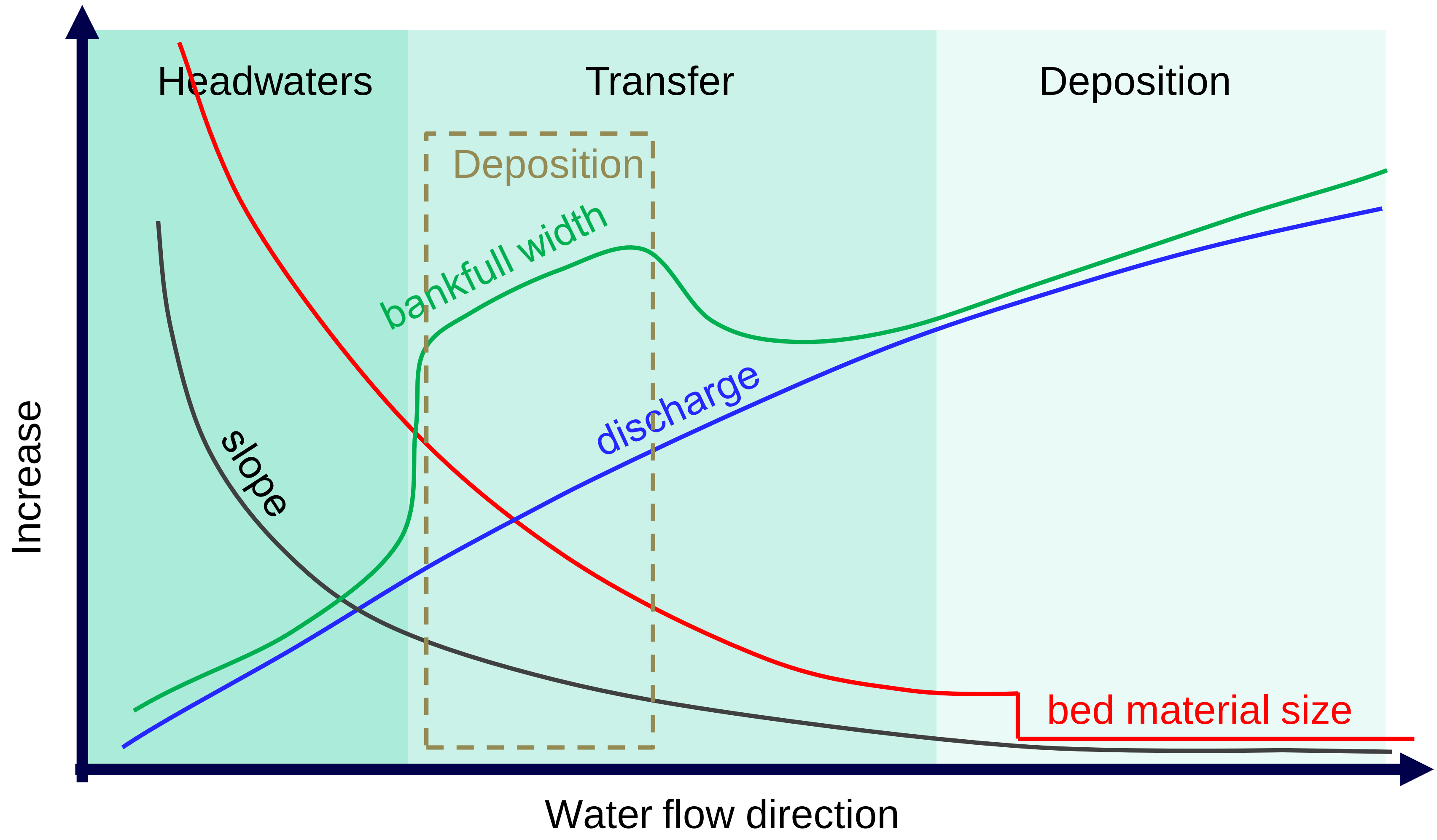
Sediment size
Sediment load
Bed roughness

Sediment

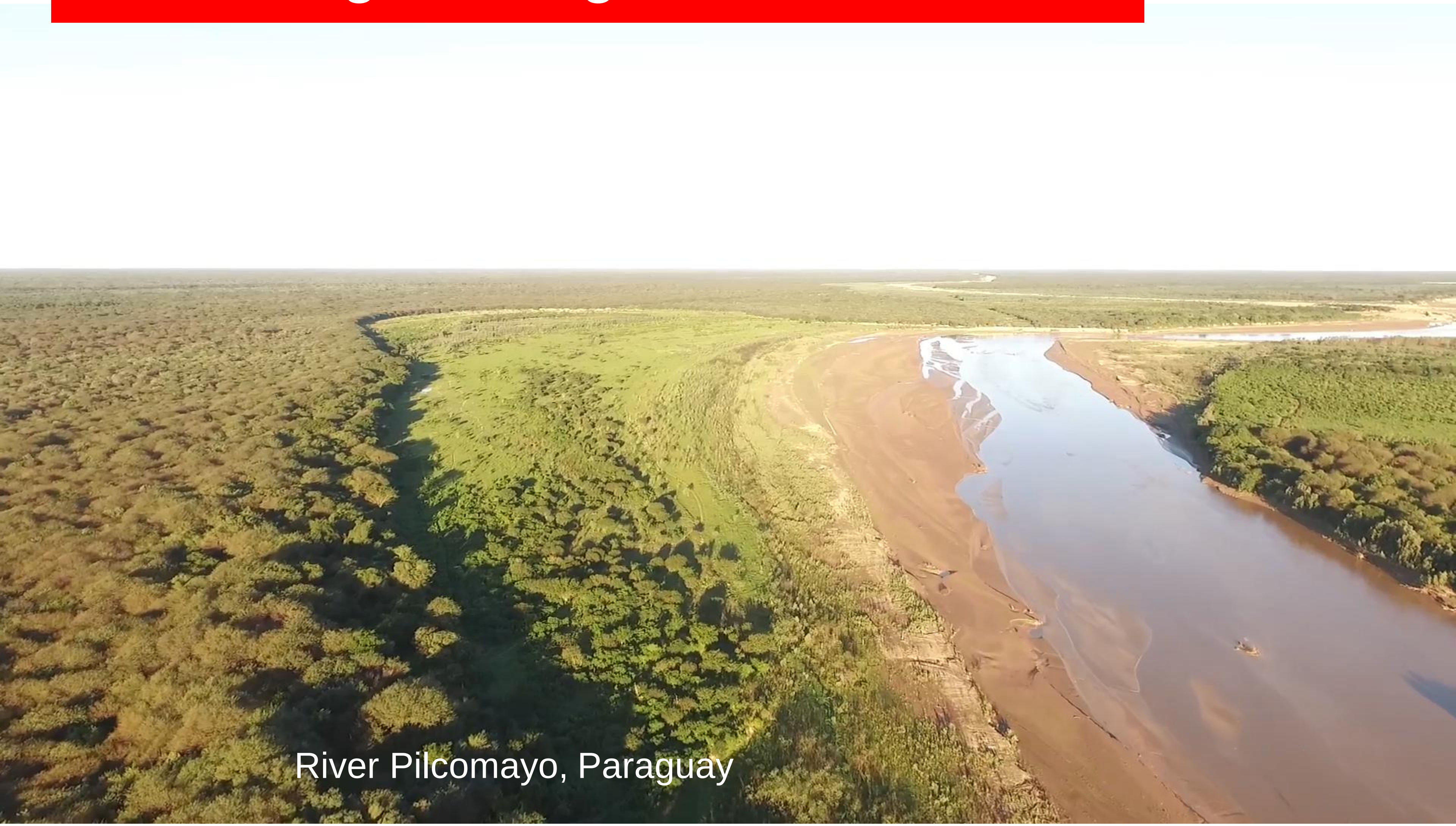
Channel width

And what about the channel width?

