# River ecosystems

nature sustainability
ARTICLES
https://doi.org/10.1038/s41893-020-0559-9

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# Increasing dependence of lowland populations on mountain water resources

Daniel Viviroli[1], Matti Kummu[2], Michel Meybeck[3], Marko Kallio[2,4] and Yoshihide Wada[5,6]

'…~1.5 billion people (24% of the world's lowland population) are projected to depend critically on runoff contributions from mountains by 2025 under a 'middle of the road' scenario, compared with ~0.2 billion (7%) in the 1960s. This striking rise is mainly due to increased local water consumption in the lowlands, whereas changes in mountain and lowland runoff play only a minor role.…'

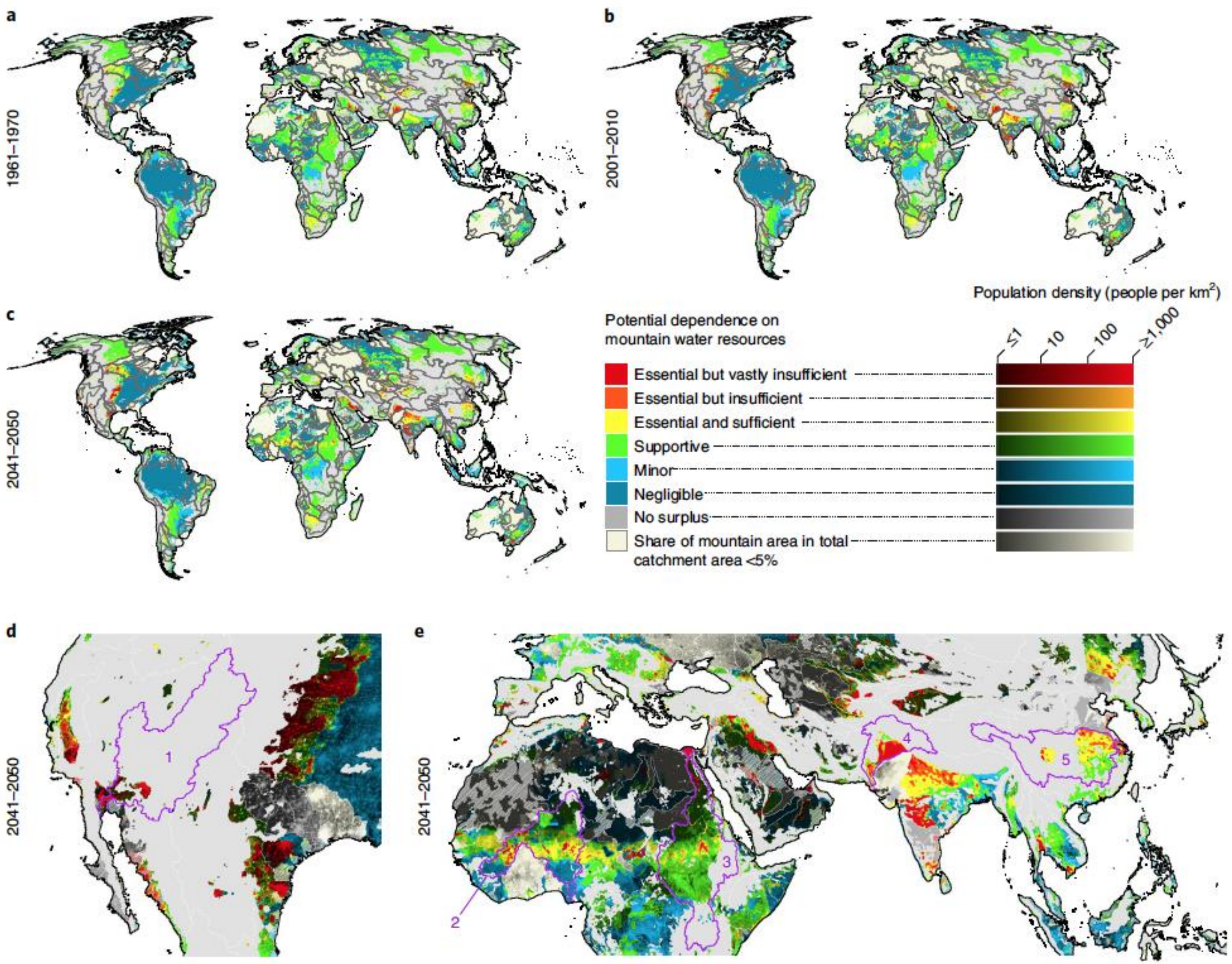


**Fig. 3 | Spatial patterns in dependence on mountain water resources from 1961 to 2050. a–c**, The maps show the water resources index (*W*) (Methods) for 1961–1970 (**a**), 2001–2010 (**b**) and 2041–2050 (SSP2-RCP6.0) (**c**). Beige denotes areas where mountains occupy less than 5% of the total catchment area, and an assessment of their contributing potential to lowland water resources should only be done carefully (shown in Supplementary Fig. 2). **d,e**, Magnifications are shown for selected hot-spot regions in 2041–2050. These panels show population densities as well. The areas equipped for irrigation and food production are shown in Extended Data Fig. 4. The boundaries of catchments with areas of 100,000 km² and more are outlined in grey (**a–c**) and white (**d,e**) for orientation, and small catchments with areas of less than 10,000 km² are hatched in white. The locations of the example river basins presented in Box 1 are outlined in purple: (1) Colorado (United States and Mexico), (2) Niger without Benue, (3) Nile, (4) Indus and (5) Yangtze.

EPFL

ARTICLE

doi:10.1038/nature09440

# Global threats to human water security and river biodiversity

C. J. Vörösmarty[1]*, P. B. McIntyre[2]*†, M. O. Gessner[3], D. Dudgeon[4], A. Prusevich[5], P. Green[1], S. Glidden[5], S. E. Bunn[6], C. A. Sullivan[7], C. Reidy Liermann[8] & P. M. Davies[9]

'…nearly 80% of the world's population is exposed to high levels of threat to water security.
Massive investment in water technology enables rich nations to offset high stressor levels without remedying their underlying causes, whereas less wealthy nations remain vulnerable.
A similar lack of precautionary investment jeopardizes biodiversity, with habitats associated with 65% of continental discharge classified as moderately to highly threatened…'

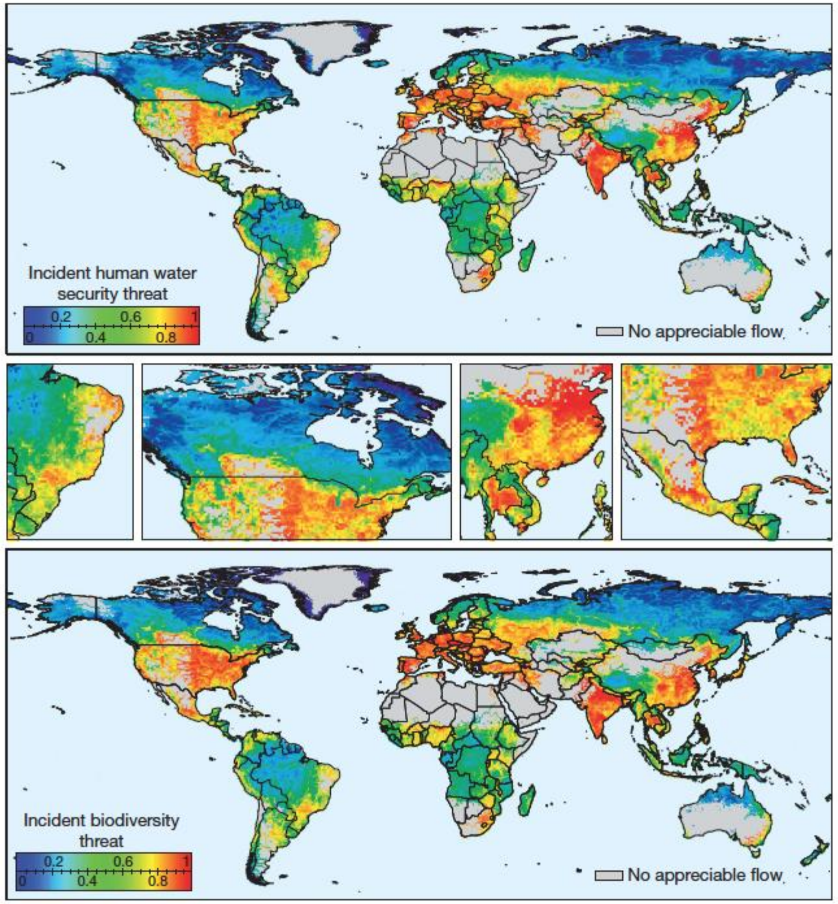


**Figure 1 | Global geography of incident threat to human water security and biodiversity.** The maps demonstrate pandemic impacts on both human water security and biodiversity and are highly coherent, although not identical (biodiversity threat = 0.964 × human water security threat + 0.018; $r = 0.97$, $P < 0.001$). Spatial correlations among input drivers (stressors) varied, but were generally moderate (mean $|r| = 0.34$; $n = 253$ comparisons). Regional maps exemplify main classes of human water security threat (see main text and Supplementary Fig. 4). Spatial patterns proved robust in a variety of sensitivity tests (Supplementary Methods and Supplementary Discussion). Threat indices are relative and normalized over discharging landmass.

ARTICLE
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## Drivers of water security and river biodiversity imperilment

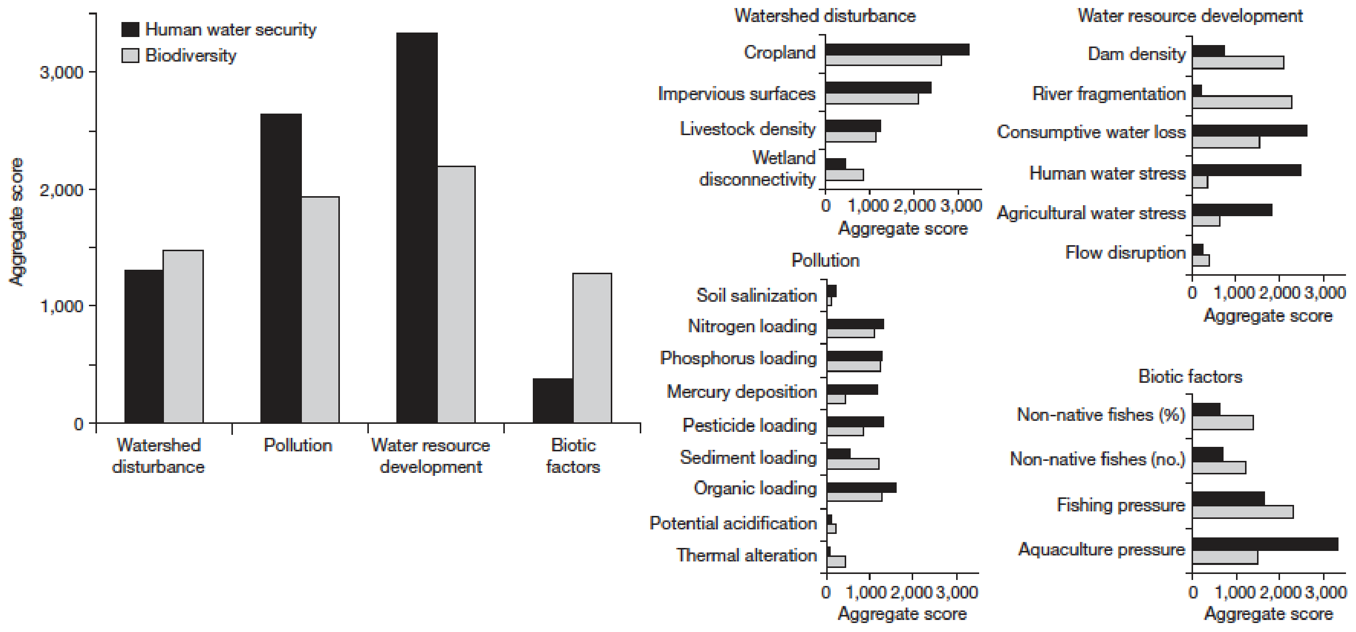


**Figure 3 | Theme and driver contributions in areas where incident threat exceeds the 75th percentile.** High incident threat typically arises from the spatial coincidence of multiple themes and/or drivers of stress acting in concert. Each aggregate score represents the number of grid cells exceeding the 75th percentile for each individual theme or driver over the high incident threat areas. Influence of each of the four themes (left) is relative to its contribution to overall incident threat. For the individual drivers (right), scores are relative to other drivers in the same theme. Bars summarize results over the entire discharging landmass.

ARTICLE

Corrected: Author Correction

https://doi.org/10.1038/s41586-019-1111-9

# Mapping the world's free-flowing rivers

G. Grill[1]*, B. Lehner[1]*, M. Thieme[2], B. Geenen[3], D. Tickner[4], F. Antonelli[5], S. Babu[6], P. Borrelli[7,8], L. Cheng[9], H. Crochetiere[10], H. Ehalt Macedo[1], R. Filgueiras[11,36], M. Goichot[12], J. Higgins[13], Z. Hogan[14], B. Lip[15], M. E. McClain[16,17], J. Meng[18,19], M. Mulligan[20], C. Nilsson[21,22], J. D. Olden[23], J. J. Opperman[2], P. Petry[24,25], C. Reidy Liermann[26], L. Sáenz[27,28], S. Salinas-Rodríguez[29], P. Schelle[30], R. J. P. Schmitt[31], J. Snider[10], F. Tan[1], K. Tockner[32,33,37], P. H. Valdujo[34], A. van Soesbergen[20] & C. Zarfl[35]

'…Free-flowing rivers (FFRs) support diverse, complex and dynamic ecosystems globally, providing important societal and economic services.
Infrastructure development threatens the ecosystem processes, biodiversity and services that these rivers support…'

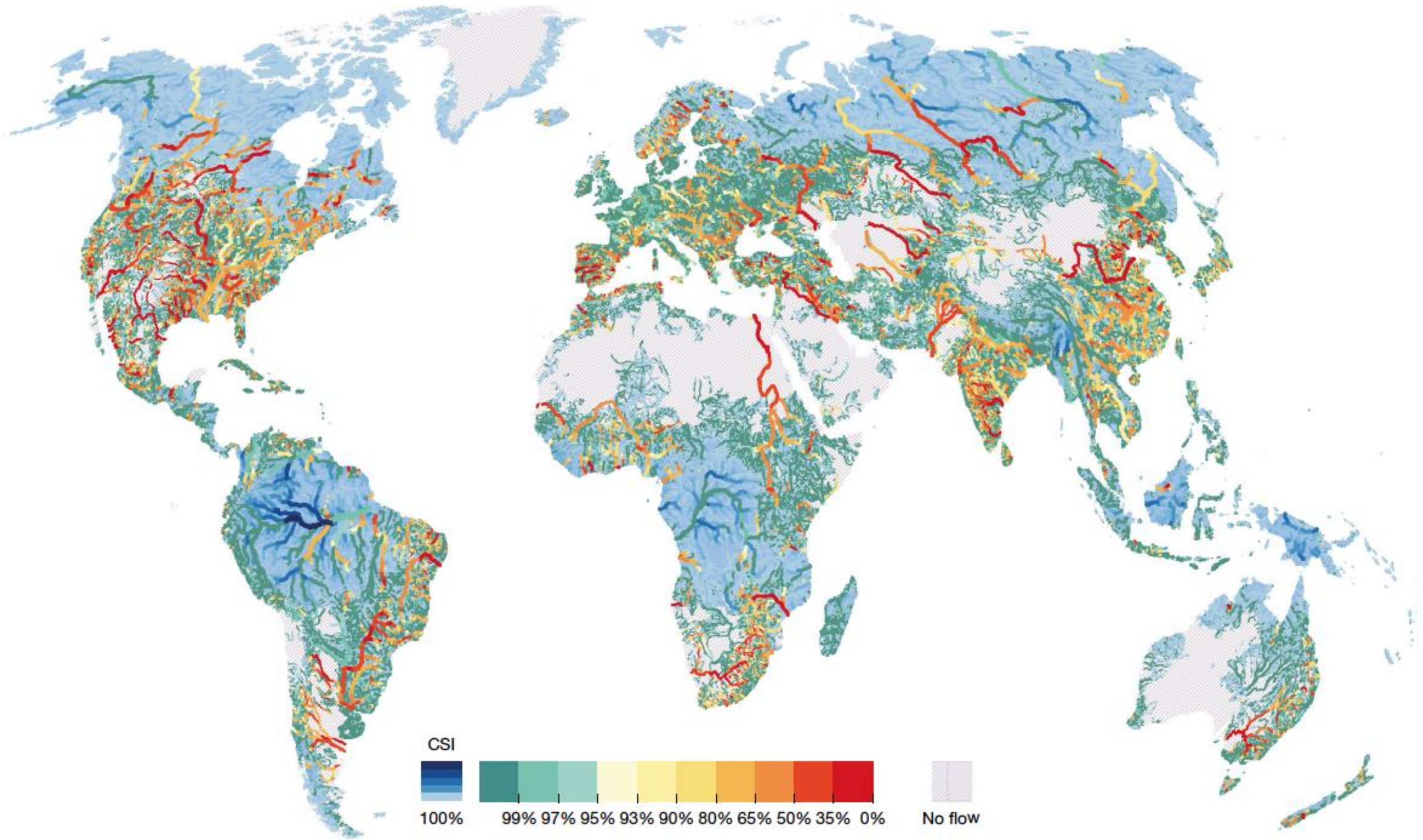


**Fig. 1 | Connectivity status index of the world's river reaches.** Of all river reaches in the database, 48.2% (by number) are impaired by diminished river connectivity to various degrees (CSI < 100%). The blue shades represent the magnitude of river discharge for river reaches with CSI = 100% (that is, darker shades for larger rivers).

# ARTICLE

Corrected: Author Correction
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## Mapping the world's free-flowing rivers

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'…Only 37% of rivers longer than 1,000 kilometres remain free-flowing over their entire length and 23% flow uninterrupted to the ocean.

