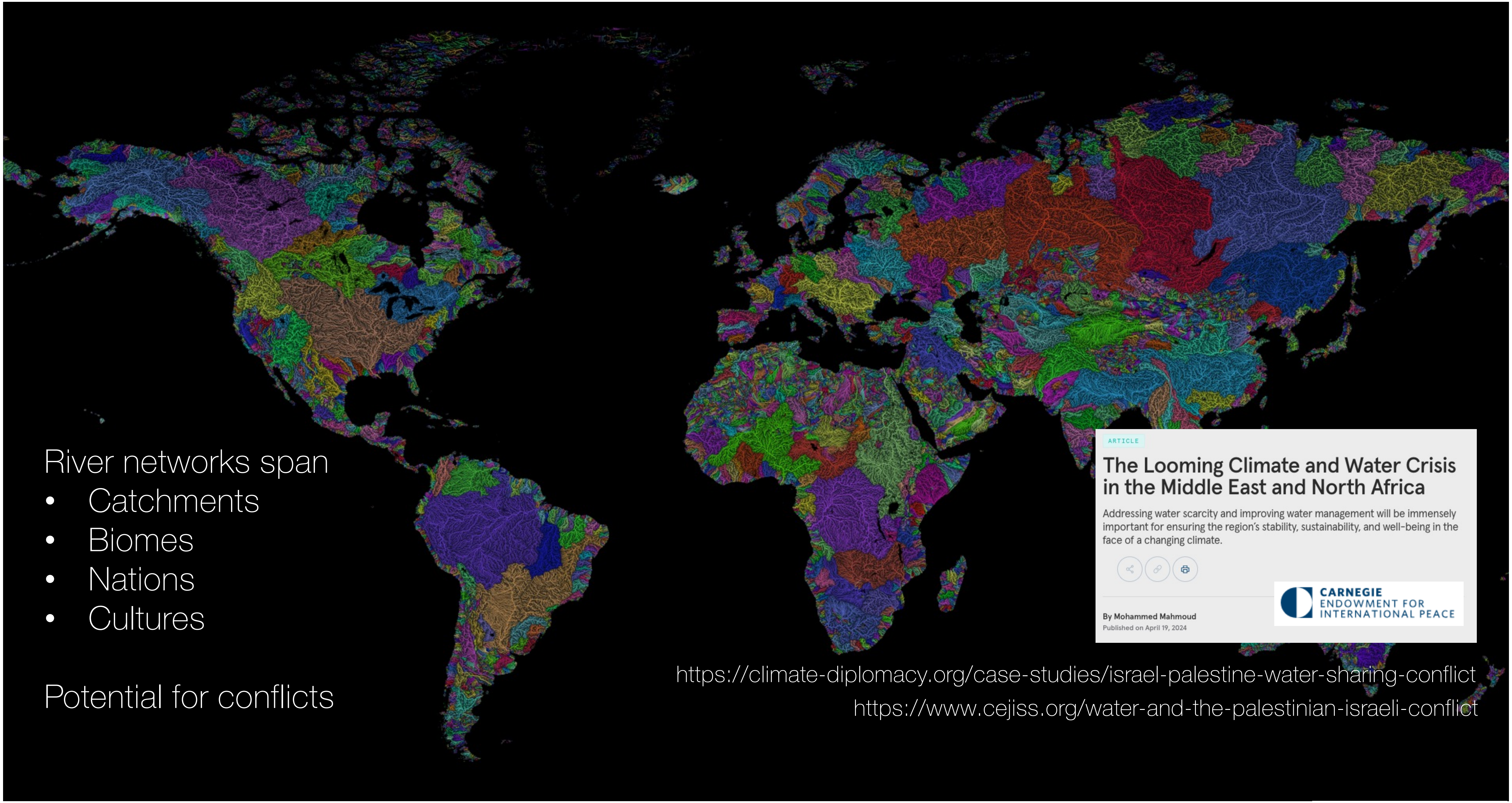
Hydrological and hydraulic perspectives of fluvial ecosystems

- Rivers as networks
- The four dimensions of river ecosystems
- Spatial heterogeneity



River networks span
- Catchments
- Biomes
- Nations
- Cultures

Potential for conflicts

ARTICLE

The Looming Climate and Water Crisis in the Middle East and North Africa

Addressing water scarcity and improving water management will be immensely important for ensuring the region's stability, sustainability, and well-being in the face of a changing climate.