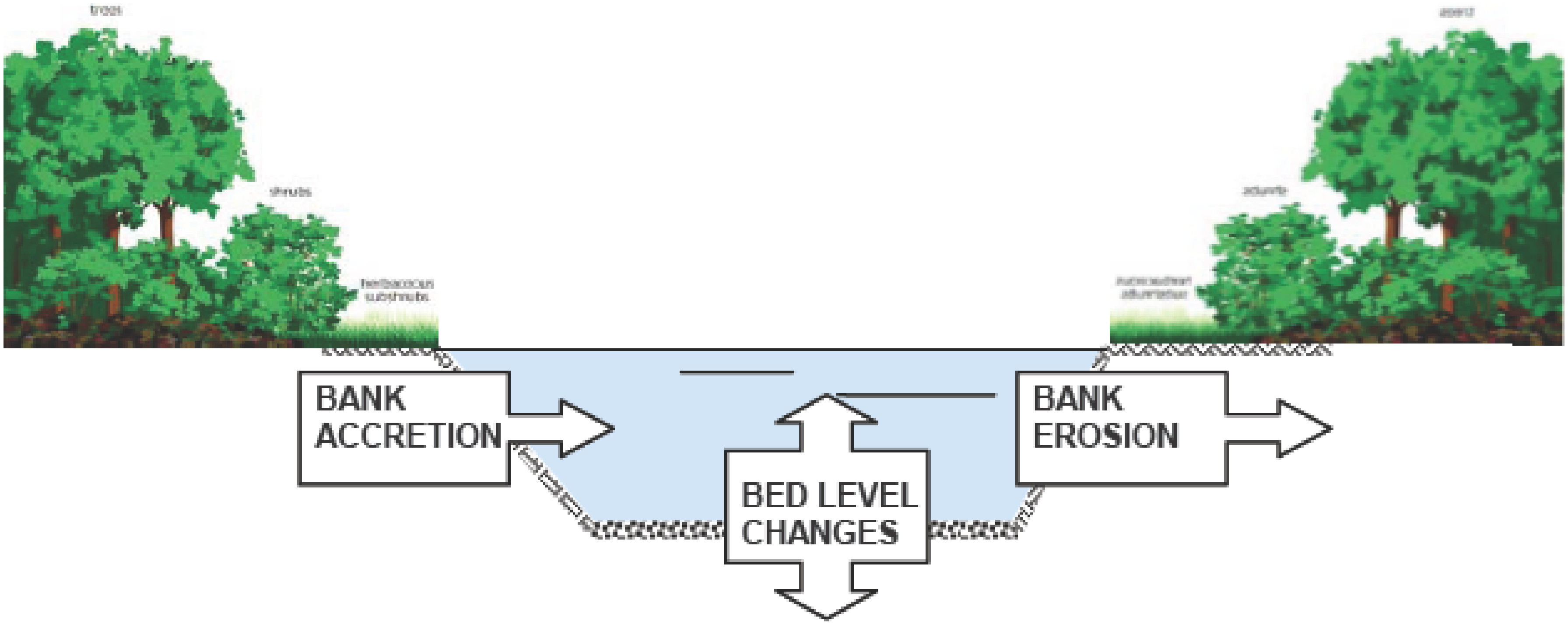
Discharge, slope, sediment and width



4 Factors governing the channel width



River width processes: bank erosion and accretion



Bank erosion

1. Flow capturing sediment particles directly from the bank
2. Bank failure caused by geotechnical instability, triggered by bank toe erosion

Capturing of sediment particles dominates non-cohesive banks

River Cellina, Italy

Failure dominates steep cohesive banks

River Meuse, the Netherlands (courtesy G. Duró)

Bank accretion

1. Near-bank sediment deposition
2. Soil stabilization by plants and consolidation processes
3. Sedimentation and level raise

Colorado River, Colorado

Vegetation affects bank erosion and accretion by:

(bio-stabilization)

- Reinforcing soil by roots
- Protecting soil by cover
- Decreasing local flow velocity
- Deflecting the flow

- Colonization
- Enhancing local deposition
- Favoring vegetation growth

(bio-engineering)

Sarca River, Italy

Factors governing the channel width

Bank material (bank erodibility)

Sediment (near-bank deposition/scour)

Discharge (sediment entrainment/scour)

Vegetation (bank erodibility, bank accretion)

FOCUS

Groundwater flow (bank erodibility)

Existing empirical relations for channel width

Example: Leopold and Maddock (1953)

$$B = \alpha_B Q_W^{\beta_B}$$

power law of "bankfull discharge"

Channel width and depth as a function of discharge and sediment size:

- Parker et al. (2007): gravel-bed rivers
- Wilkerson and Parker (2011): sand-bed rivers

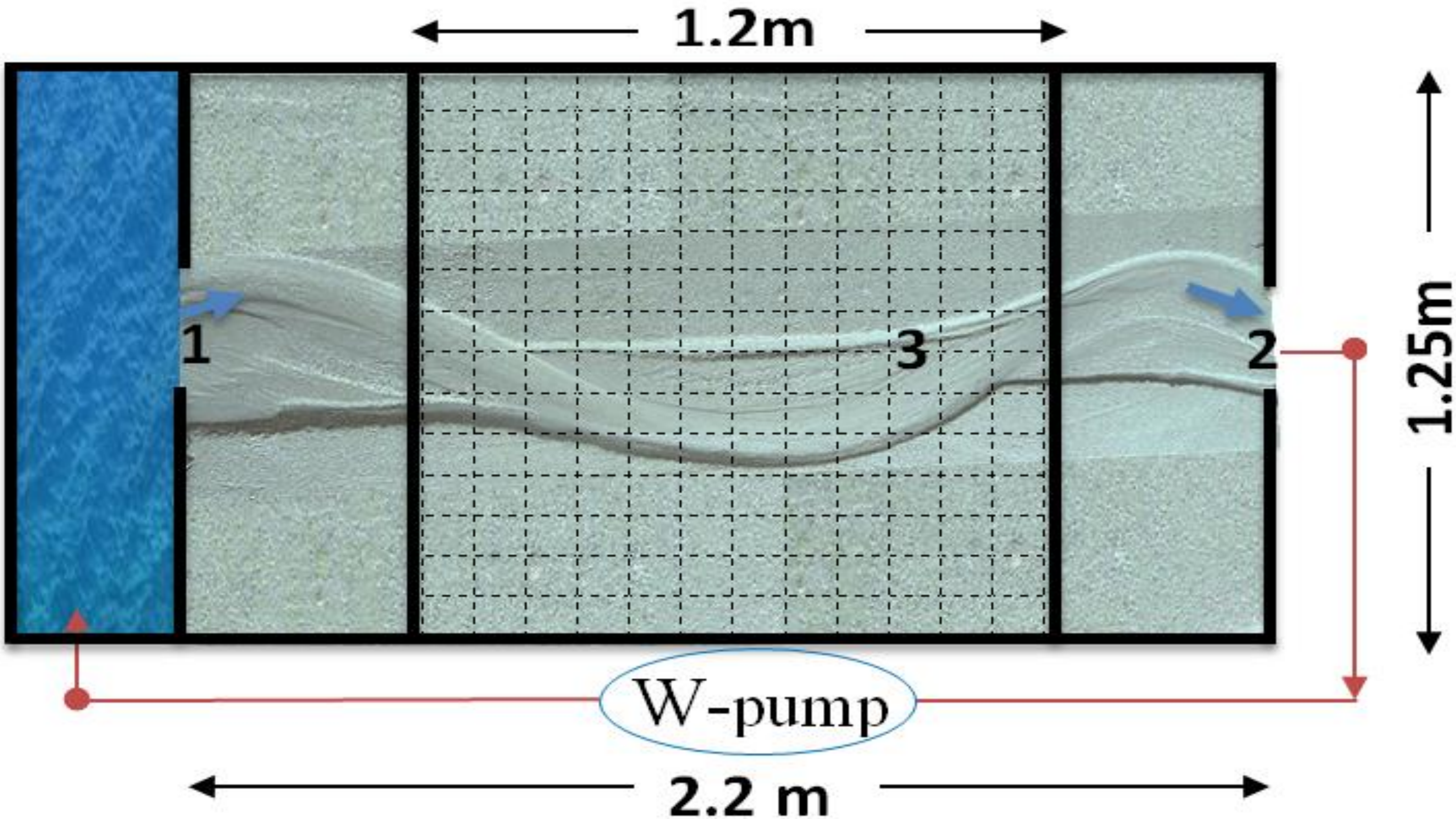
among others

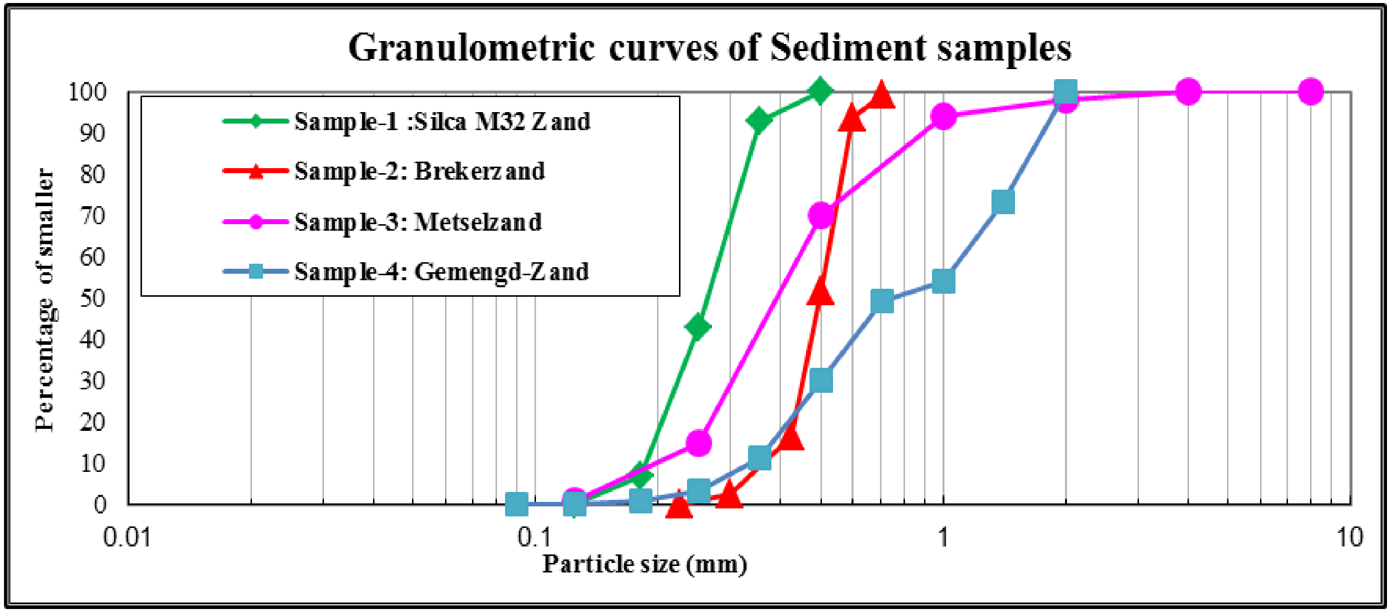
5 Effects of discharge, sediment, vegetation