Very long FFRs are largely restricted to remote regions of the Arctic and of the Amazon and Congo basins.…'

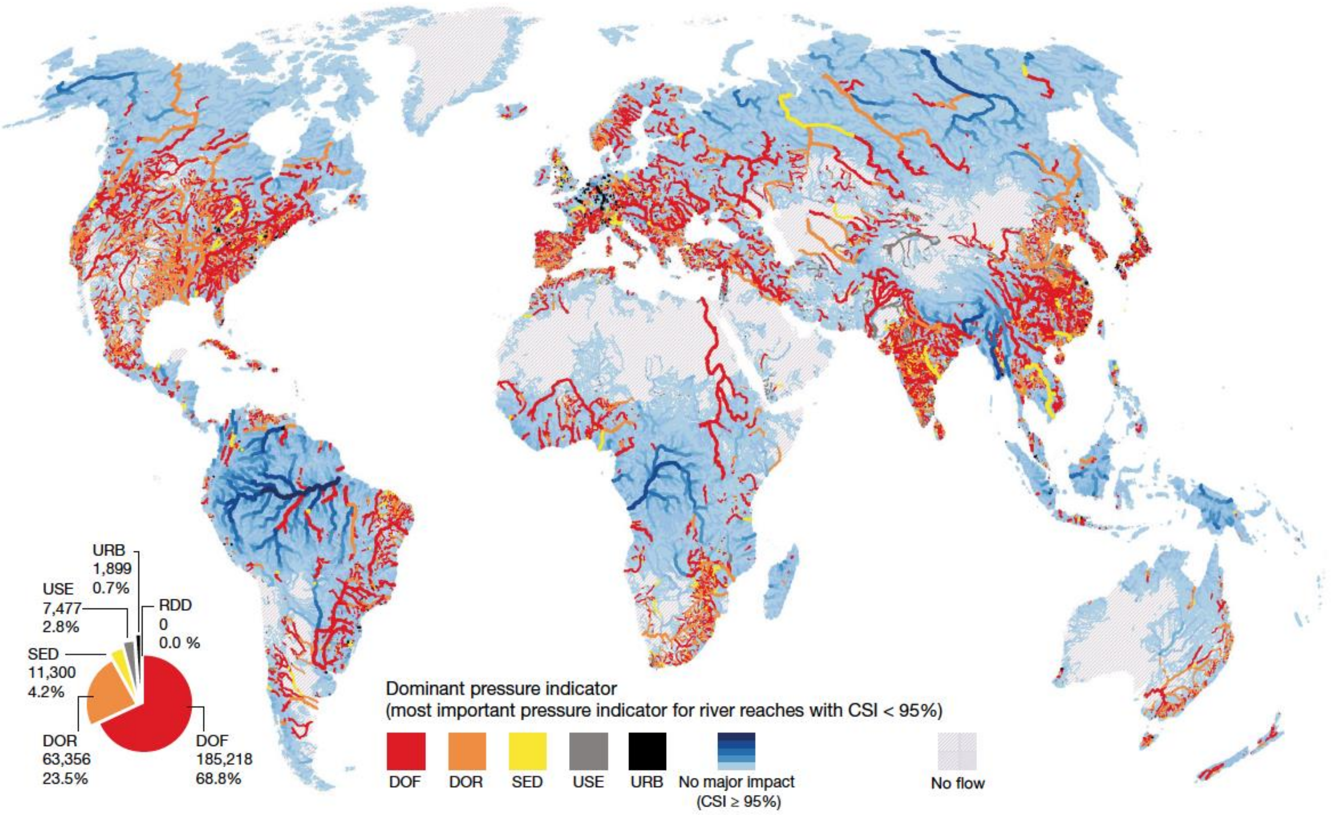



**Fig. 2 | Dominant pressure indicator for global river reaches below the CSI threshold of 95%.** The dominant pressure indicator—the most important pressure indicator for river reaches with CSI < 95%—contributed the most to the final CSI value after applying the weighting scheme. Pressure indicators include the DOF (degree of fragmentation), DOR (degree of regulation), SED (sediment trapping), USE (consumptive water use) and URB (urban areas). The RDD (road density) does not occur as a dominant pressure indicator on the map. The inset shows the number and proportion of river reaches per dominant pressure indicator at the global scale.

CSI: Connectivity Status Index

EPFL

Allen and Pavelsky, *Science* **361**, 585–588 (2018)

# Global extent of rivers and streams

George H. Allen*† and Tamlin M. Pavelsky

Using a global database of planform river hydromorphology and a statistical approach, the authors show that global river and stream surface area at mean annual discharge is 773,000±79,000 km$^2$ (0.58±0.06%) of Earth's non-glaciated land surface, an area 44±15% larger than previous spatial estimates.

By spatial extent, rivers contribute relatively little to the continents — but rivers are hotspots of biodiversity and biogeochemical cycling.

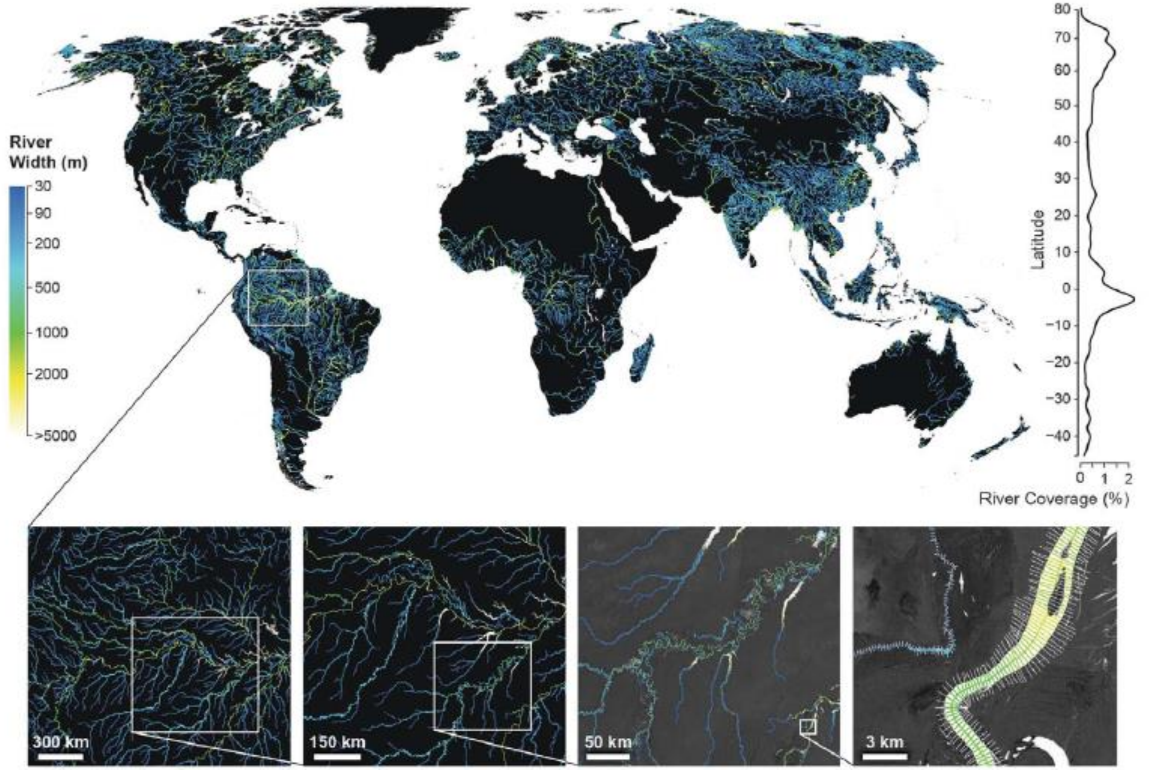
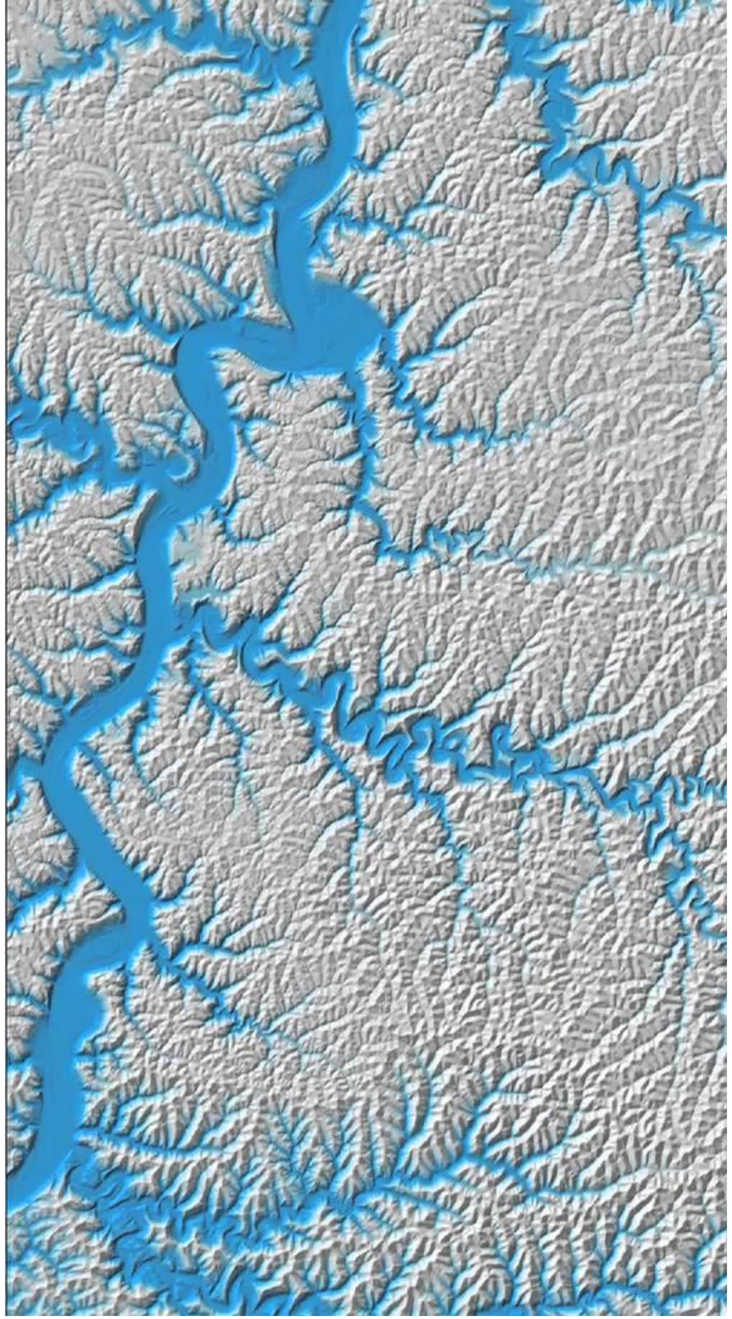


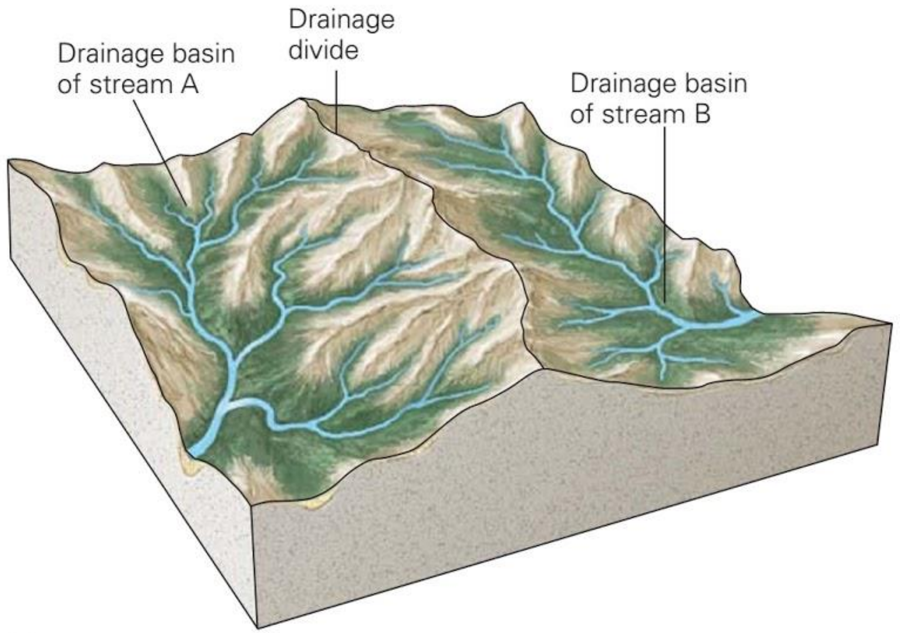

**Fig. 1. The Global River Widths from Landsat (GRWL) Database contains more than 58 million measurements of planform river geometry.** The line plot on the right shows observed river coverage as a percentage of land area by latitude, and the bottom insets show GRWL at increasing zoom. The rightmost inset shows GRWL orthogonals over which river width was calculated, with only every eighth orthogonal shown for clarity.



# Stream and river networks

# Large-scale organisation of streams and rivers

Catchments, watersheds and networks

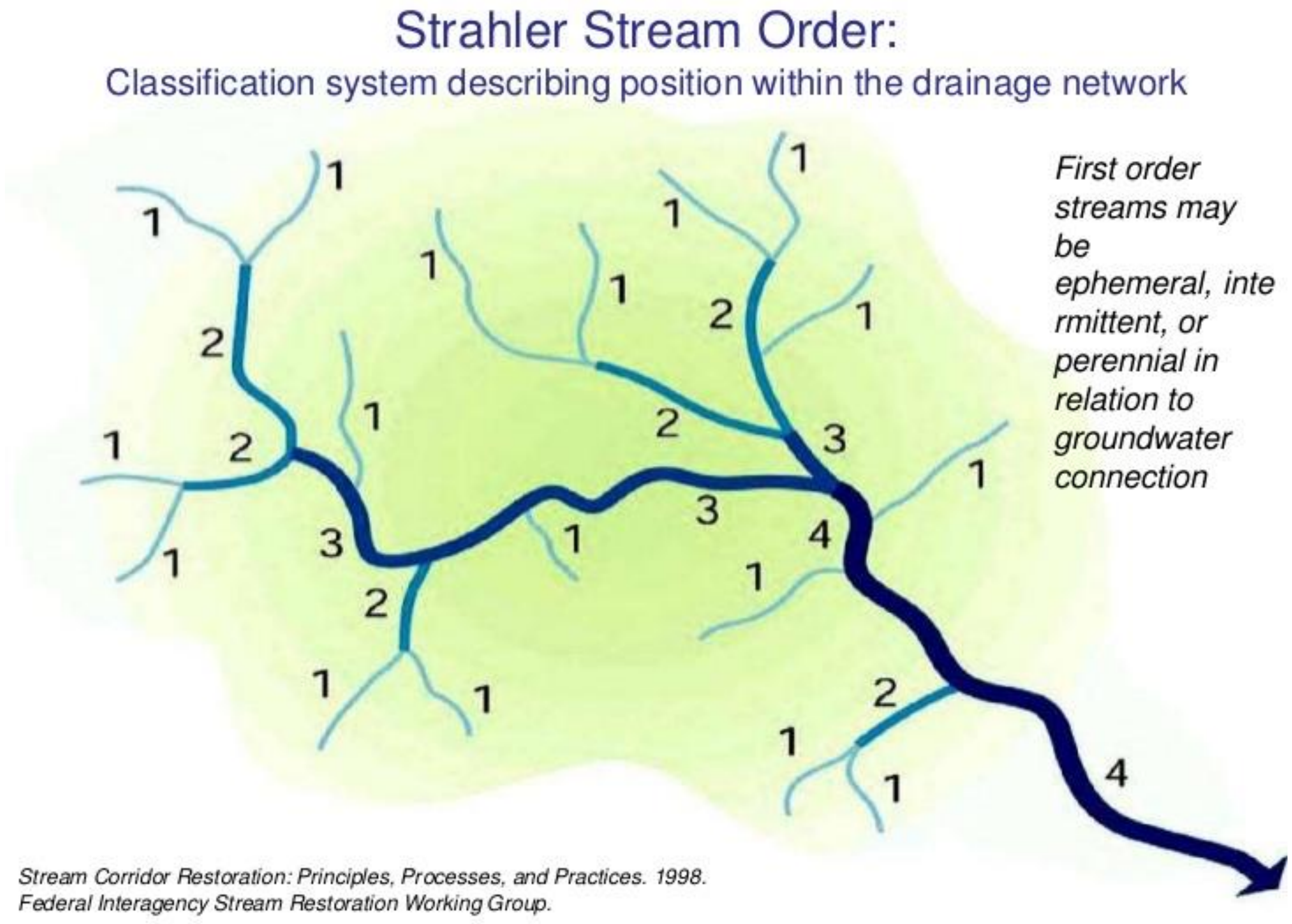



**(a)** A drainage divide is a relatively high ridge that separates two drainage basins.


**(b)** The major drainage basins of North America.

# Large-scale organisation of streams and rivers

## Networks

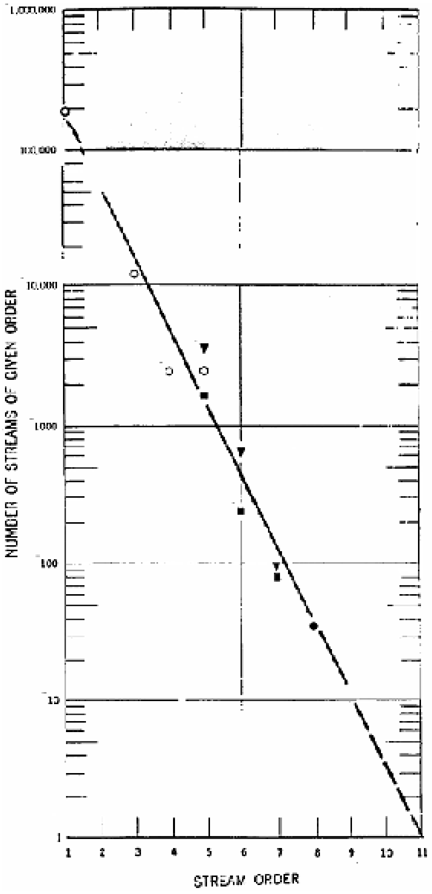


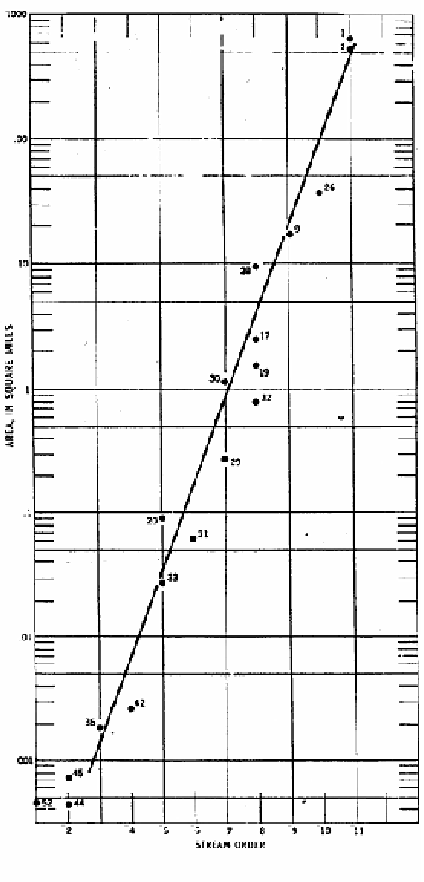
# Large-scale organisation of streams and rivers

## Basic scaling relationships

Number of streams per order

Surface area




Stream order

This has implications for

- Hydrology (e.g., responsiveness to precipitation)
- Biogeochemistry (e.g., terrestrial subsidies)
- Transport and transformation processes

# Large-scale organisation of streams and rivers

## Basic scaling relationships

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Article

### Global abundance and size distribution of streams and rivers

J.A. Downing[1], J.J. Cole[2], C.M. Duarte[3], J.J. Middelburg[4], J.M. Melack[5], Y.T. Prairie[6], P. Kortelainen[7], R.G. Striegl[8], W.H. McDowell[9], and L.J. Tranvik[10]

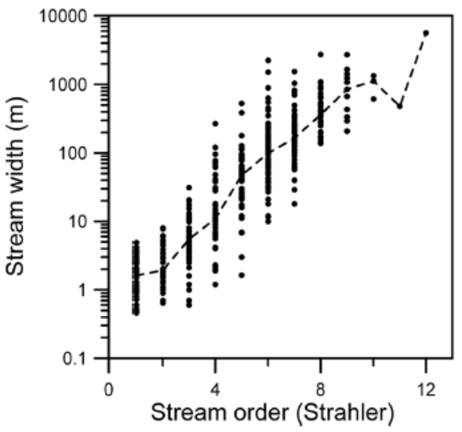



**Fig. 1.** Relationship between Strahler stream order and the mean width of rivers around the world. Data were extracted from the published literature, and some were supplemented with measurements from satellite imagery (see Supplemental Information). The dashed line connects median stream widths for each stream order.