Results of some recent studies

Effects of discharge variability and sediment on channel width - Experimental study

(Byishimo, 2014; Vargas-Luna et al., 2018)





Sample	D_{50} (mm)	Sorting index (*I*)
1	0.26	1.34
2	0.50	1.23
3	0.40	1.80
4	0.70	2.16

$$I = 0.5\left(\frac{D_{16}}{D_{50}} + \frac{D_{84}}{D_{50}}\right)$$

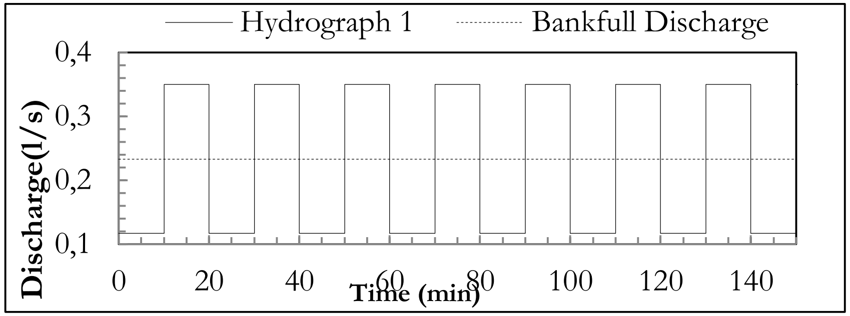
Sample 1 $D_{50} = 0.26$ *mm*

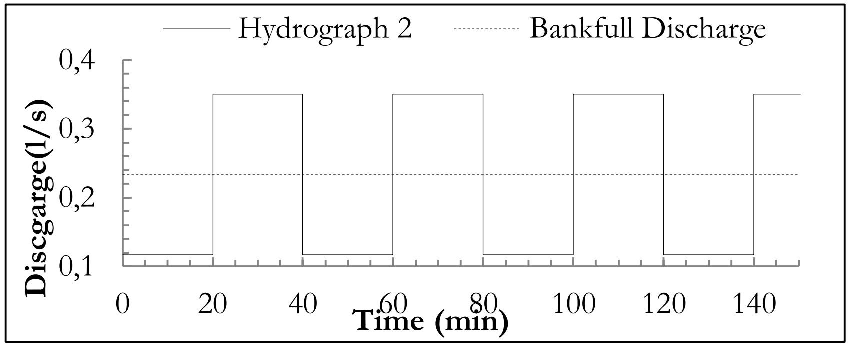
Sample 2 $D_{50} = 0.5$ *mm*

Sample 3 $D_{50} = 0.4$ *mm*

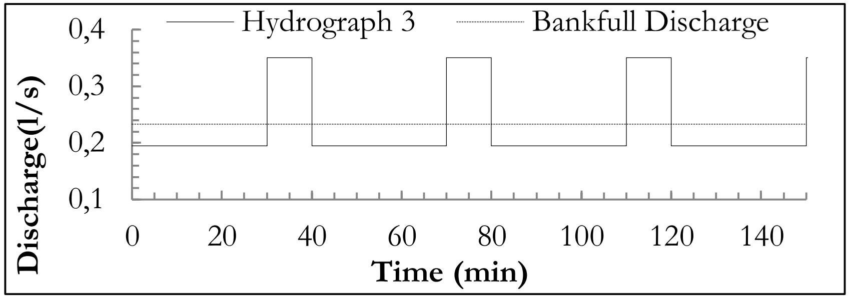
Sample 4 $D_{50} = 0.7$ *mm*

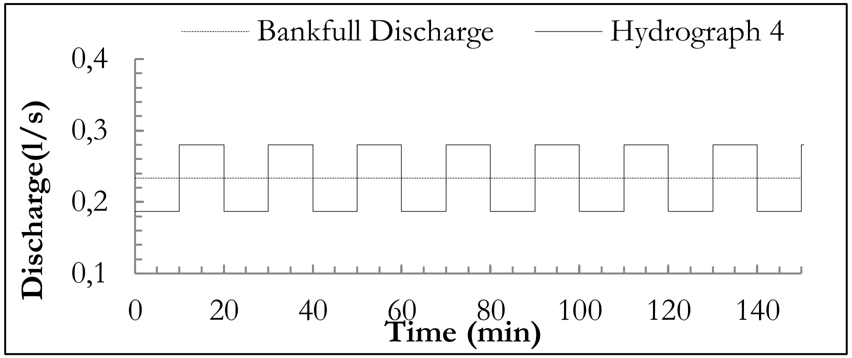
6 discharge regimes all with the same average

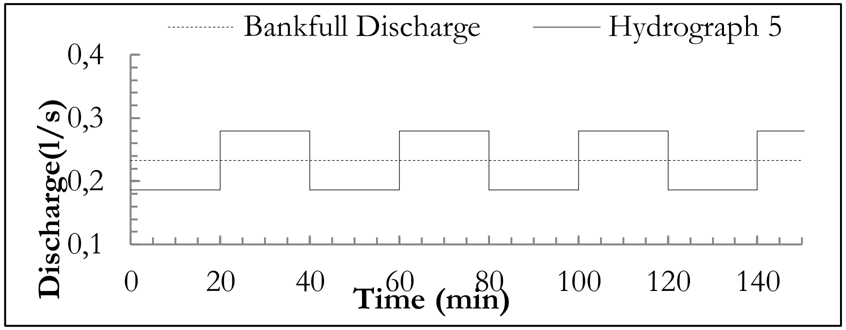




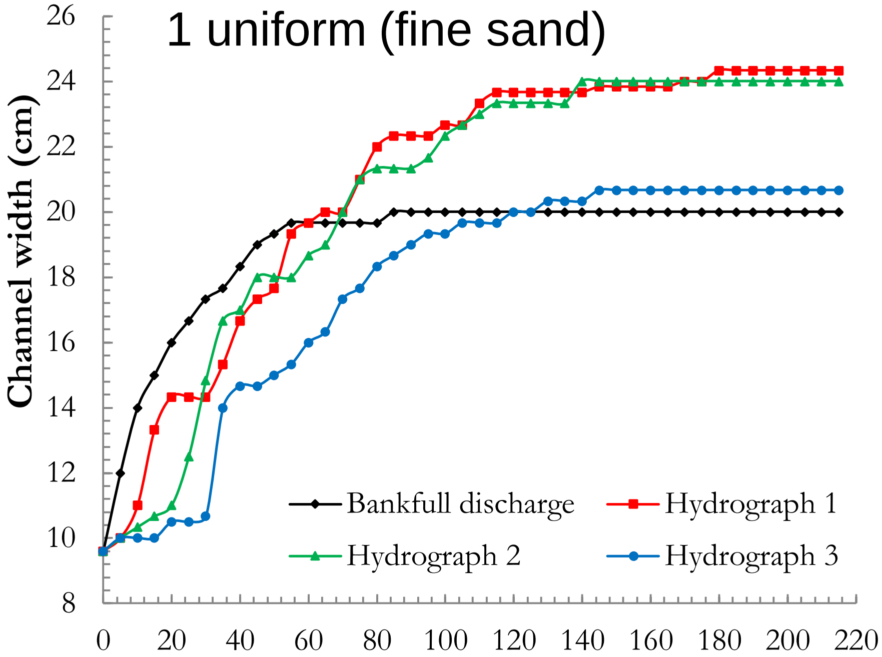
Constant (average) discharge

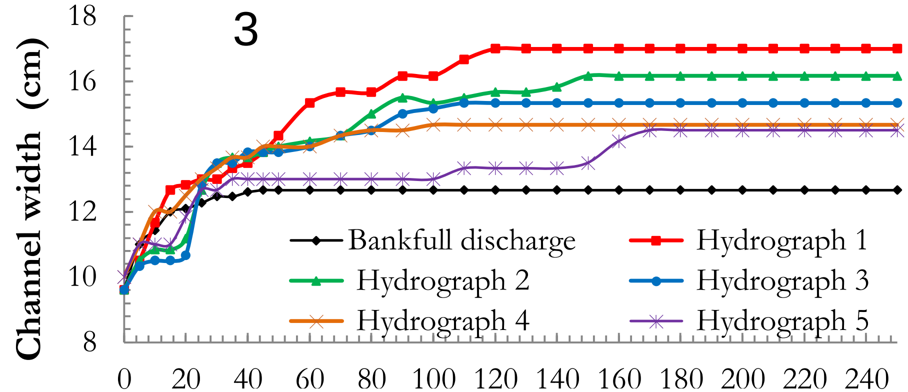




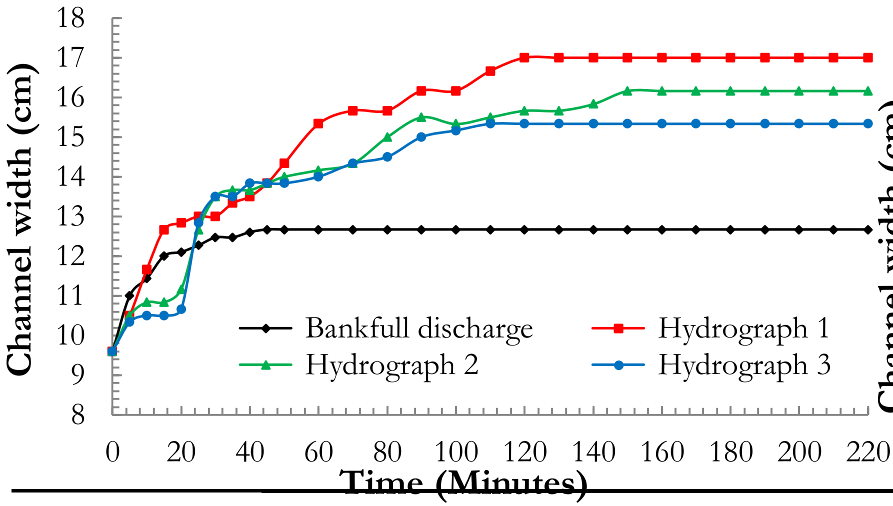


Results discharge & sediment

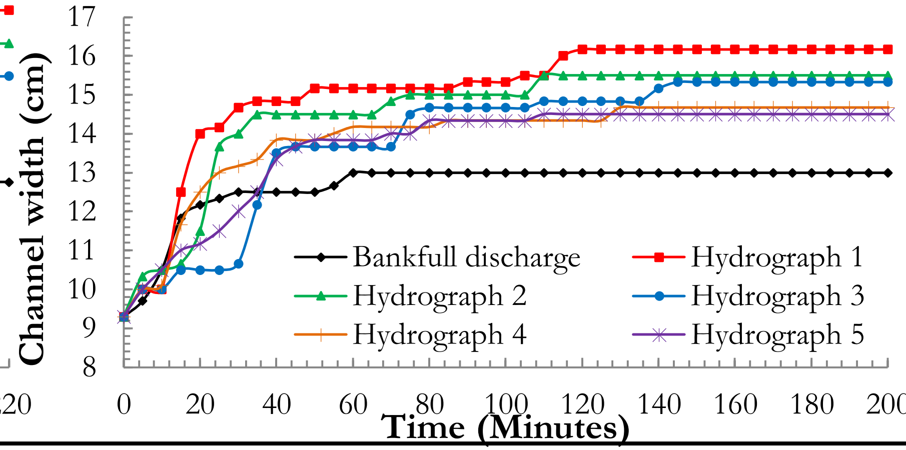




2 uniform (medium sand)



4 poorly sorted



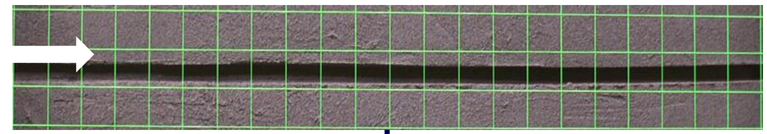
Results: effects of sediment (constant discharge)

(at the scale of the flume poorly sorted sediment behaves as cohesive)

Results formative discharge

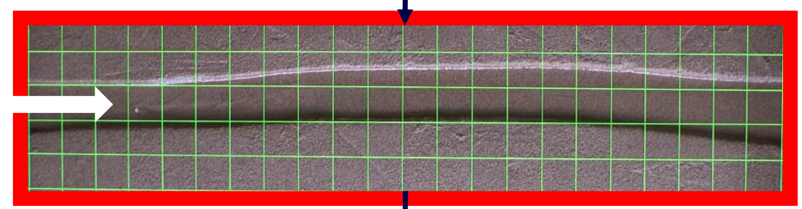
The geometric bankfull discharge is not the formative discharge

start

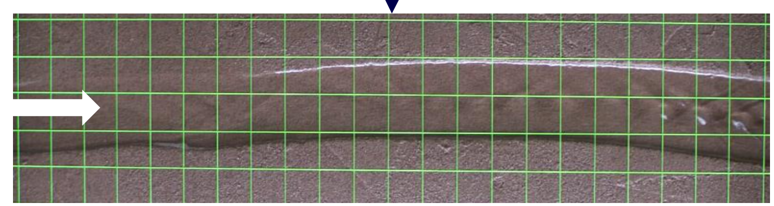


channel evolution with constant (formative) discharge

geometric bankfull discharge assessment



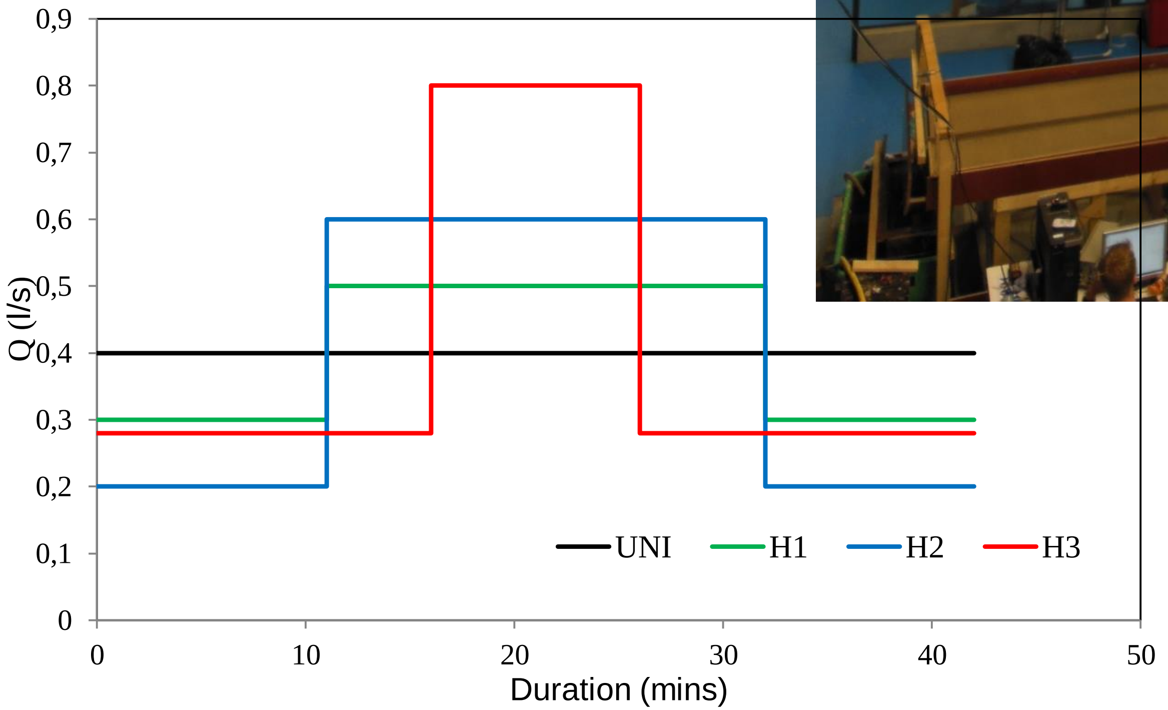
further channel evolution with assessed geometric bankfull discharge