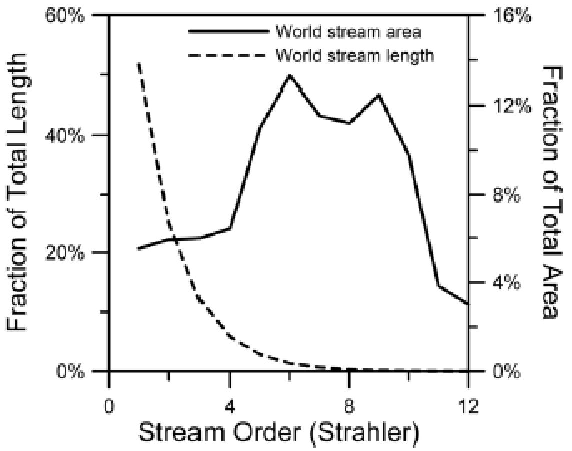



**Fig. 2.** Fraction of world river and stream area and length related to stream order. Calculations are from Table 2 and are based on a total world stream area of 662 041 km² and total world stream length of 88 320 409 km.

Hydrol. Earth Syst. Sci., 15, 2091–2099, 2011
www.hydrol-earth-syst-sci.net/15/2091/2011/
doi:10.5194/hess-15-2091-2011


Hydrology and Earth System Sciences

### Drainage basin morphometry: a global snapshot from the shuttle radar topography mission

P. L. Guth

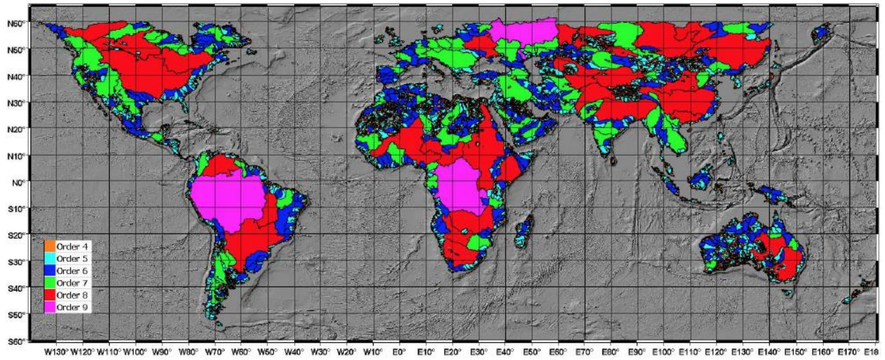
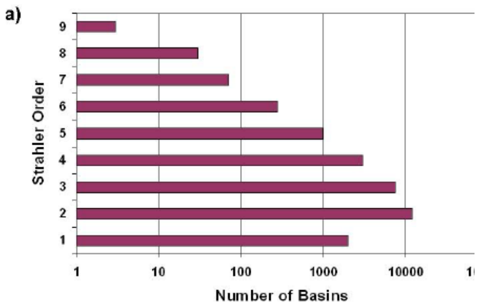
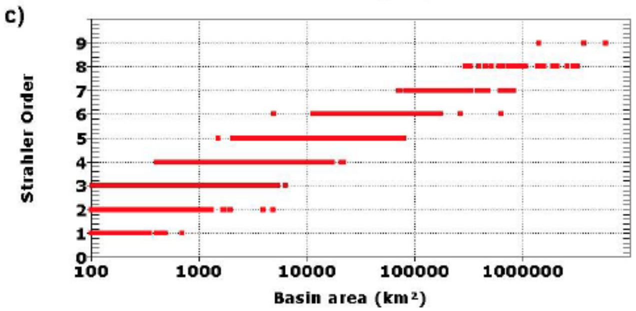
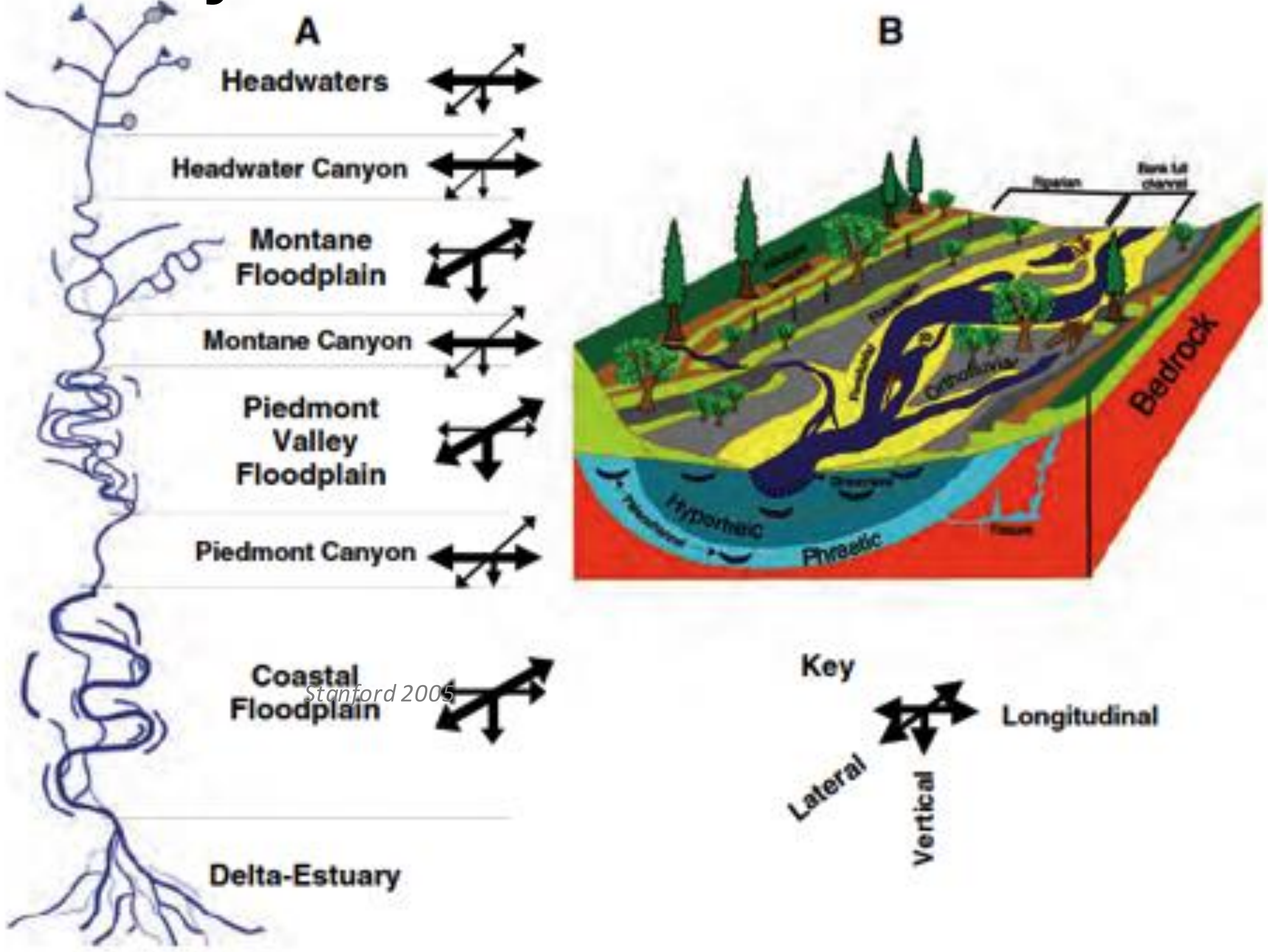



**Fig. 3.** Strahler order for the largest segment in global drainage basins.



# The 3-dimensional nature of stream and river ecosystems




Stanford 2005

## The Riverscape

- River corridor, parafluvial zone
- Longitudinal, lateral, vertical dimensions
- Connectivity of streams and rivers with the catchment

# The 3-dimensional nature of stream and river ecosystems

## The lateral dimension

### The riparian zone

- Vegetation along stream and river channels
- Consolidation of geomorphological features
- Buffering capacity towards terrestrial nutrient inputs
- Shading and thermal regimes
- Allochthonous energy sources

# The 3D nature of stream and river ecosystems

## The lateral dimension

### Floodplains

- Fringing inundation areas
- Regular overtopping of channel banks (e.g., snowmelt, monsoon)
- Hydrological residence time
- Lateral connectivity critical for biodiversity and biogeochemistry (see transition zones/ecotones)

# The 3D nature of stream and river ecosystems

## The vertical dimension

WATER RESOURCES RESEARCH, VOL. 47, W00H03, doi:10.1029/2010WR010066, 2

**Rethinking hyporheic flow and transient storage to advance understanding of stream-catchment connections**

Kenneth E. Bencala,[1] Michael N. Gooseff,[2] and Briant A. Kimball[3]

Until the 1990$^{ties}$:
The stream as a hydrological “pipe”

The stream as an integrative part of the catchment

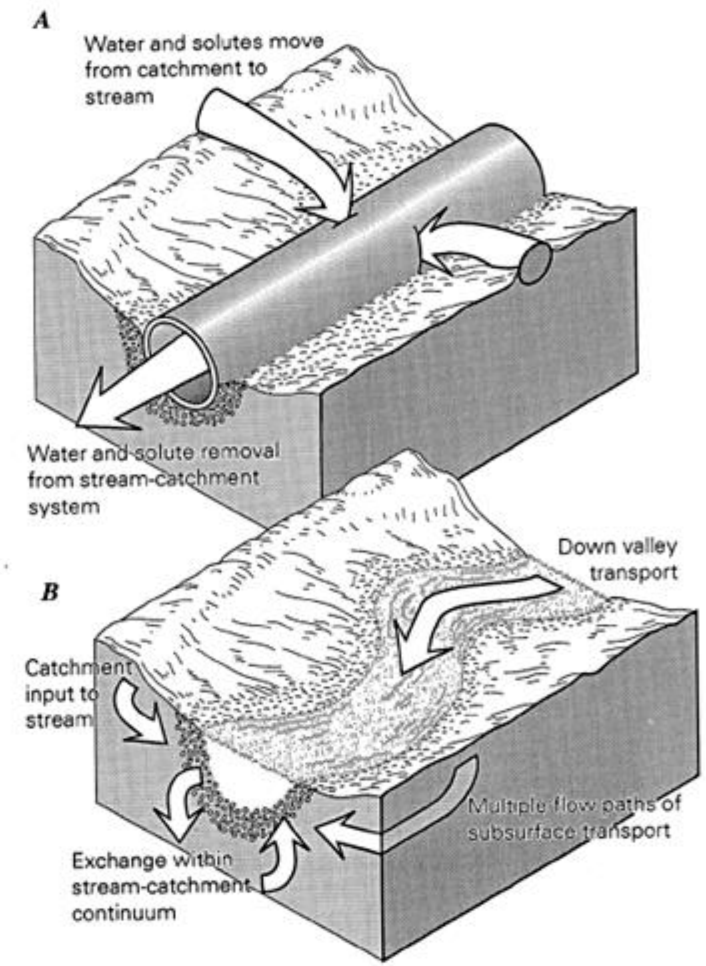



**Figure 1.** (a) The stream's function in its catchment is viewed simply as that of a pipe. (b) A contrasting view of the stream's function places the stream as an integral part of the catchment system [from *Bencala*, 1993].

# The 3-dimensional nature of stream and river ecosystems

## The vertical dimension

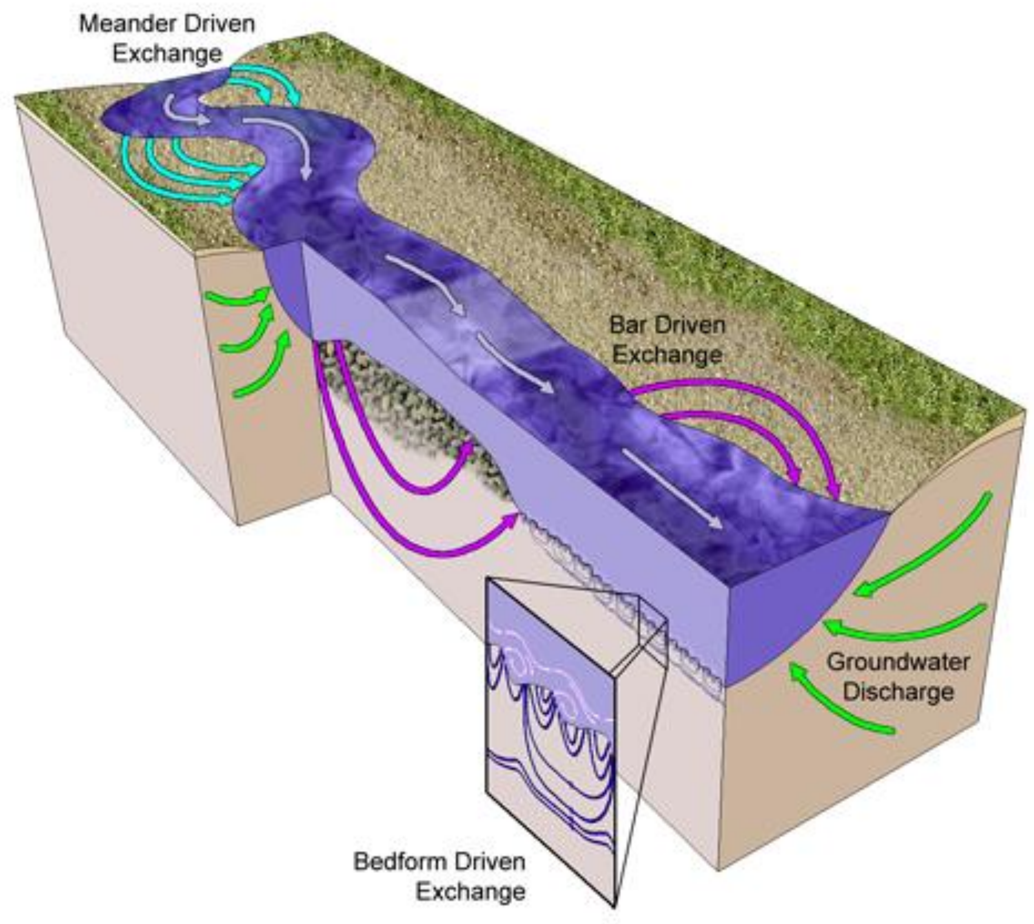
*wikipedia*

Benthic zone (the bottom of the stream/river bed)

- Interface between surface water and streambed/riverbed
- Exposed to light, primary production
- Exposed to open channel hydraulics

# The 3-dimensional nature of stream and river ecosystems

## The vertical dimension

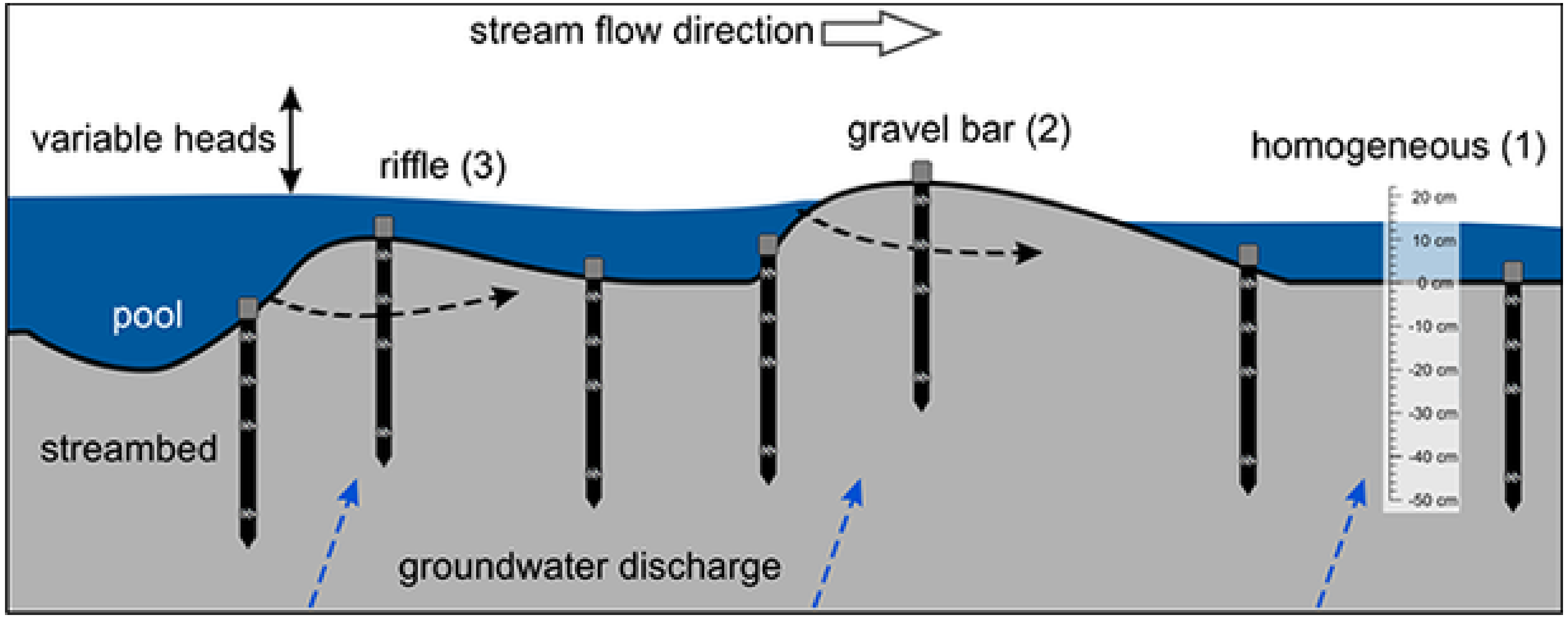



Hyporheic zone

- Interface in the streambed between surface water and groundwater
- No light, hence no primary production
- Porous - Darcy flow

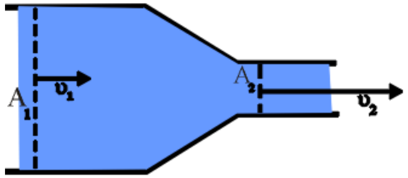
# The 3-dimensional nature of stream and river ecosystems

## The vertical dimension




Pool-riffle sequence: downwelling

Riffle-pool sequence: upwelling



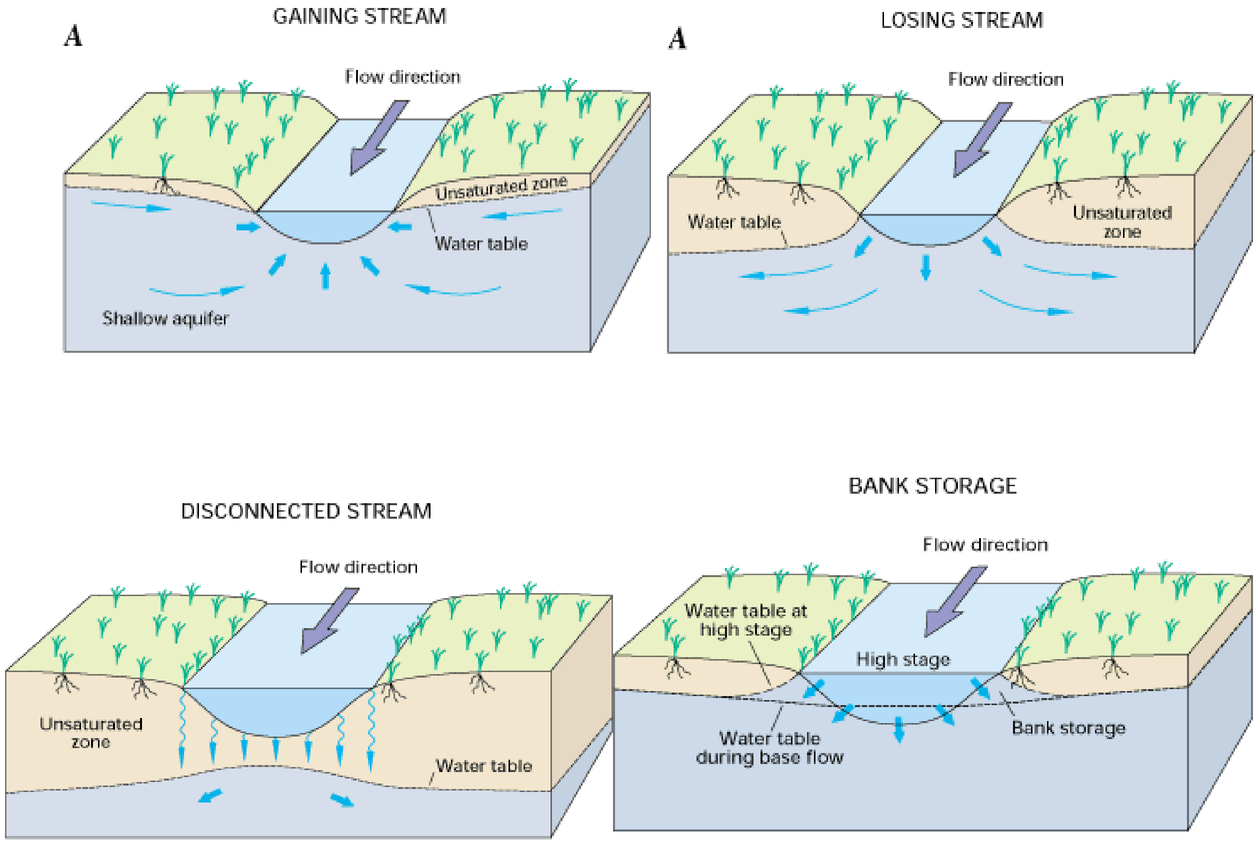
$Q = v_1 A_1 = v_2 A_2$

$Q = v\,A$ ($m/s\ m^2$)

area = width * depth

# The 3-dimensional nature of stream and river ecosystems

## The vertical dimension



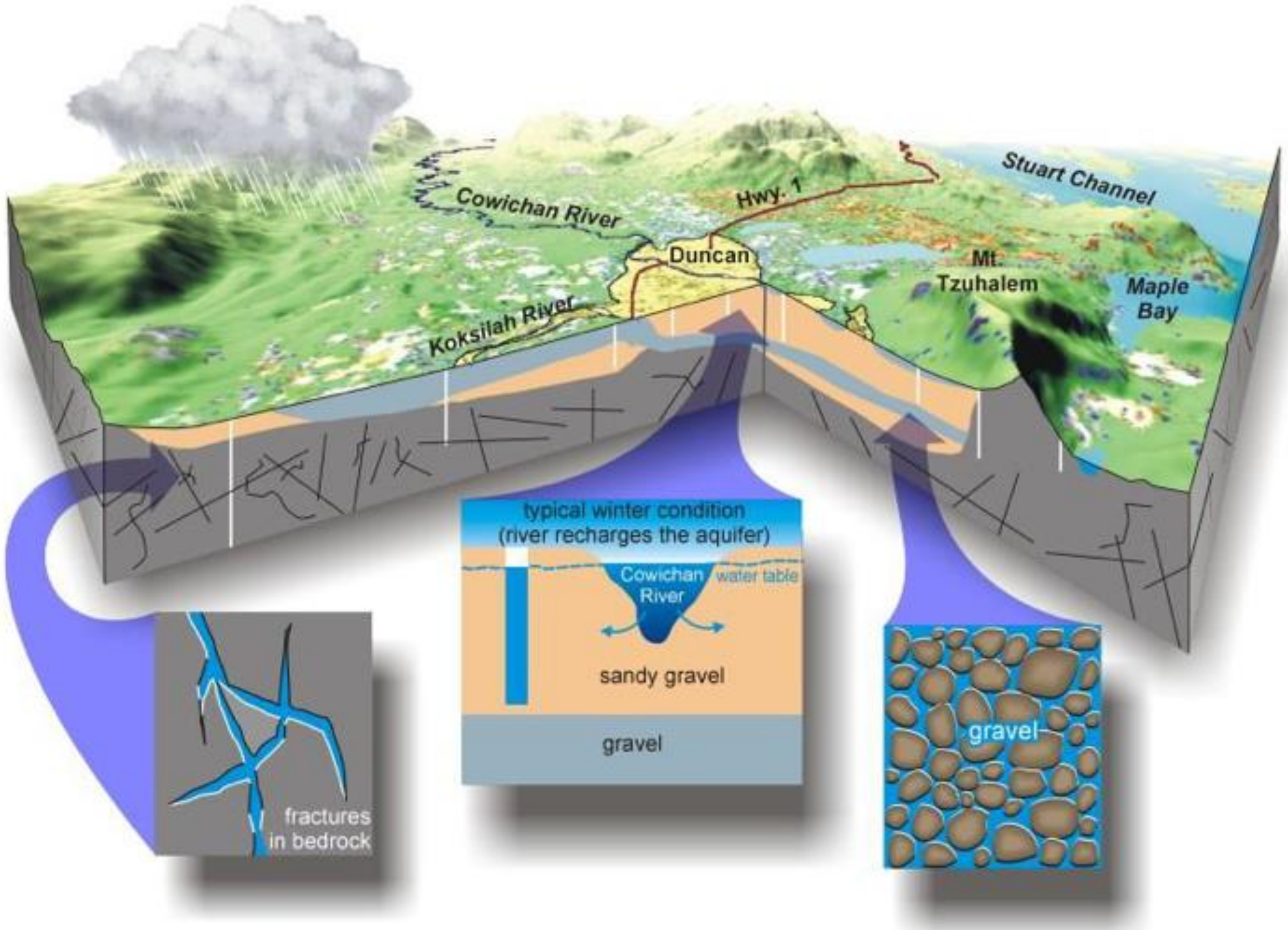

Hydrodynamic connectivity of streams to the adjacent groundwater

Similar as seen for lakes

# The 3-dimensional nature of stream and river ecosystems

## Surface water and groundwater
One single water resource

- Contaminant management
- Bank filtration, wells
- Irrigation, agriculture



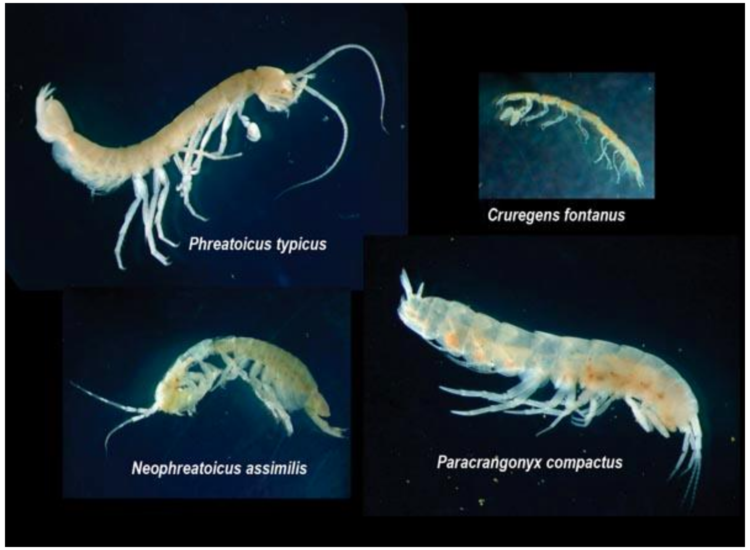
# Reasons why the hyporheic zone matters

(1) “Bioreactor”
- Large surface area (sediments)
- Increased residence time
- Chemical and biological processes (biogeochemistry)
- Filtration (fine particles)
- Contaminant and organics degradation (selfpurification)

(2) Ecology
- Resilience/stability → buffering capacity
- Refugium for animals during storm events, droughts etc
- Biodiversity

# Hyporheos

(the organisms living in the hyporheic zone)




- Several millions of organisms per $m^3$ within the hyporheic zone
- Colorless and elongated body shape

# The 3D nature of stream and river ecosystems

## The vertical dimension

J. N. Am. Benthol. Soc., 2010, 29(1):26–40
© 2010 by The North American Benthological Society
DOI: 10.1899/08-017.1
Published online: 5 February 2010

**Ecology and management of the hyporheic zone: stream–groundwater interactions of running waters and their floodplains**

Andrew J. Boulton[1,6], Thibault Datry[2,7], Tamao Kasahara[3,8], Michael Mutz[4,9], AND Jack A. Stanford[5,10]

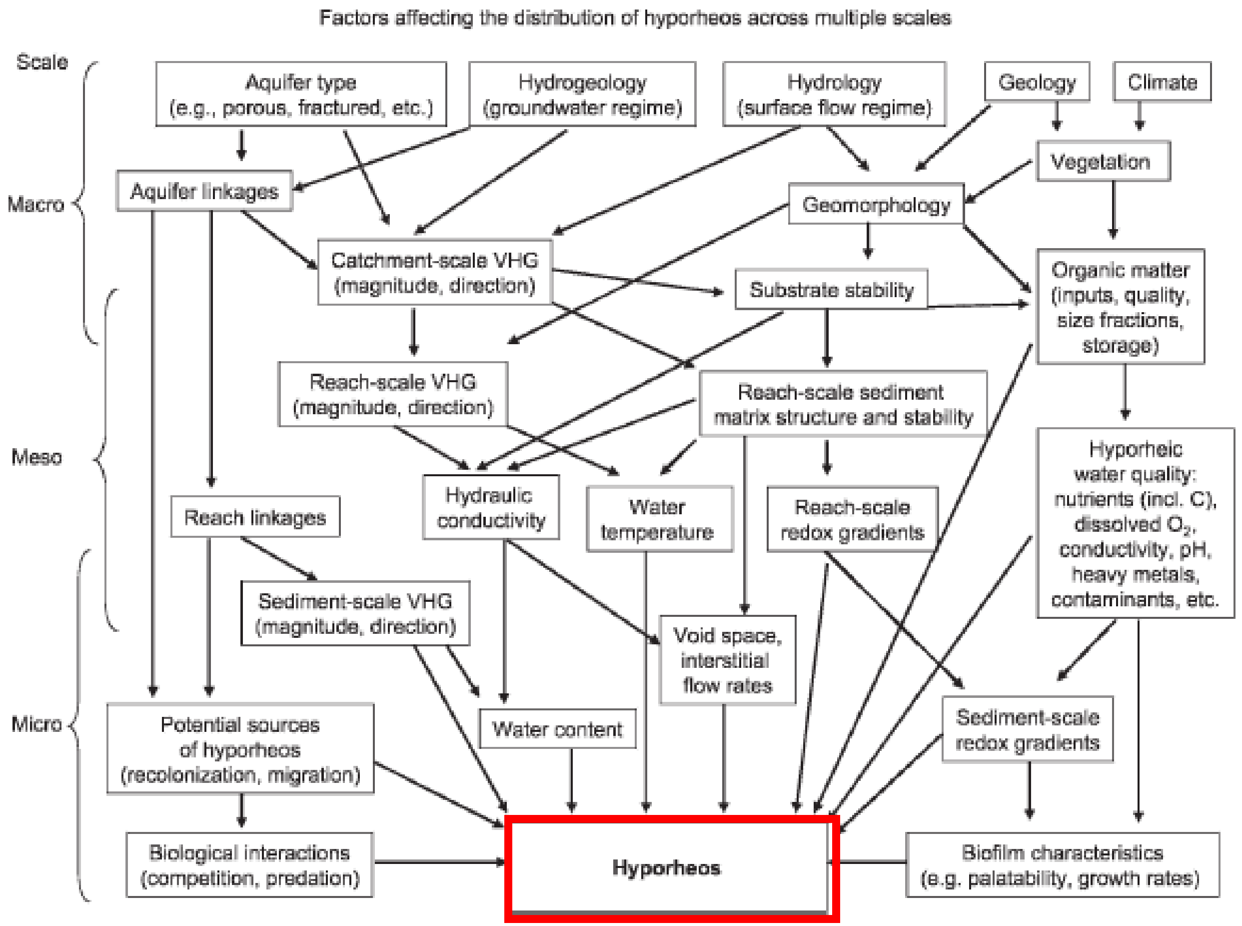



FIG. 2. Simplified diagram of the interactions among variables across 3 overlapping spatial scales (macro = landscape–catchment, meso = catchment–reach, micro = reach–sediment particle) that potentially influence the distribution and composition of the hyporheos.

- Hierarchical organization of drivers that act across spatial scales on the biodiversity within the hyporheic zone
- Physical, chemical and biological in nature

# The 3D nature of stream and river ecosystems

## The longitudinal dimension

PERSPECTIVES

**The River Continuum Concept**[1]

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AND COLBERT E. CUSHING
*Ecosystems Department, Battelle-Pacific Northwest Laboratories, Richland, WA 99352, USA*

VANNOTE, R. L., G. W. MINSHALL, K. W. CUMMINS, J. R. SEDELL, AND C. E. CUSHING. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37: 130–137.

- Hydrology, geomorphology
- Ecosystem metabolism and biogeochemistry
- Ecology and biodiversity

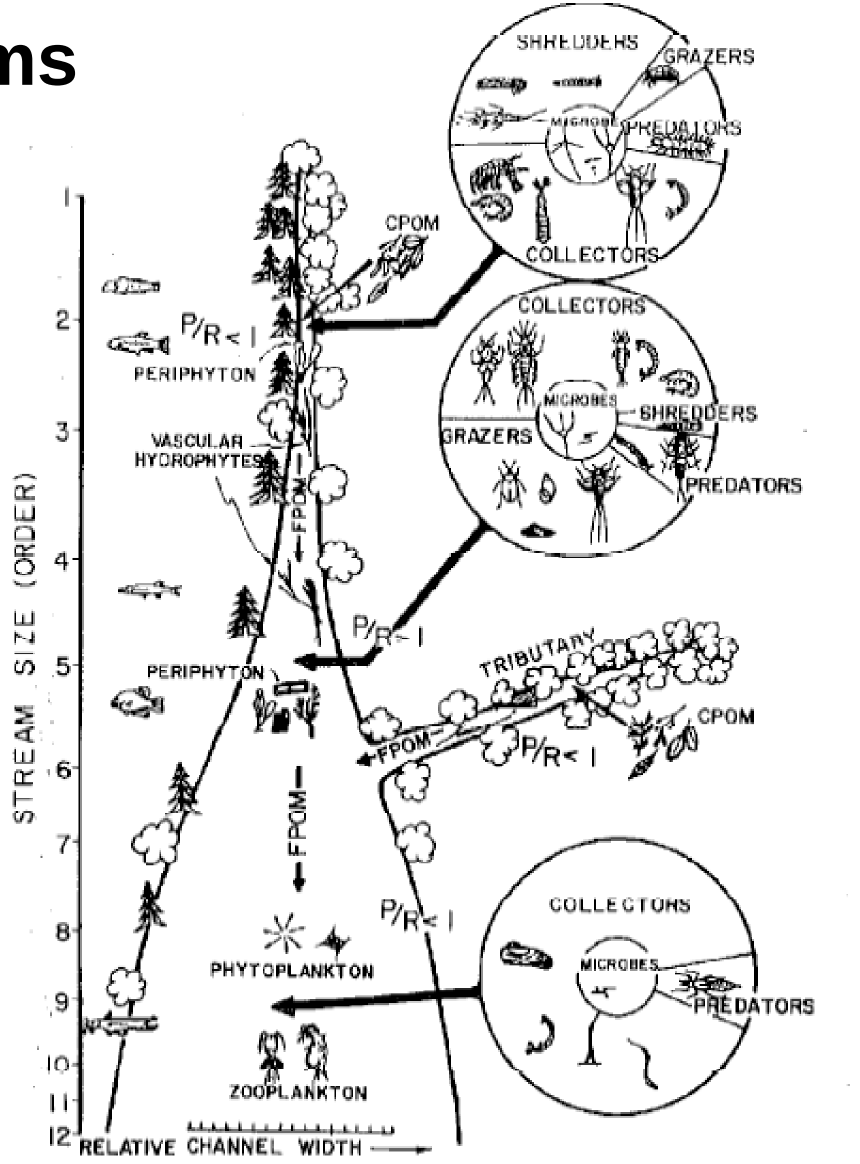



FIG. 1. A proposed relationship between stream size and the progressive shift in structural and functional attributes of lotic communities. See text for fuller explanation.

EPFL

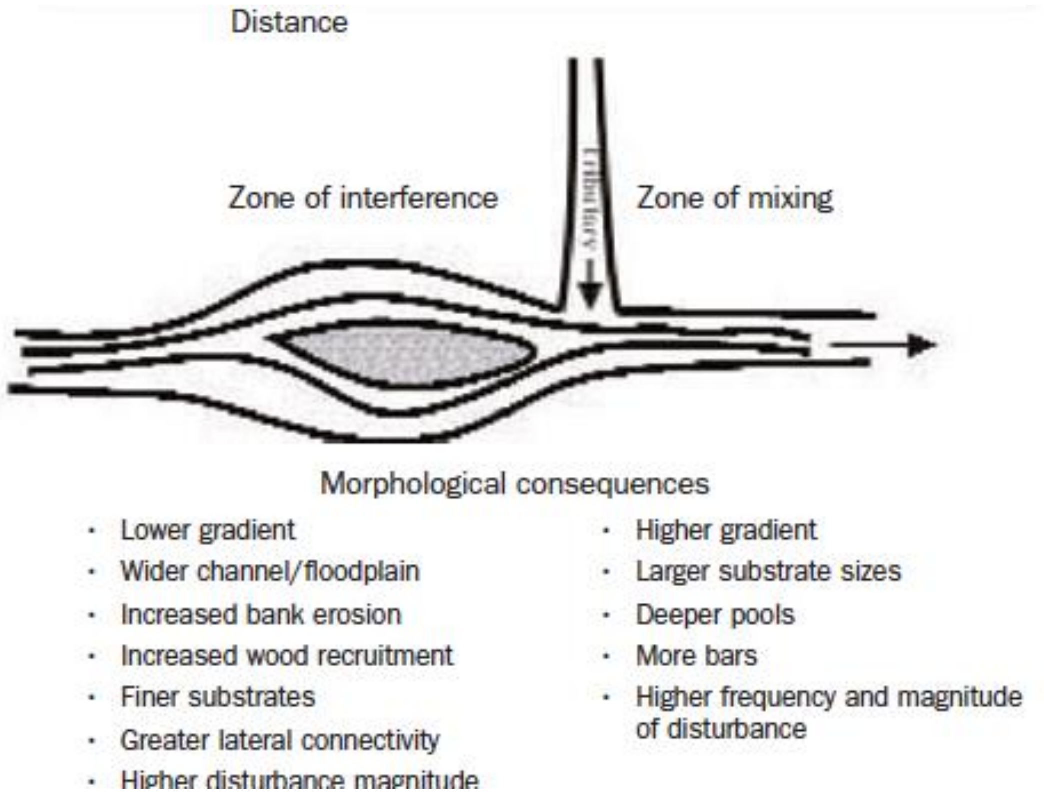
# The 3D nature of stream and river ecosystems

## The longitudinal dimension

**The Network Dynamics Hypothesis: How Channel Networks Structure Riverine Habitats**

*May 2004 / Vol. 54 No. 5* • BioScience 413

LEE BENDA, N. LEROY POFF, DANIEL MILLER, THOMAS DUNNE, GORDON REEVES, GEORGE PESS, AND MICHAEL POLLOCK




- Confluences change the hydraulics, sediment dynamics (often with bar formation)
- Because of increased environmental heterogeneity, confluences can also be hotspots for biodiversity
- Depends on stream/river size