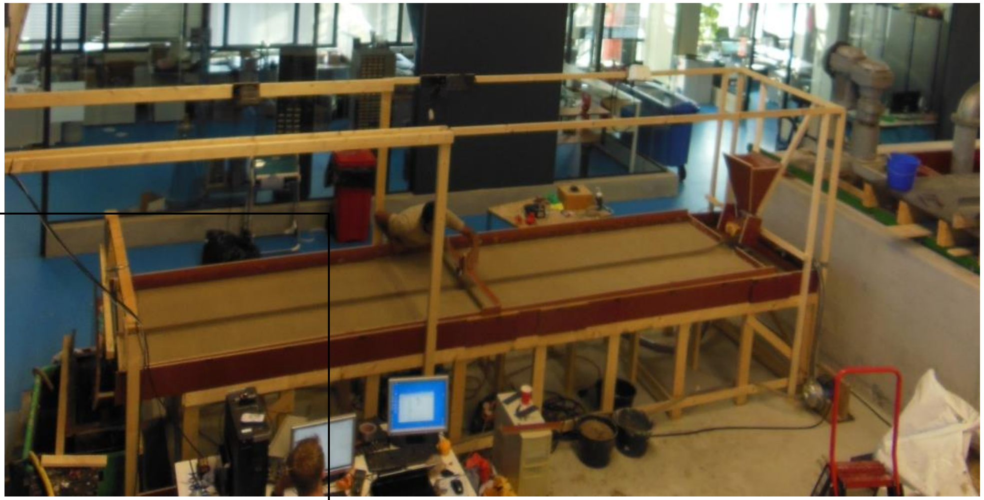


With variable flow the formative discharge corresponds to the frequent peak flow
From literature: in real rivers, the flow with return period of 1 to 2 years

Effects of starting condition and sediment load on channel width – Experimental study

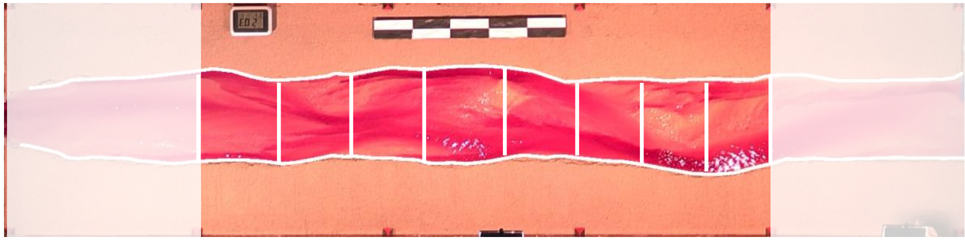
(Singh, 2015)



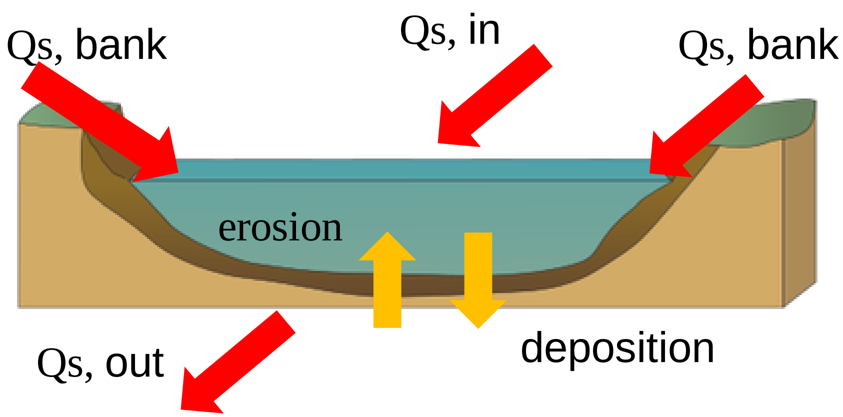


Variable discharge
4 different starting widths
Sediment: D_{50} = 1 mm
(poorly sorted)

Channel width measurement



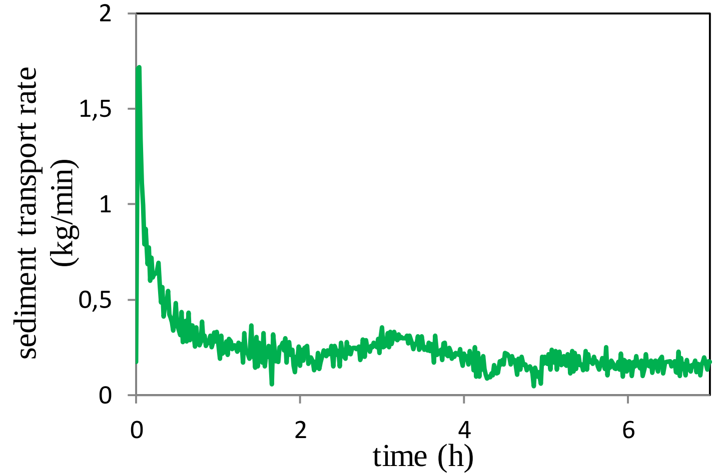
Sediment budget calculations



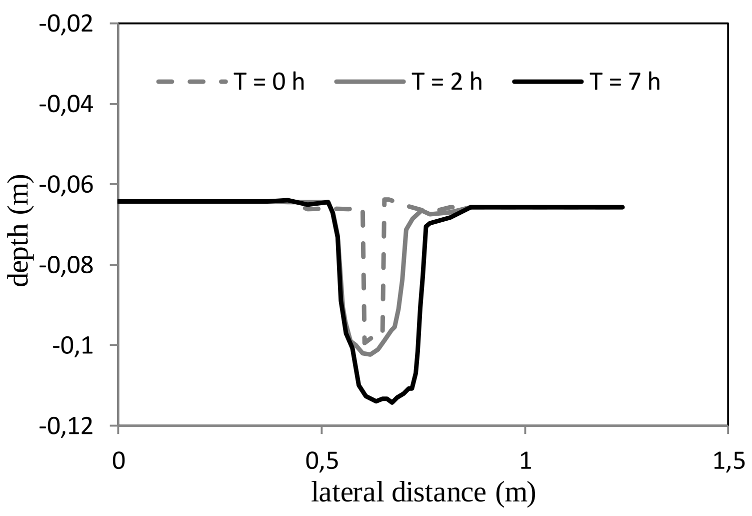
Four different initial widths, 0.04 m, 0.1 m, 0.25 m and 0.4 m

- Without sediment supply
- With sediment supply: Q_s = 90 (g/min)

Sediment transport rate measurement



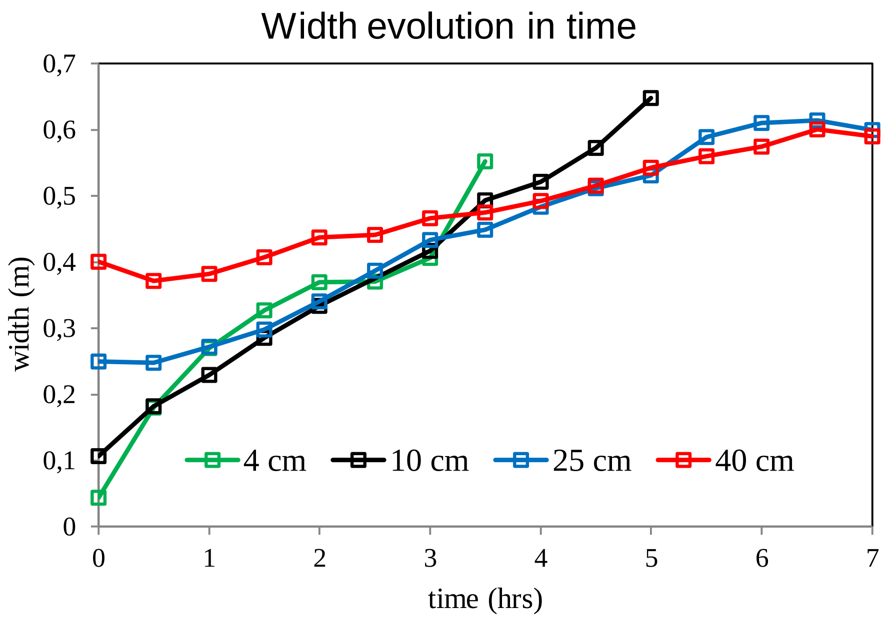
Cross-section measurement



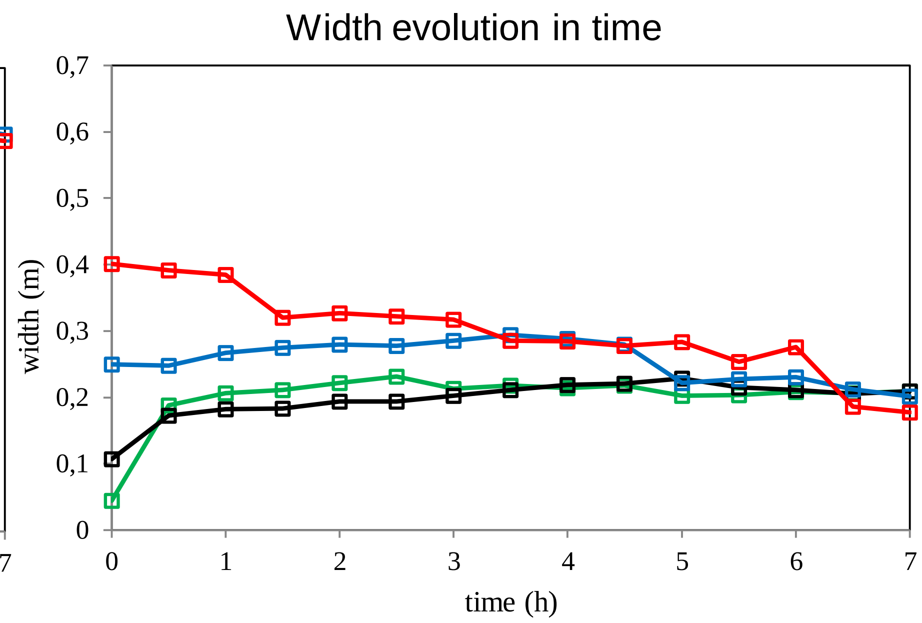
Results: effects of starting *B* and sediment load