# The 3D nature of stream and river ecosystems

## The longitudinal dimension

**The Network Dynamics Hypothesis: How Channel Networks Structure Riverine Habitats**

*May 2004 / Vol. 54 No. 5* • BioScience 413

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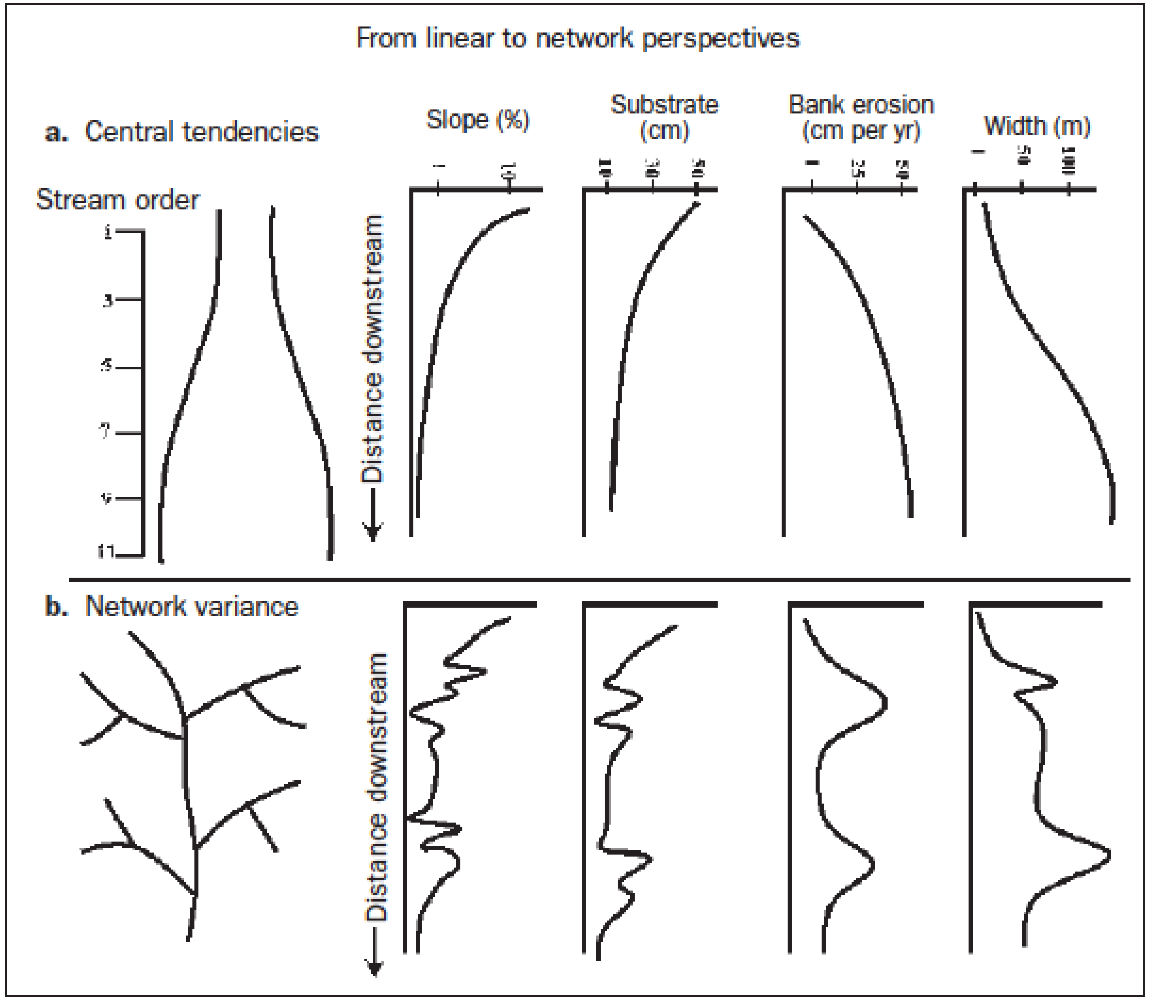
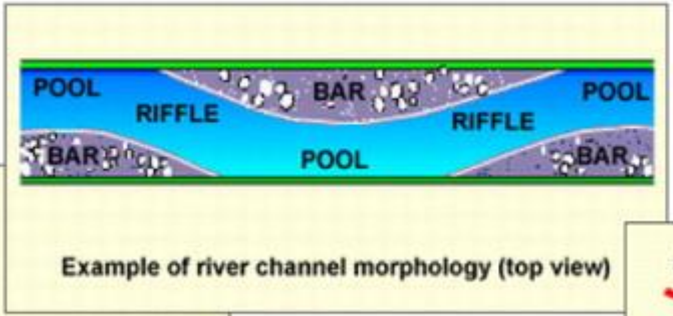



- From a linear model (see River Continuum Concept) to a network perspective
- Branching interrupts the downstream longitudinal continuum of geomorphological, hydrological and ecological properties

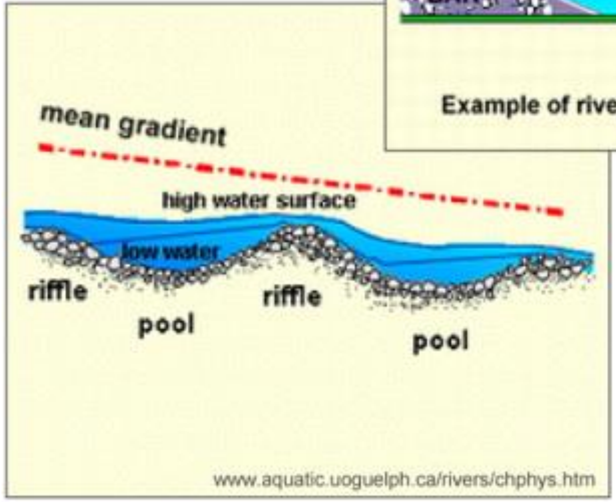
EPFL

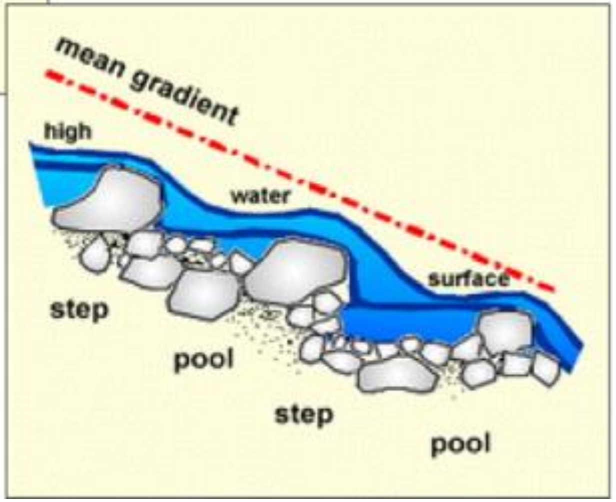
# Basic stream and river geomorphological units

Riffle-pool sequence
Step-pool sequence



Example of river channel morphology (top view)

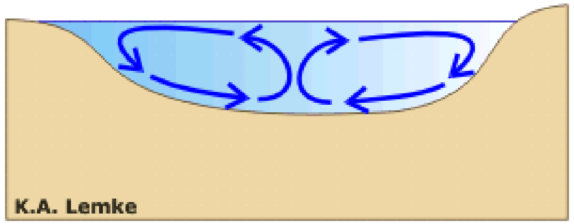


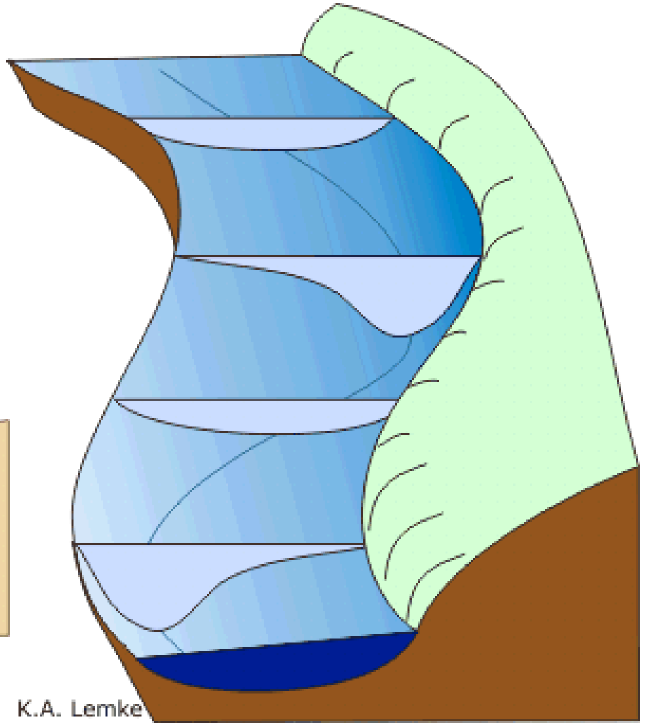




# Basic stream and river geomorphological units

## Riffle

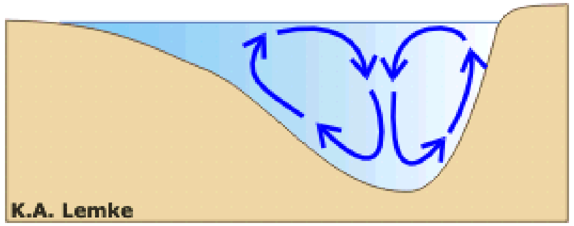
divergent flow
(deposition)




## Pool

convergent flow
(scouring)




- shallow (& wide)
- high velocity
- steep water surface gradient
- coarse-grained bed material

- deep (& narrow)
- low velocity
- gentle water surface gradient
- fine-grained bed material

# Geomorphology, habitats and functions

Debris dams

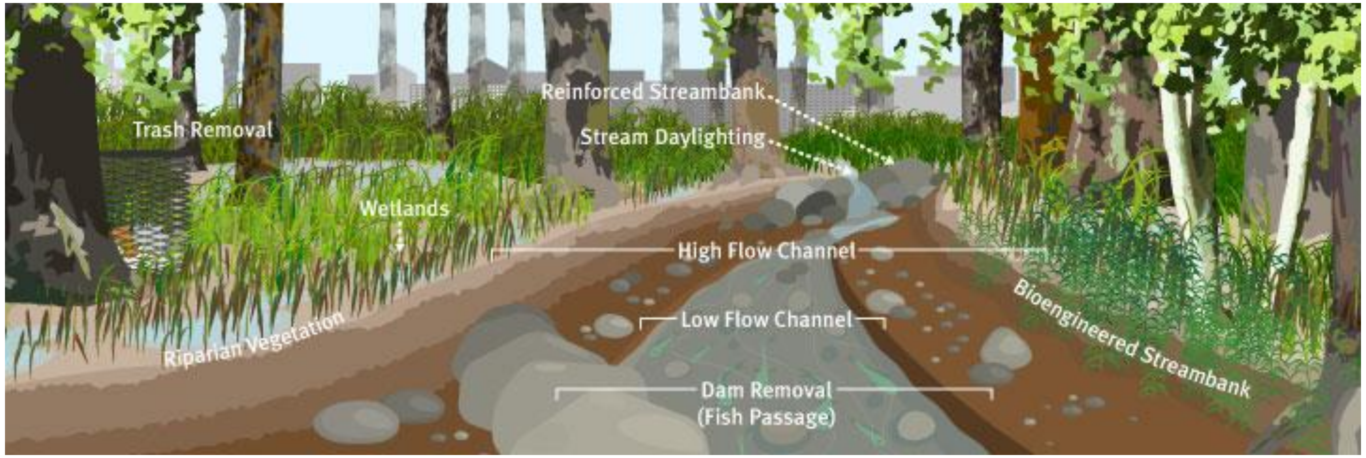
Induce hyporheic exchange

Biodiversity

# Geomorphology, habitats and functions

- Macrophyte stands
- Residence time
- Biodiversity
- Primary production

# Geomorphology, habitats and functions




- Channel regulation
- Removal of riparian vegetation
- Stream bottom sealing

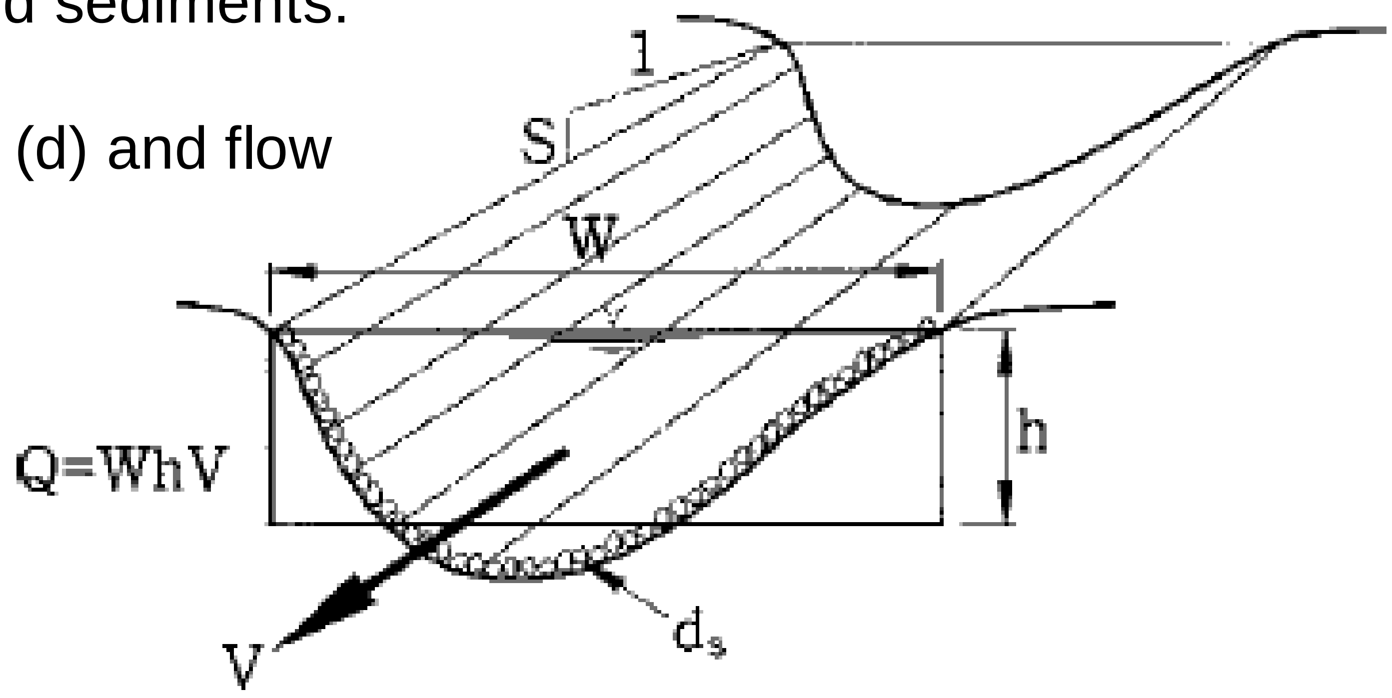
Channel geomorphology and hydraulics

# Hydraulic geometry

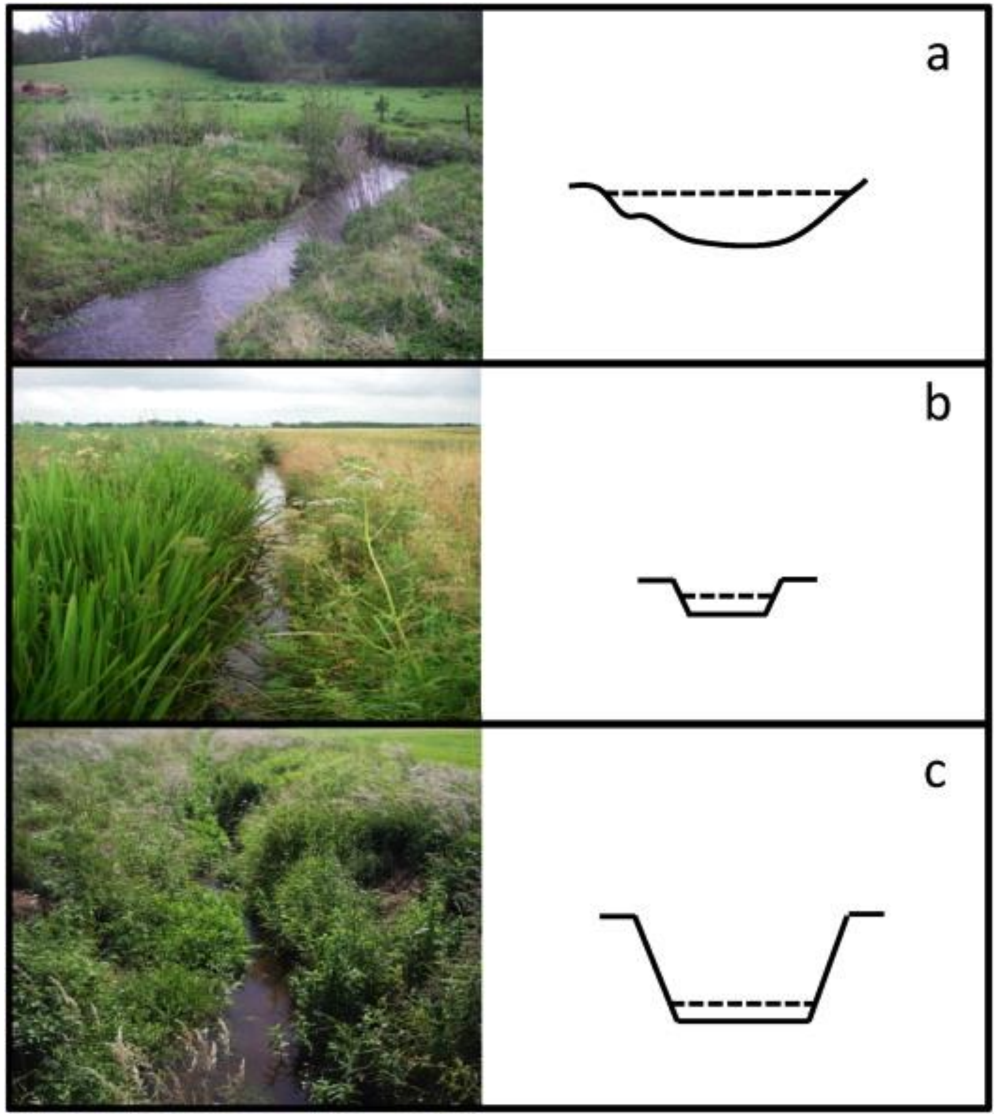
The downstream change of channel geometry to accomodate discharge and sediments

- The geometry of the channel is configured such that is can receive and transport upstream deliveries of water and sediments.

- Channel width (w), water depth (d) and flow velocity (v).

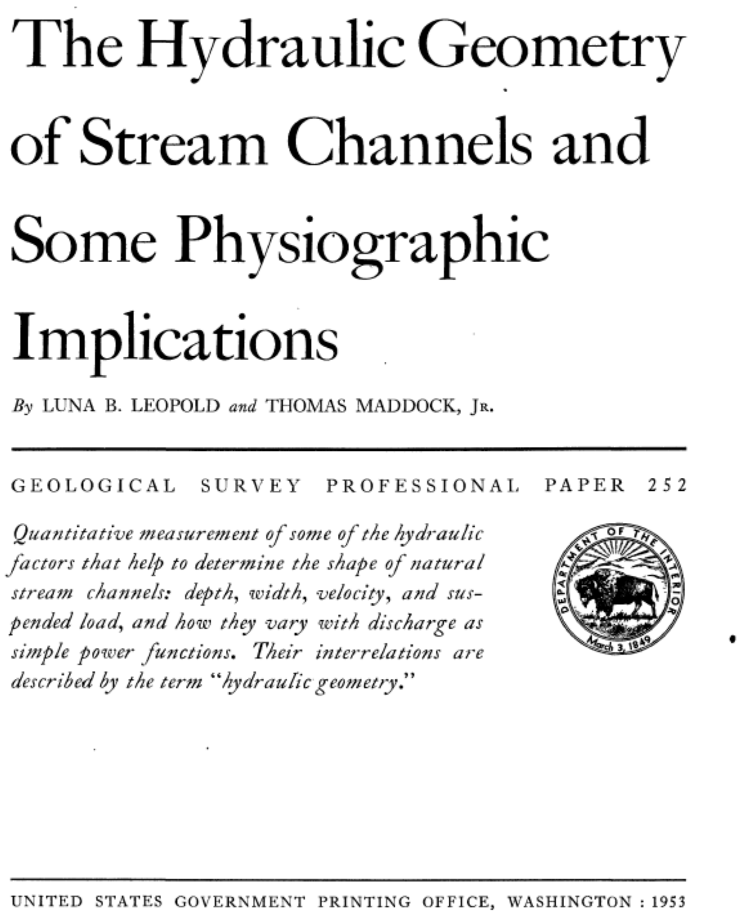


# Hydraulic geometry




Depending on the catchment geology, position within the network, terrain slope, but also riparian vegetation (land use), stream channels can differ in average width and depth, as does velocity.

# Hydraulic geometry



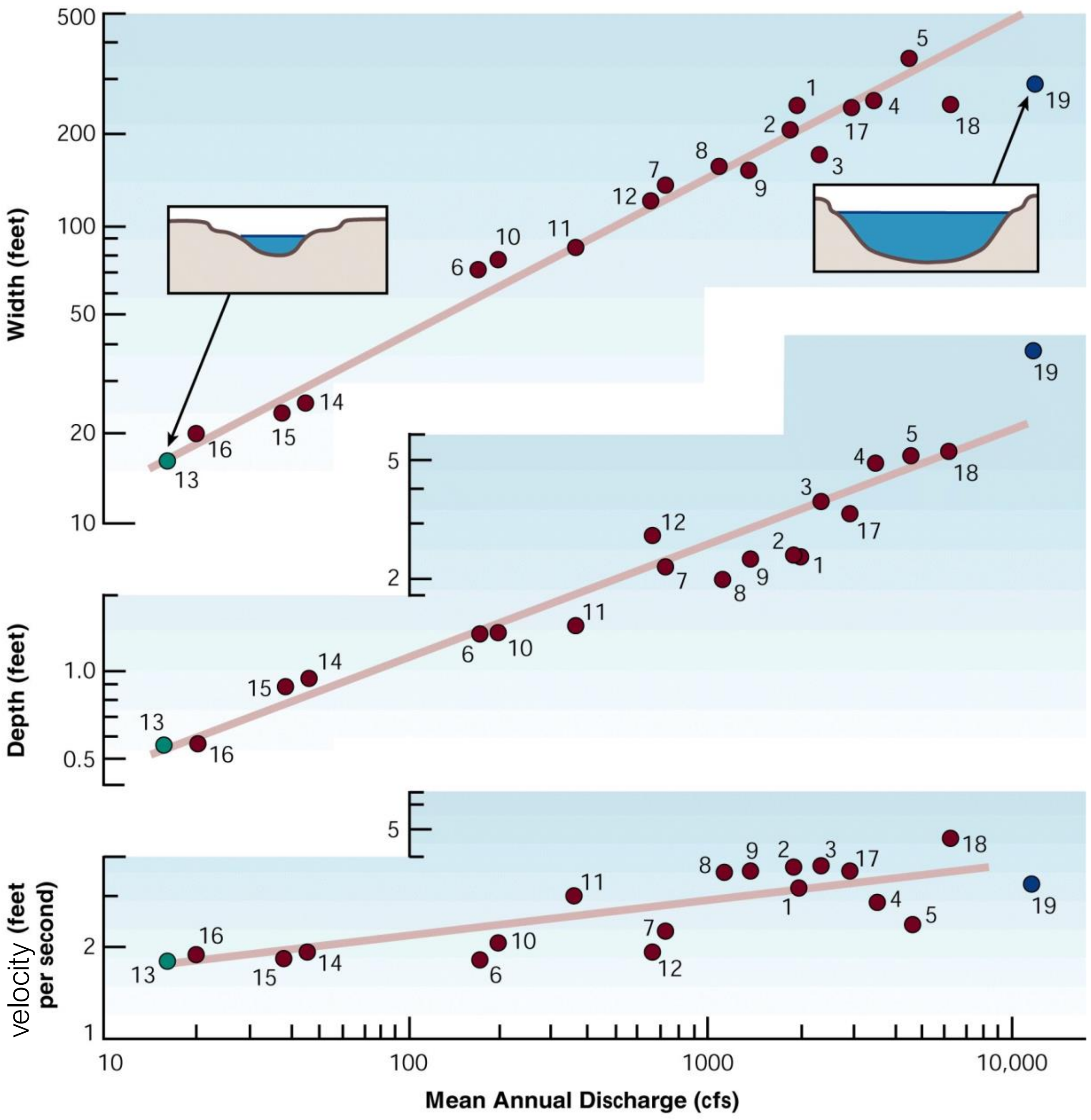
# The Hydraulic Geometry of Stream Channels and Some Physiographic Implications

By LUNA B. LEOPOLD and THOMAS MADDOCK, Jr.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 252

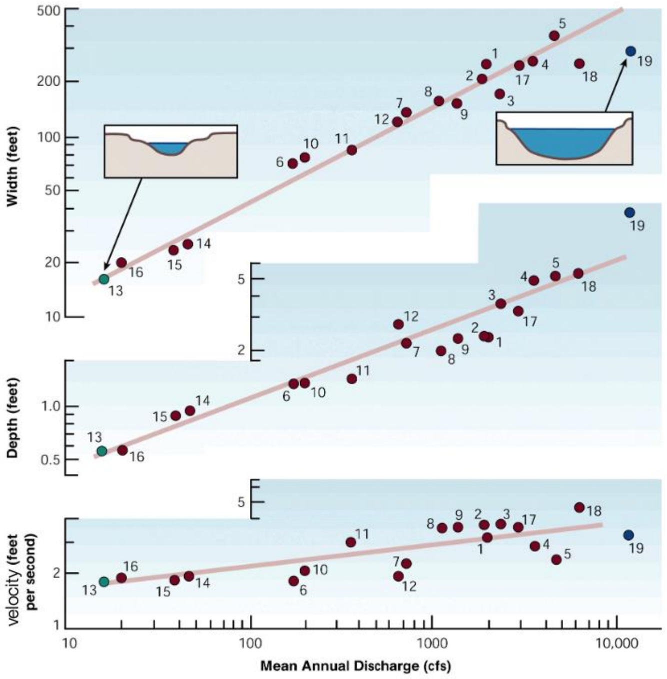
*Quantitative measurement of some of the hydraulic factors that help to determine the shape of natural stream channels: depth, width, velocity, and suspended load, and how they vary with discharge as simple power functions. Their interrelations are described by the term "hydraulic geometry."*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1953




From Leopold and Maddock, 1953.

# Hydraulic geometry




Relationships between the mean stream channel form and discharge downstream along a stream network (or at a station).

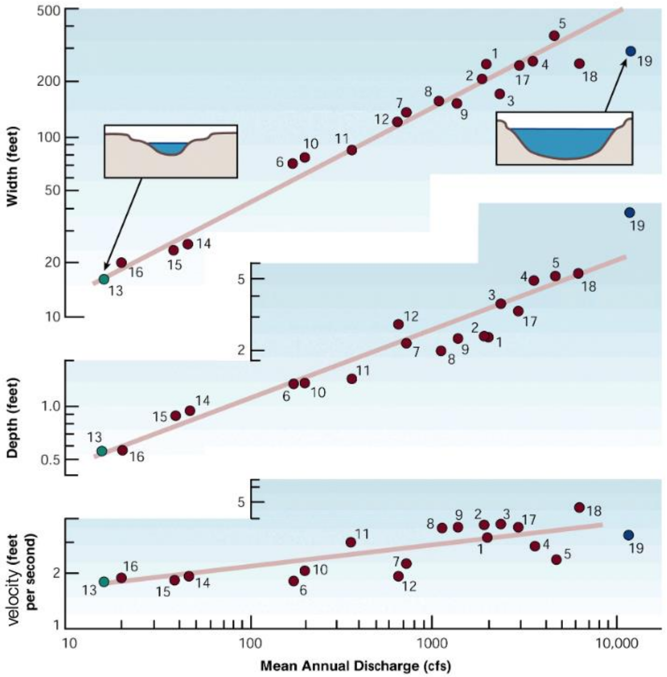
Hydraulic geometry: relationship for a channel in the form of power functions of discharge as:

$$w = aQ^b \quad d = cQ^f \quad v = kQ^m$$

where w = width, d = depth, v = velocity

Exponents (b, f, m) indicate rate of increase in a hydraulic variable (w, d, v) with increasing Q

# Hydraulic geometry




Q is the product of w, d and v, therefore

$$Q = (aQ^{b})\,(cQ^{f})\,(kQ^{m}) \text{ or}$$
$$Q = ack\,Q^{\,b+f+m}$$

and $b+f+m = 1$

Exponents (b, f, m) change with position in the network, climate, and discharge conditions

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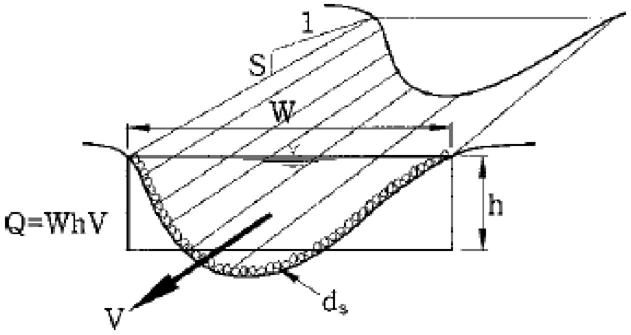
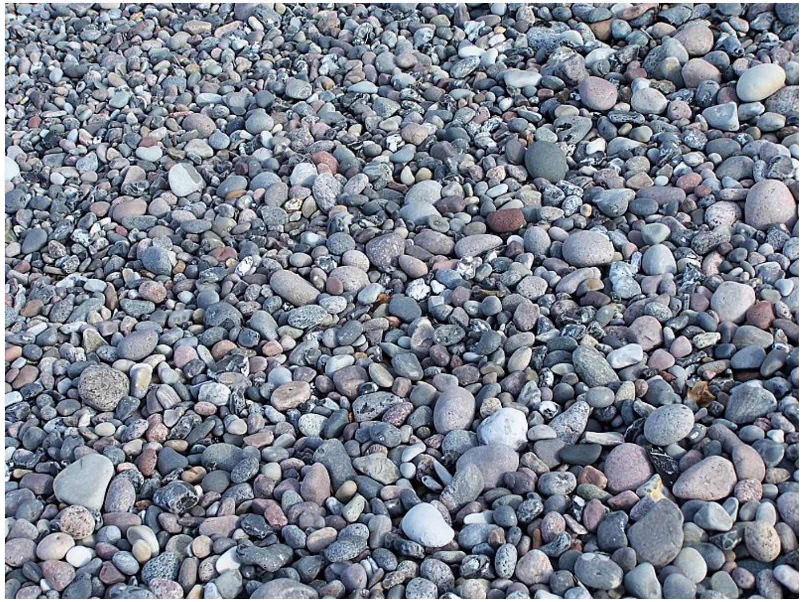
# Hydraulic geometry




Hydraulic geometry relates to

- hydrogeomorphology to position in the stream network
- sediment characteristis
- hydraulics
- benthic life
- ecosystem processes

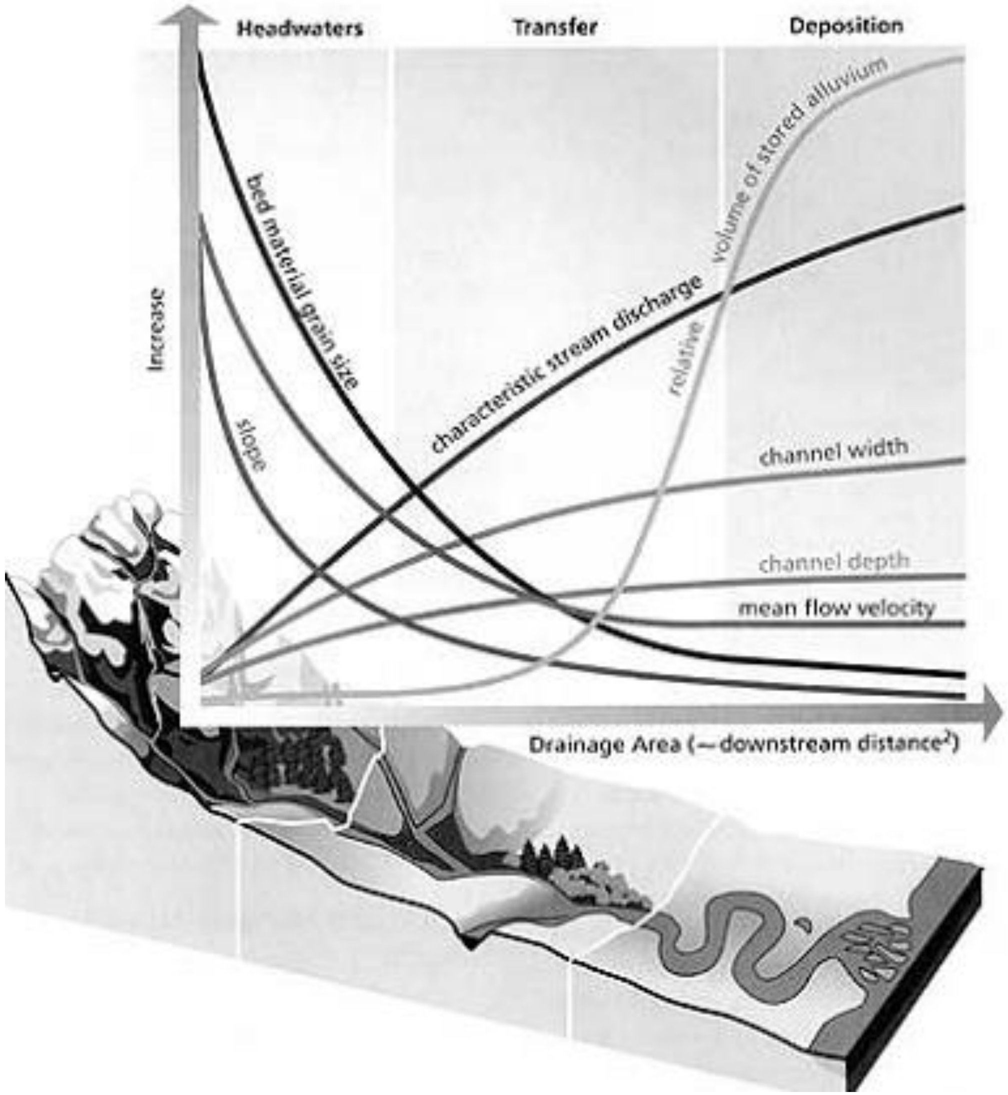
# Sedimentary dynamics



- Stream energy (e.g., channel slope, velocity)
- Sediment composition

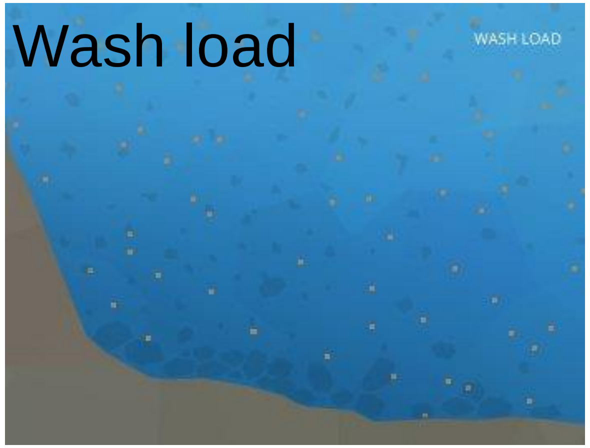
# Sedimentary dynamics

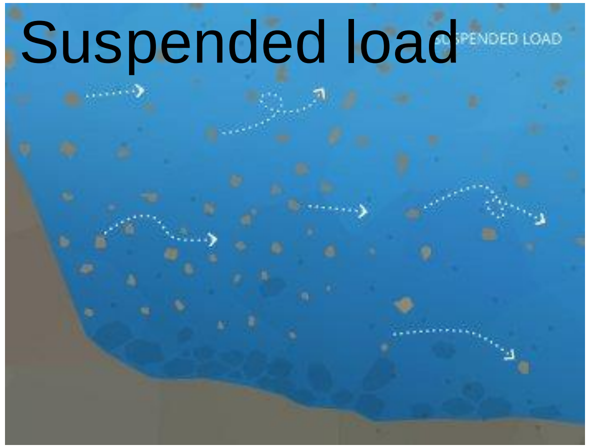
## Downstream gradients

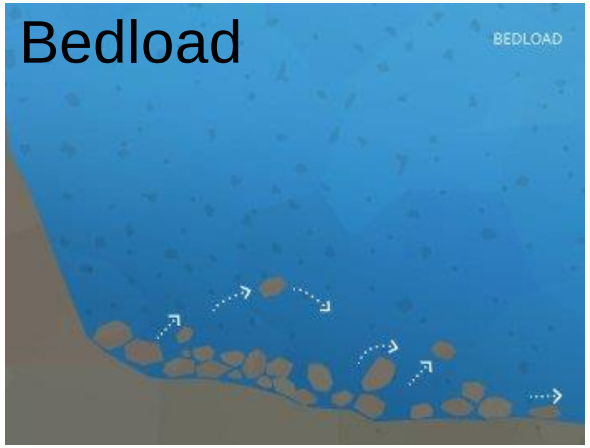


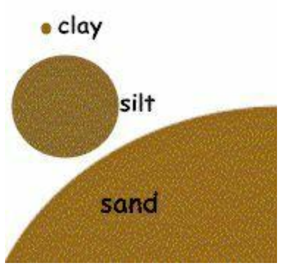

- Mean flow velocity and channel properties change downstream (see hydraulic geometry)
- How are sedimentary dynamics affected?