Constant discharge

with upstream sediment supply



no upstream sediment supply



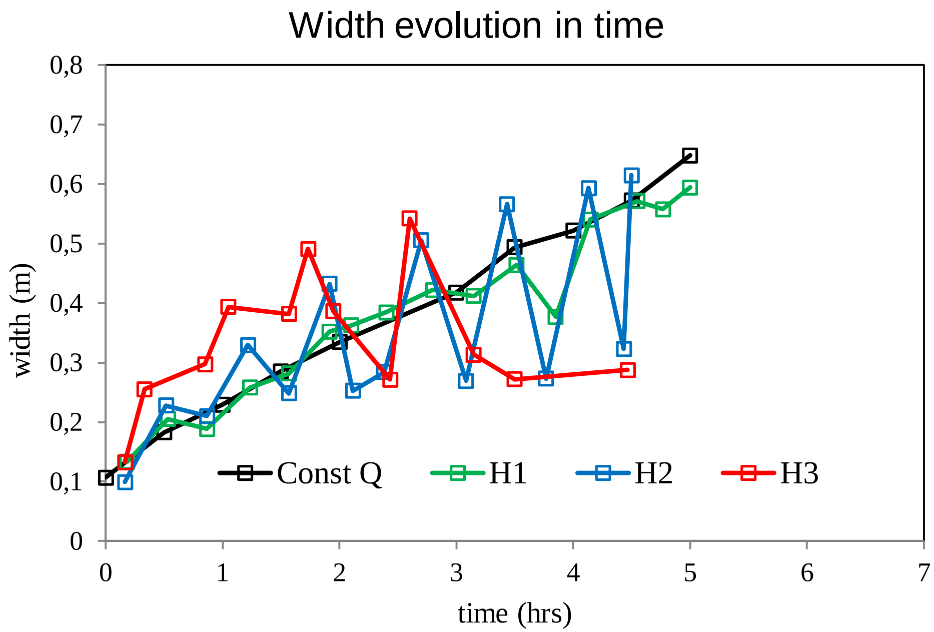
Narrower initial channels => wider channels

Same final river width

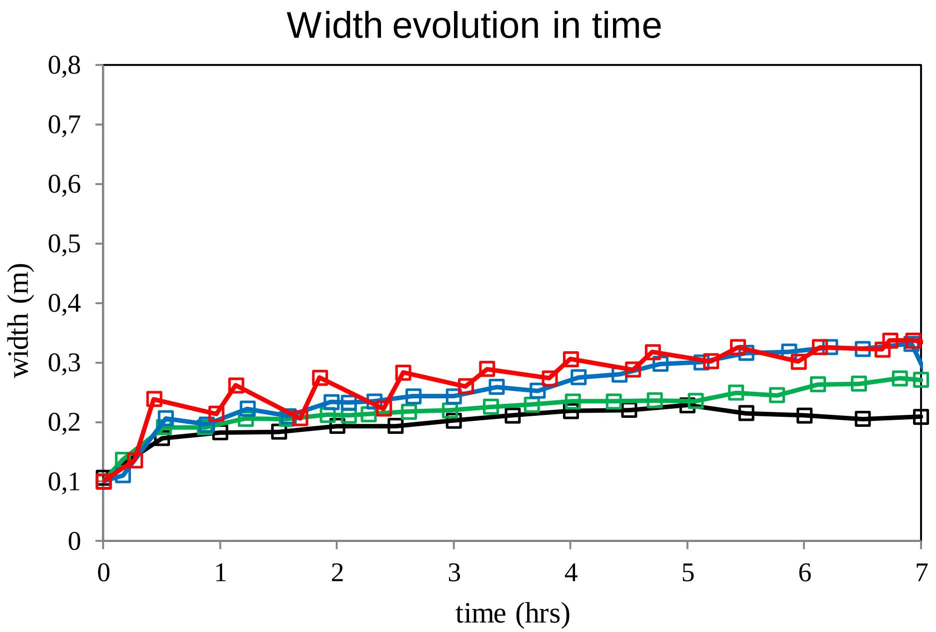
Results: effects of discharge and sediment load

Different discharge regimes

with upstream sediment supply



no upstream sediment supply



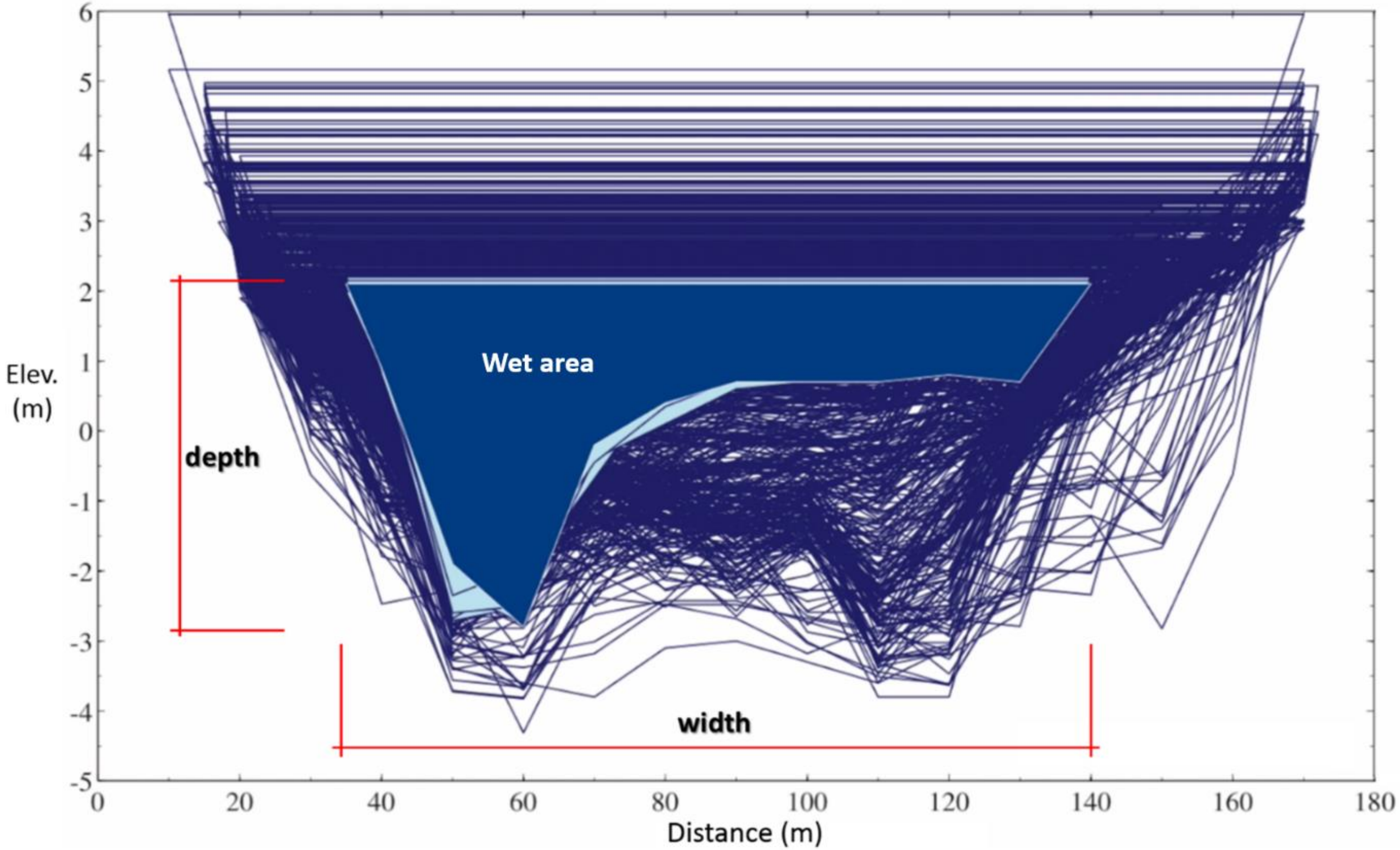
Note: same sediment supply rate of 90 g/min

Effects of discharge and vegetation on channel cross-section - Numerical study Pilcomayo River

(Grissetti, Crosato, Bregoli, 2019)

Strong and quick morphological variations, high sediment transport rates
Sand-bed, floodplain vegetation, semi-arid climate
Daily data series on: discharge (up to 4,600 m^3/s), water levels and cross-sections. Sediment sampling data

Strong daily evolution Pilcomayo River:
quick adaptation of cross-section to discharge

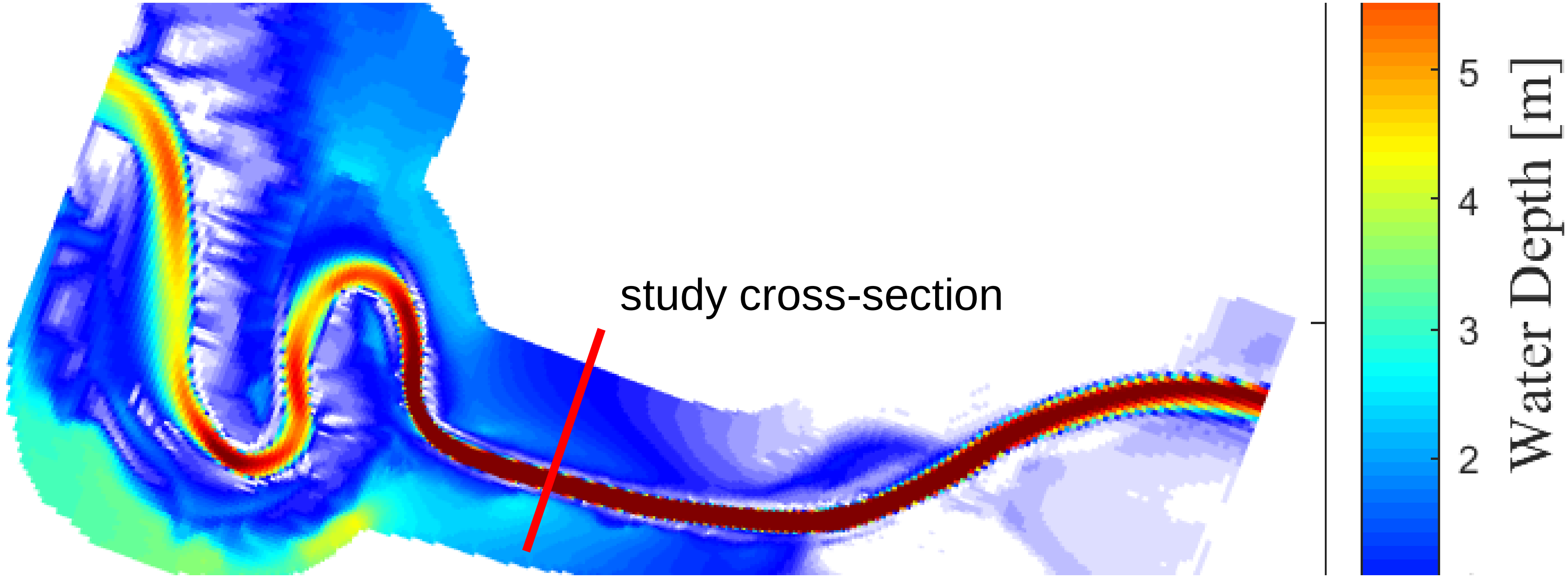


(Capapé and Martín-Vide, 2015)

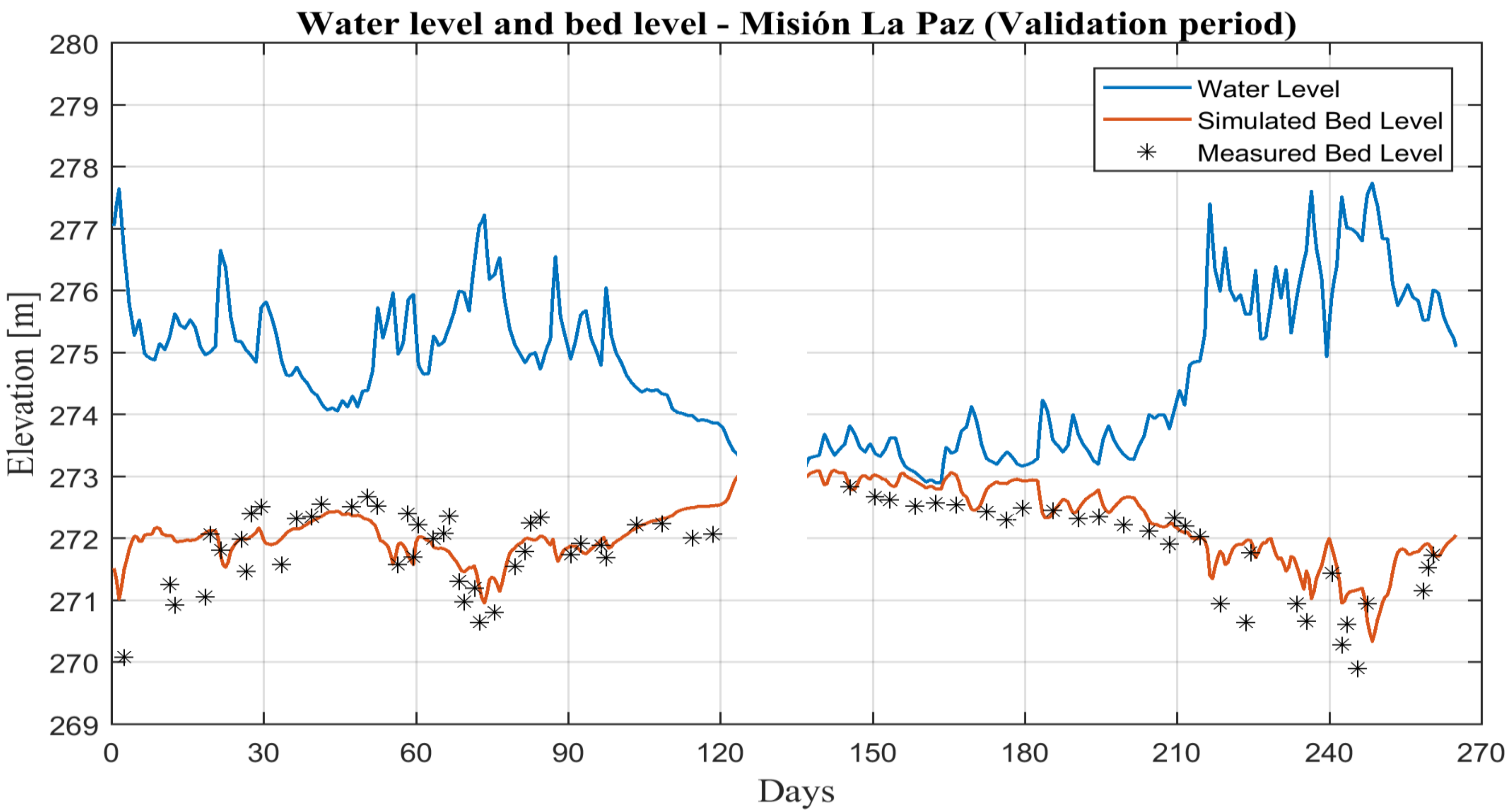
2D Model construction with Delft3D

- Model calibration 1972-1973 (Chézy coeff., transverse slope effects)
- Model validation 1980-1981
- Model runs:
  - Present situation (B.C.)
  - Present situation without floodplain vegetation
  - Combinations:

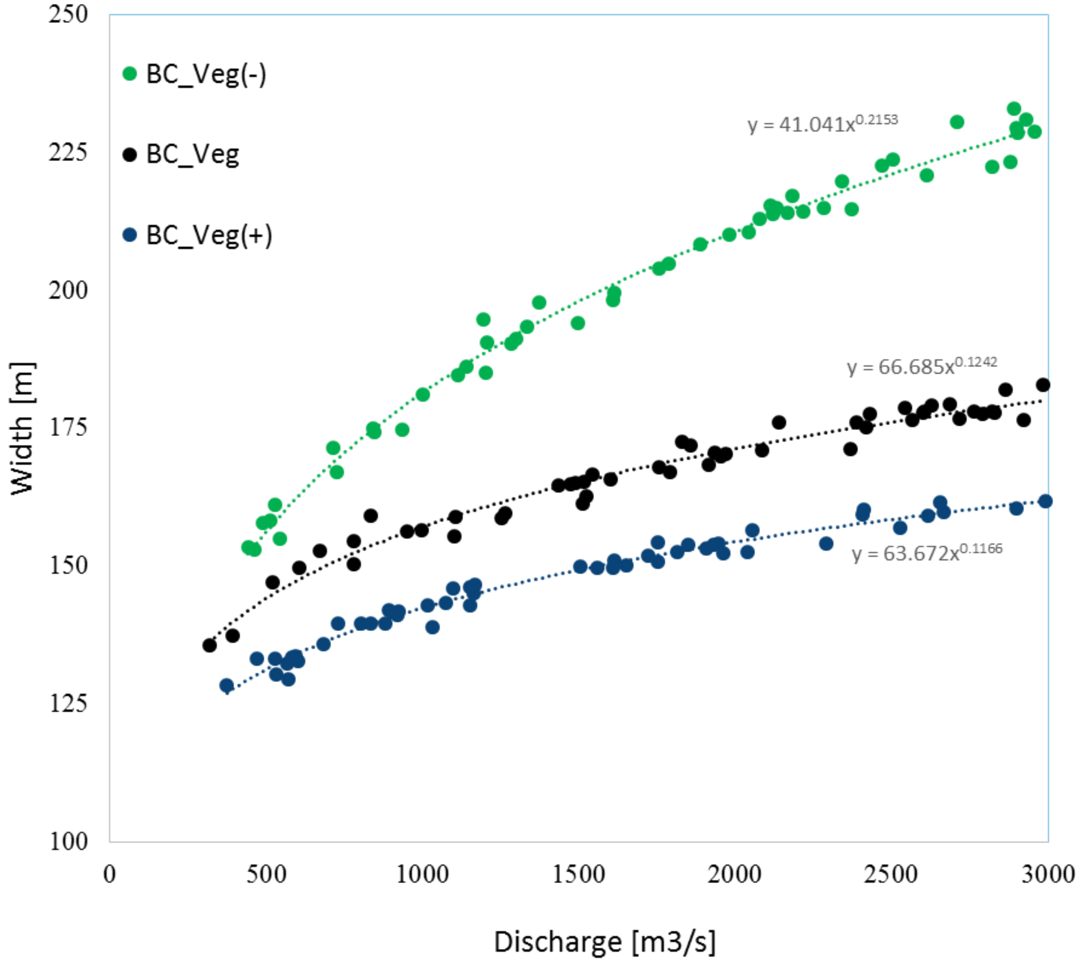
    More/less floodplain vegetation - Higher/lower discharges