# Sedimentary dynamics and the Hjulstrom curve

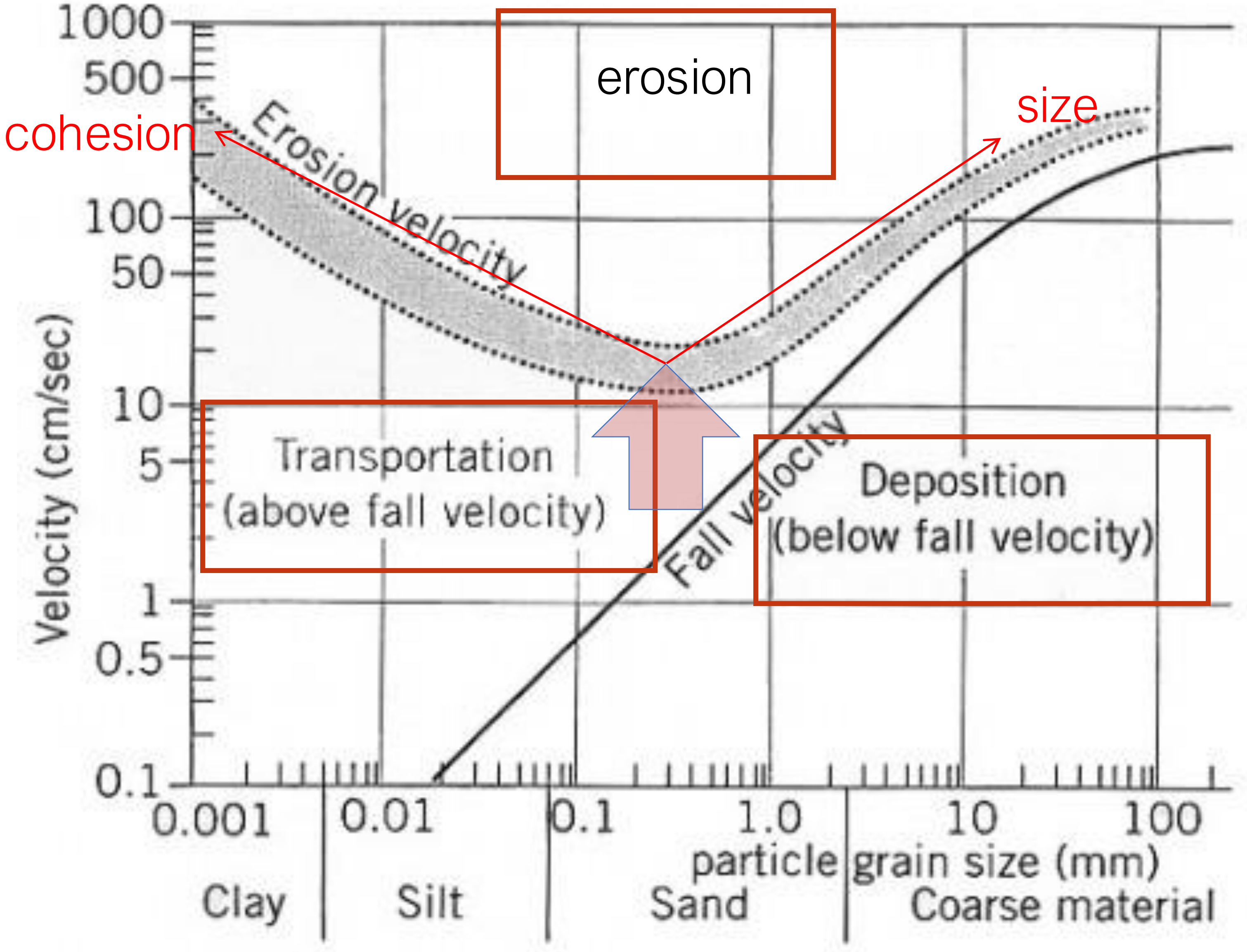


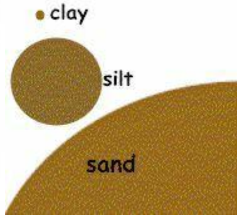



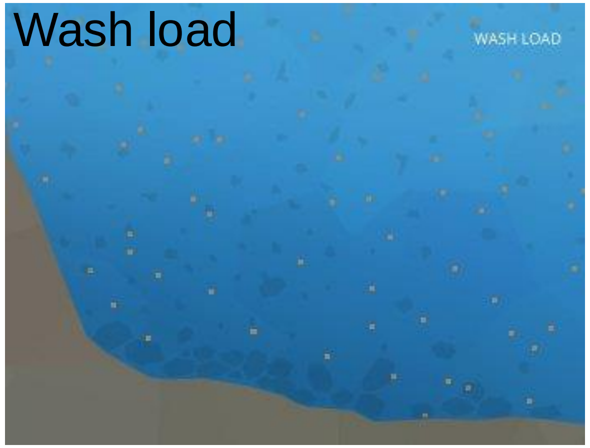



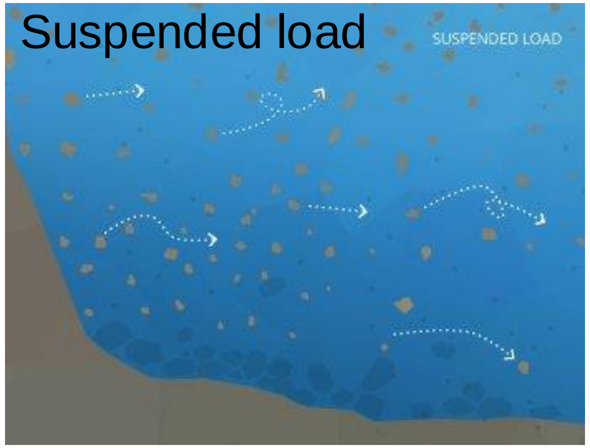



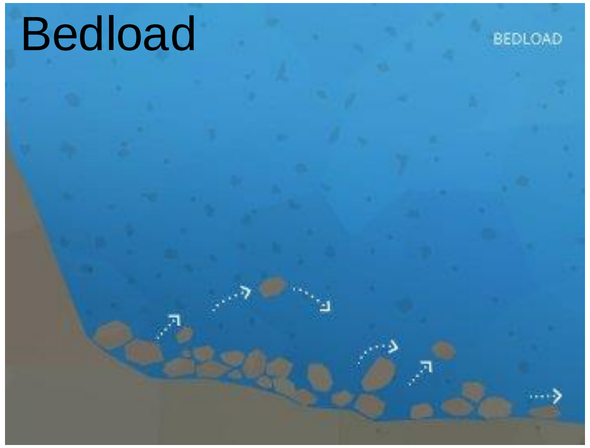
# Sedimentary dynamics and the Hjulstrom curve

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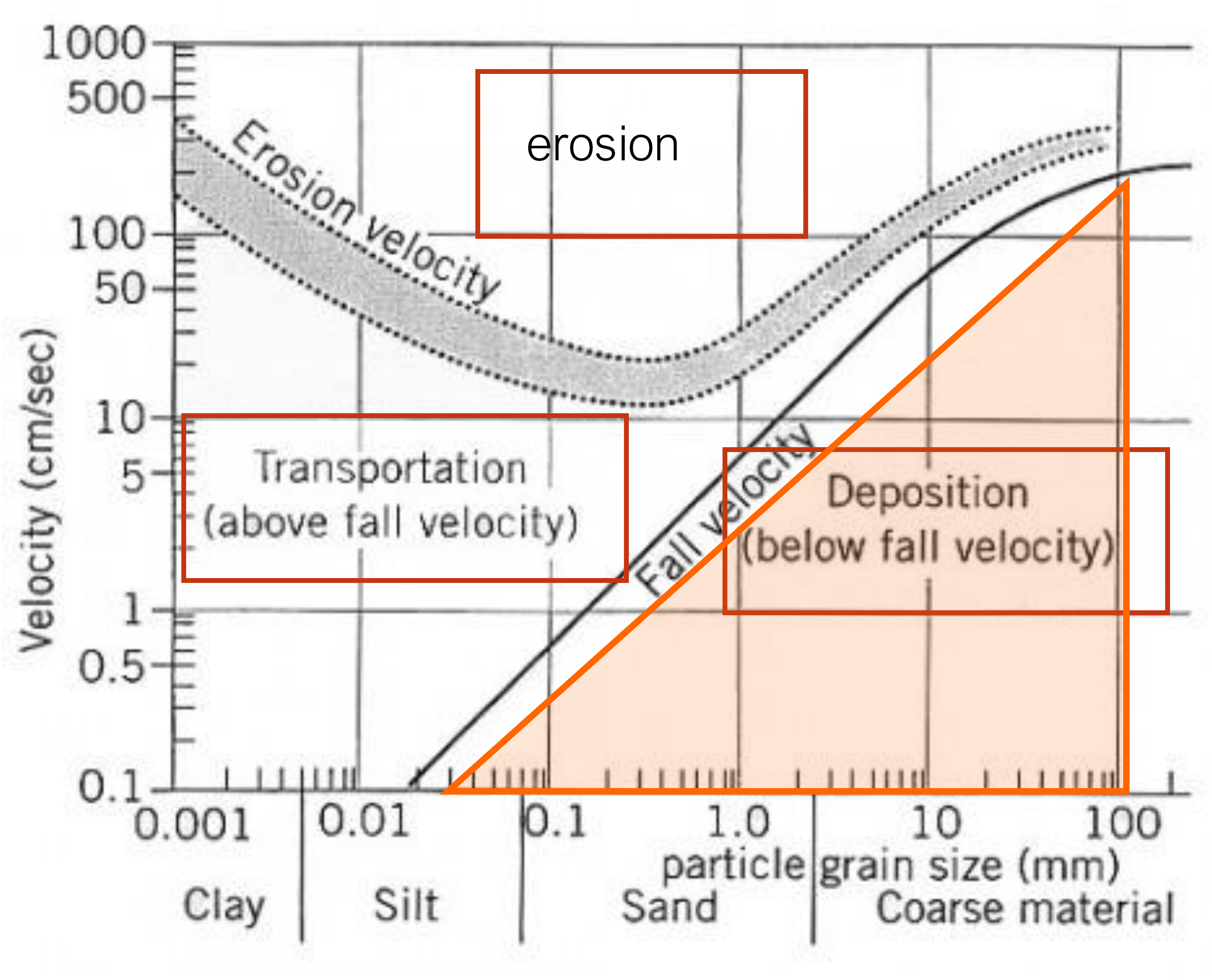
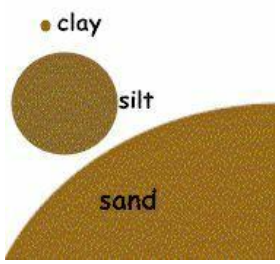
# Sedimentary dynamics and the Hjulstrom curve




Downstream sorting

- Coarser sediments accumulate upstream
- Fine sediments accumulate downstream
- Turbidity increases downstream (implications for light availability)

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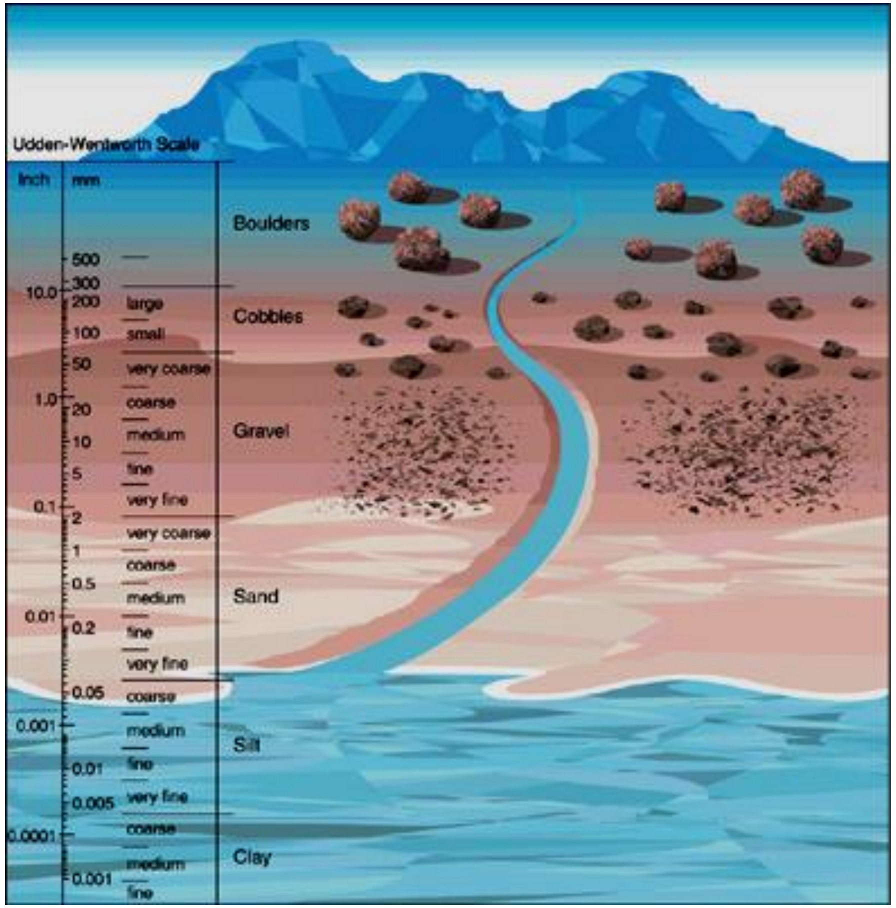
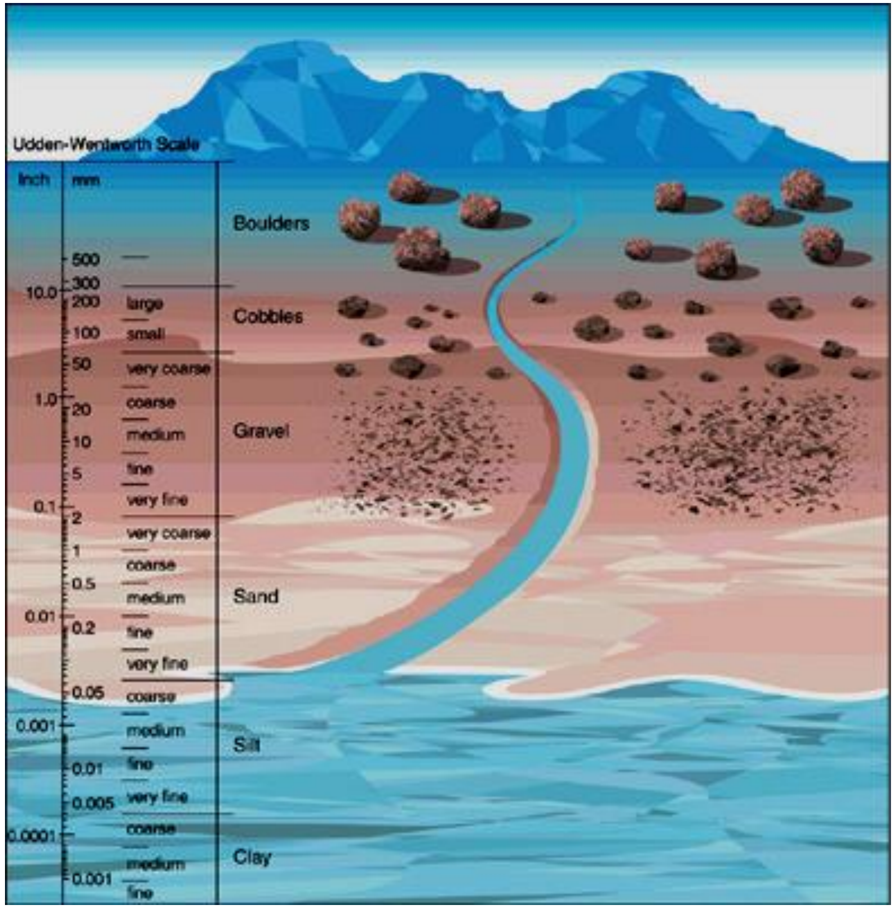
# Consequences

## Downstream fining/sorting



# Consequences

## Downstream fining/sorting




*Progress in Physical Geography* 22,1 (1998) pp. 1–32

**Patterns and processes of sediment sorting in gravel-bed rivers**

D. Mark Powell

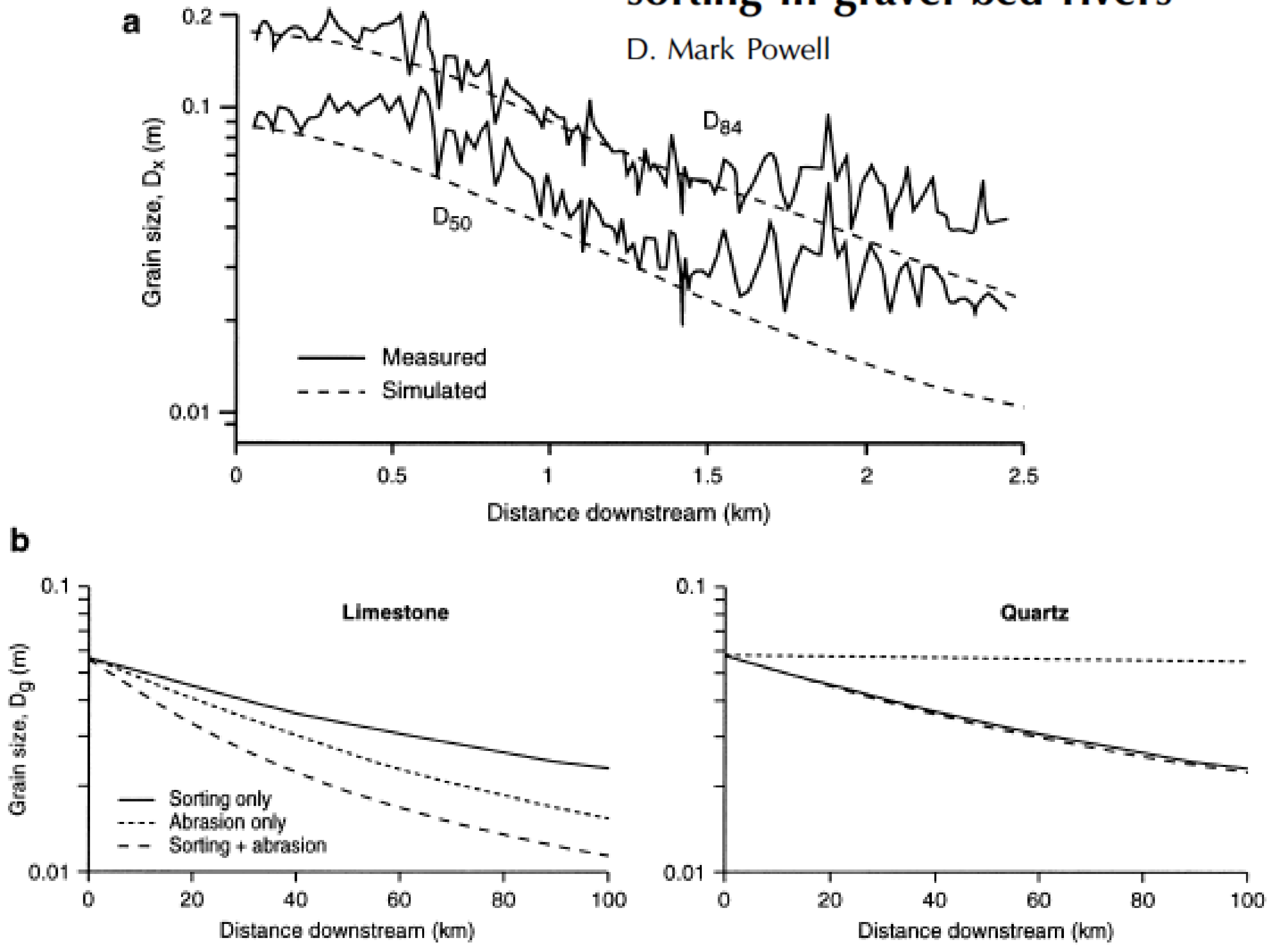



**Figure 6** Numerical simulations of downstream fining. (a) The role of size-selective entrainment, the Alt Dubhaig, after Hoey and Ferguson (1994); (b) the relative roles of selective entrainment and abrasion, two hypothetical rivers with contrasting lithologies, after Parker (1991b), reproduced with the kind permission of the ASCE. $D_x$ and $D_g$ are the *x*th percentile and geometric mean of the grain size distribution respectively