Results of model validation

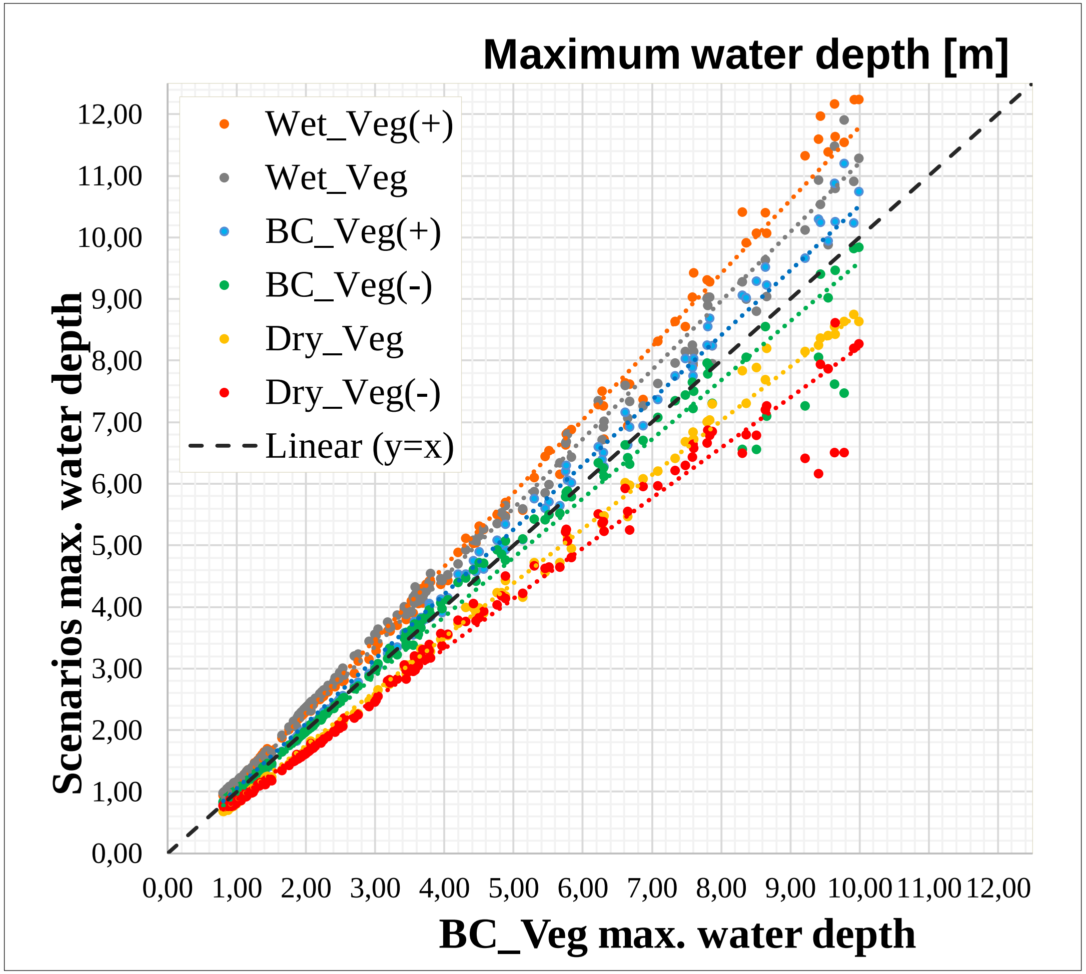


Results: channel width compared to Base Case



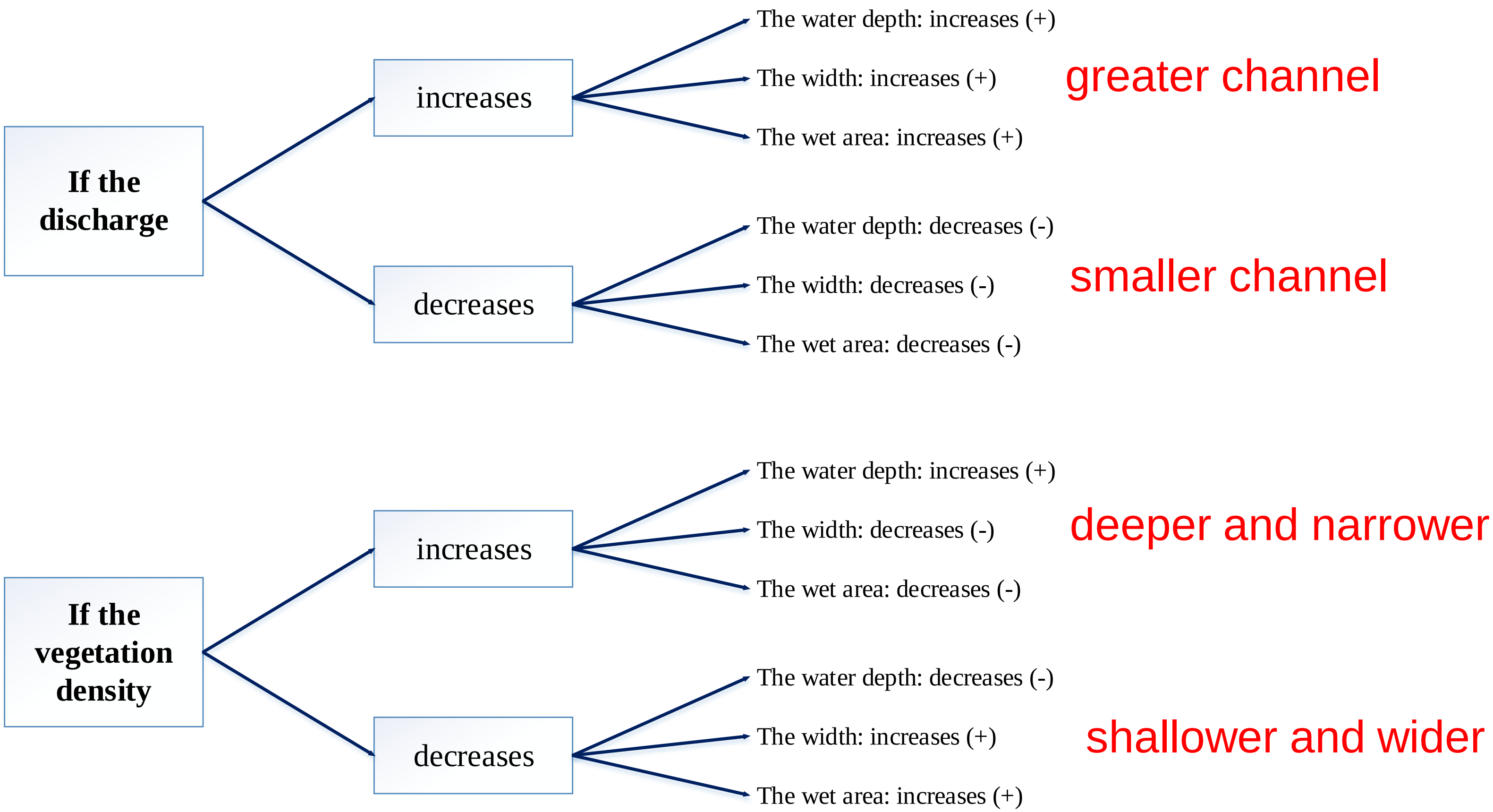
vegetation has a strong impact on width

Results: Thalweg depth compared to Base Case



discharge
has more impact
on depth
than vegetation

River channel response to variations of floodplain vegetation and discharge



THANK YOU

Questions?