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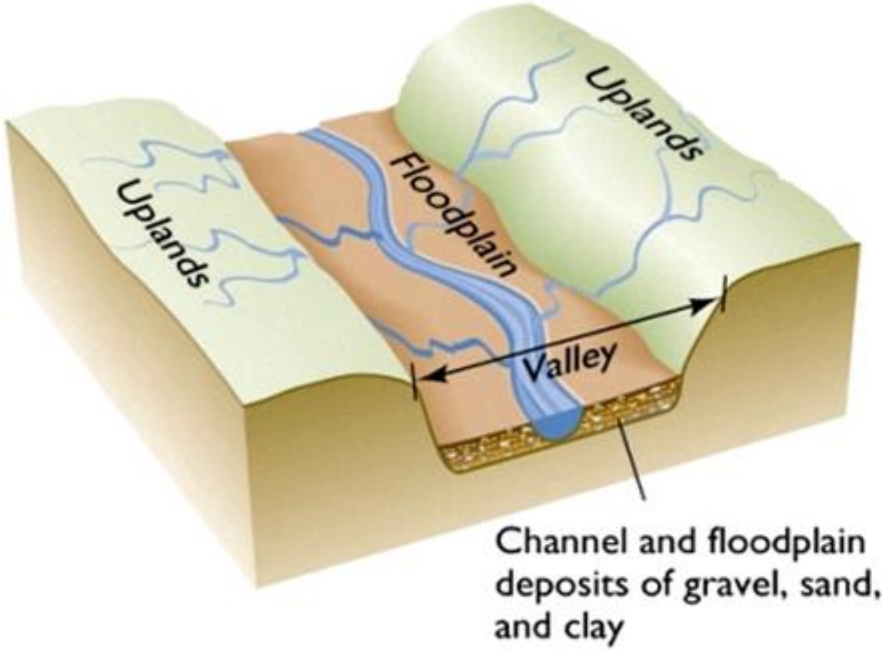
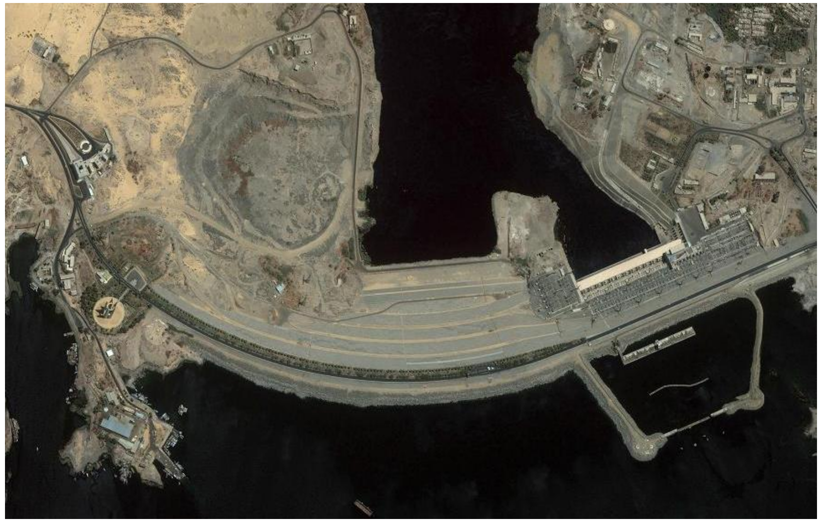
# Consequences

- High productivity of floodplains, estuaries
- (hydraulic geometry, Hjulstroem)
- Downstream accumulation of fine sediments
- Lateral accumulation of fine sediments within the floodplain during the receding limb of the storm hydrograph

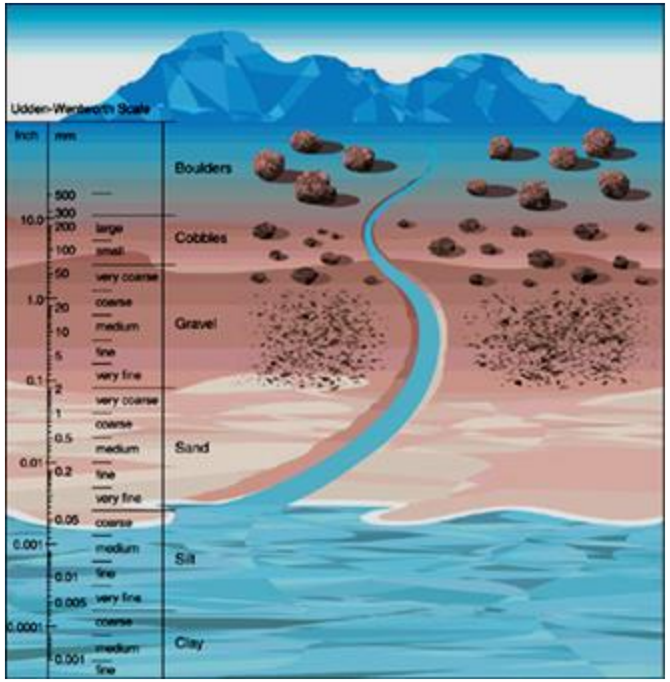



Aswan Dam



# Consequences

## Hydrodynamic exchange




## Vertical sorting of sediments

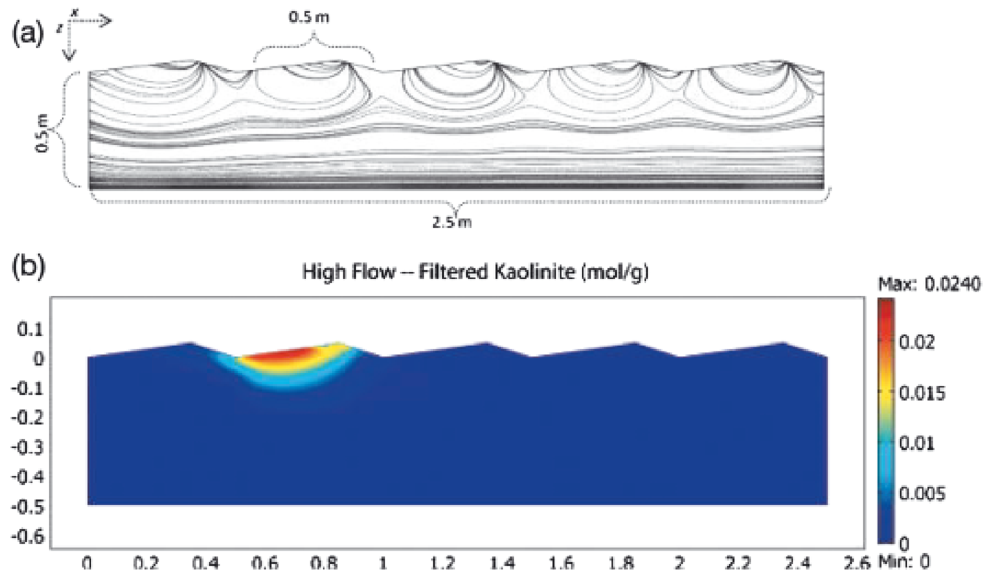
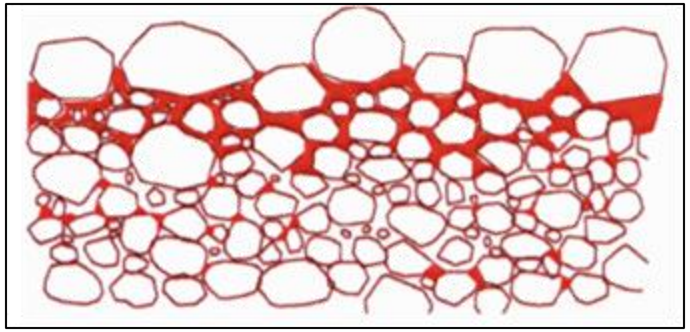
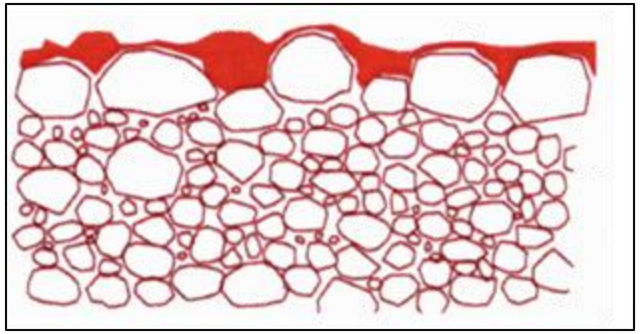



**Figure 24.** Spatial patterns of pore water flow and clay deposition in a streambed simulated by *Karwan and Saiers* [2012]. Compare simulated particle accumulation with typical experimental observations in Figure 25.

Internal clogging



External clogging



Reduced permeability and hydrodynamic exchange

# Consequences

## Hydrodynamic exchange

- Reduction of permeability
- From macro-porous to micro-porous flow
- Impacts on hydrodynamic exchange
- Shifting chemical gradients
- Habitat deterioration (siltation and anoxia)


Département de la mobilité, du territoire et de l'environnement
**Service de l'environnement**

Departement für Mobilität, Raumentwicklung und Umwelt
**Dienststelle für Umwelt**

CANTON DU VALAIS
KANTON WALLIS

**Le Rhône**

Campagne 2017

**Observation de la qualité des eaux de surface**

**Rapport et annexes**

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Août 2018

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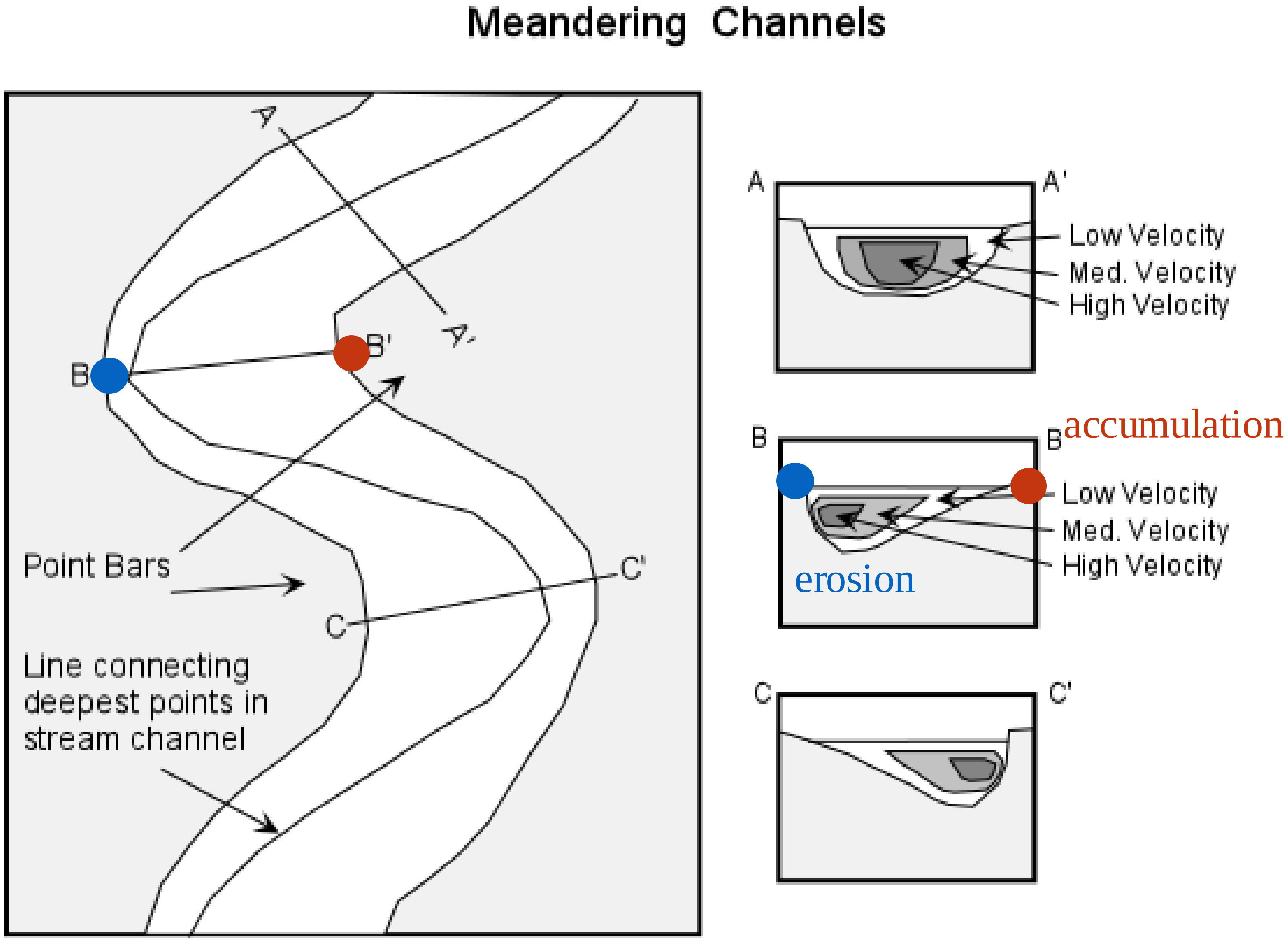
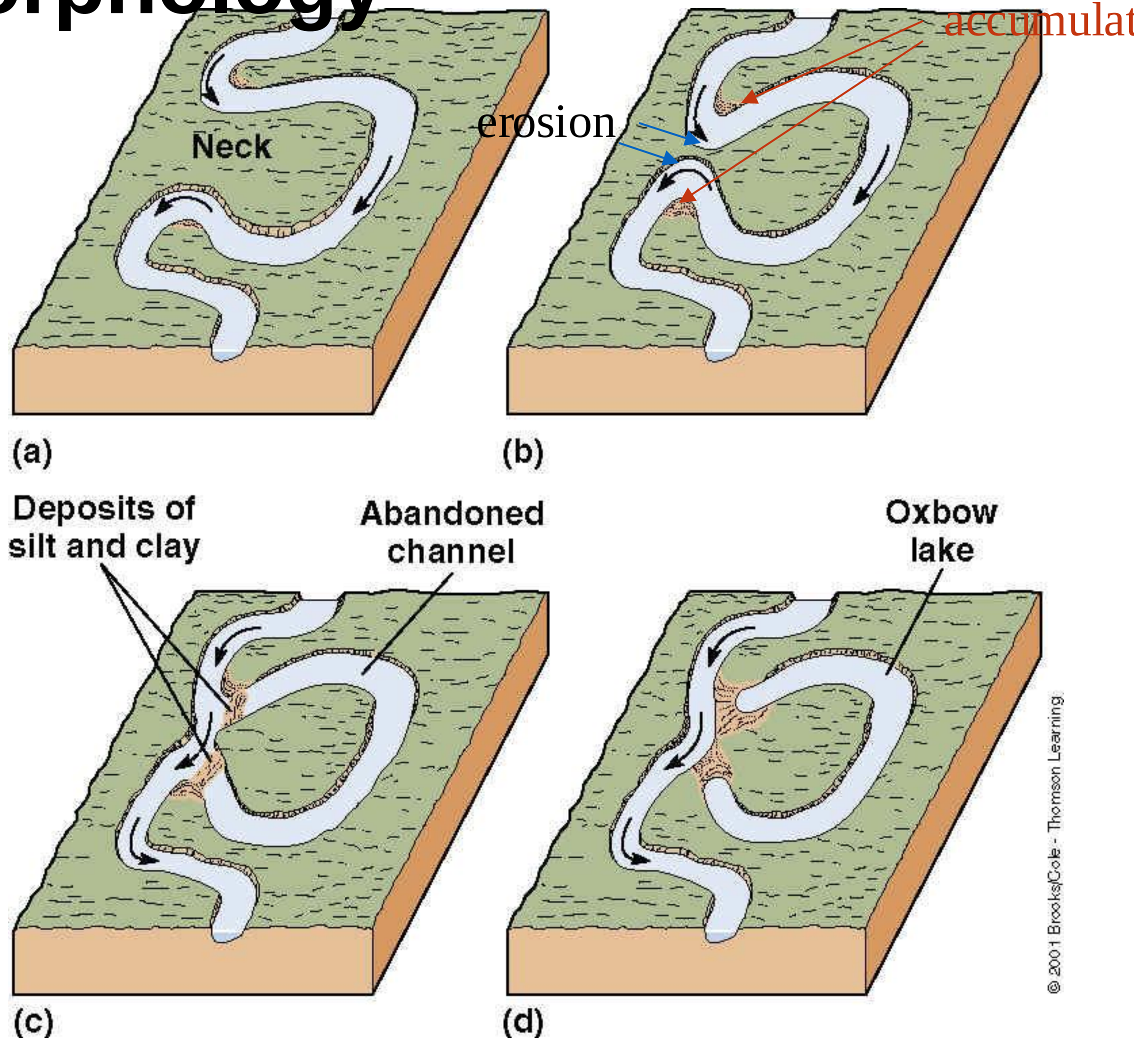
# Consequences for channel geomorphology




- Low gradients
- Easily eroded banks
- Straight channels eventually eroding into meandering channels
- Erosion: outer parts of the meander bends with highest velocity
- Sediment deposition along the inner meander bends with lowest velocity

# Consequences for channel geomorphology

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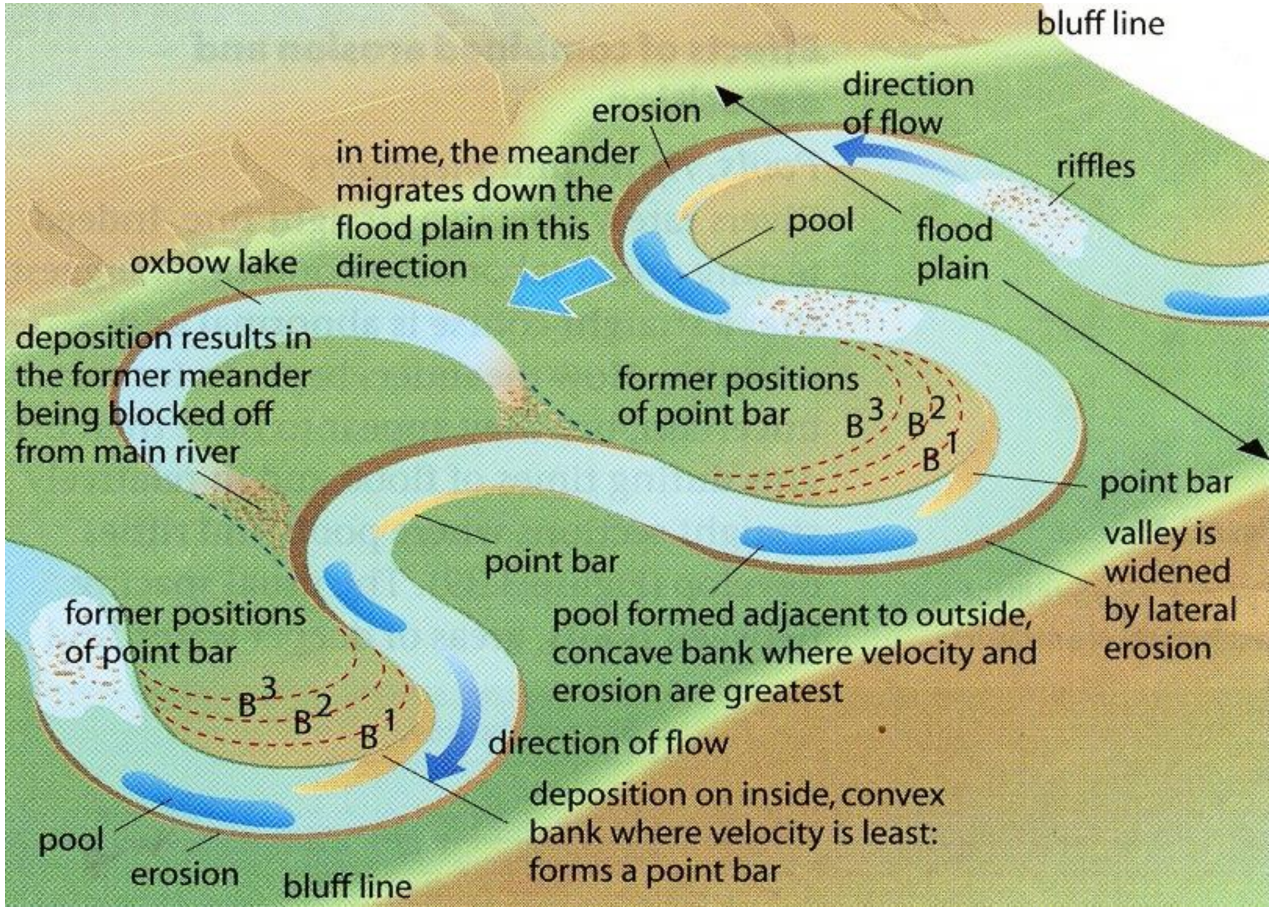
# Consequences for channel geomorphology




Meanders

- Interplay between erosion and accumulation
- Horizontal sorting of sediments
- Shaping the landscape, its environmental heterogeneity and biodiversity
- Shaping hydrodynamic exchange