CARNEGIE ENDOWMENT FOR INTERNATIONAL PEACE

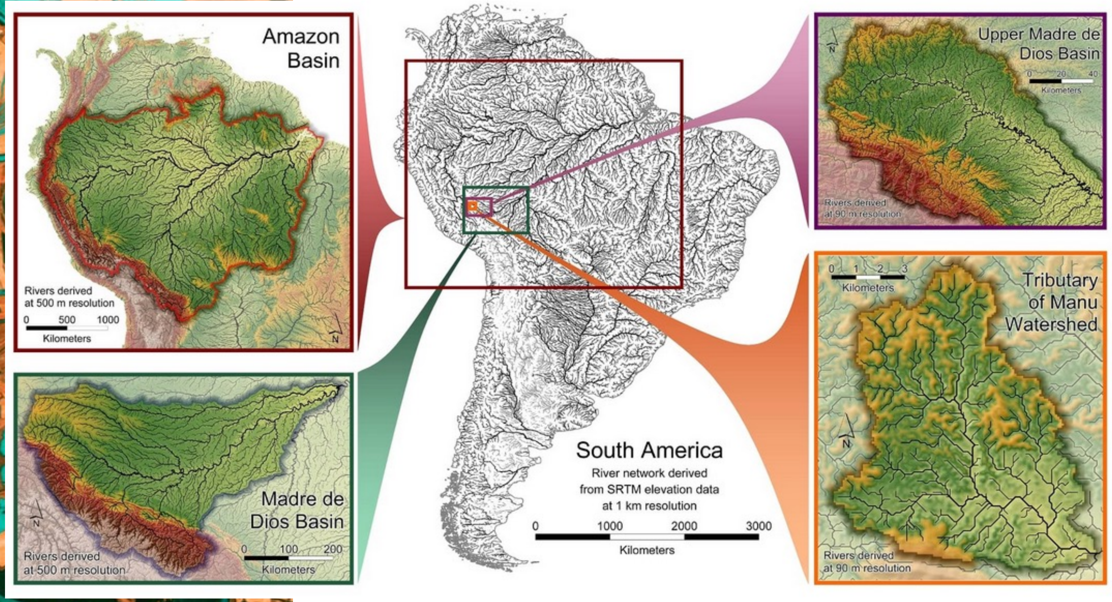
By Mohammed Mahmoud
Published on April 19, 2024

https://climate-diplomacy.org/case-studies/israel-palestine-water-sharing-conflict
https://www.cejiss.org/water-and-the-palestinian-israeli-conflict

The Decolonial Atlas

HydroSHEDS

Home About Products Applications FAQ



The core data products of HydroSHEDS v1 are:

- A void-filled digital elevation model underpinning HydroSHEDS v1 (DEM)
- A hydrologically conditioned version of the digital elevation model (CON)
- A drainage direction map derived from the conditioned elevation data (DIR)
- A flow accumulation map derived from the flow direction map, either as number of upstream grid cells (ACC) or as upstream area (ACA)
- A flow length map derived from the flow direction map, either measured in upstream direction (LUP) or in downstream direction (LDN)
- A landmask grid which indicates the land-ocean distribution and the location of coastal and inland sinks (MSK)

Lehner, B., Verdin, K., Jarvis, A. (2008). New global hydrography derived from spaceborne elevation data. Eos, Transactions, American Geophysical Union, 89(10): 93–94. https://doi.org/10.1029/2008eo100001

How river networks form

Branching river networks in runoff-generating areas are naturally fractal — there are basins within basins within basins, all of them looking alike.

Fluvial landforms show deep similarities of the parts and the whole across up to six orders of magnitude despite the great diversity of their drivers and controls—geology, exposed lithology, vegetation, and climate

River networks are spanning trees: spanning, because there is a route for water to flow from every location of the basin to the main stream; and a tree, because of the absence of loops.

PNAS
INAUGURAL ARTICLE
ENVIRONMENTAL SCIENCES

Evolution and selection of river networks: Statics, dynamics, and complexity

Andrea Rinaldo[a,b,1], Riccardo Rigon[c], Jayanth R. Banavar[d], Amos Maritan[e], and Ignacio Rodriguez-Iturbe[f]

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Contributed by Andrea Rinaldo, December 27, 2013 (sent for review November 30, 2013)

This contribution is part of the special series of Inaugural Articles by members of the National Academy of Sciences elected in 2012.

Moving from the exact result that drainage network configurations minimizing total energy dissipation are stationary solutions of the general equation describing landscape evolution, we review the static properties and the dynamic origins of the scale-invariant structure of optimal river patterns. Optimal channel networks (OCNs) are feasible optimal configurations of a spanning network mimicking landscape evolution and network selection through imperfect searches for dynamically accessible states. OCNs are spanning loopless configurations, however, only under precise physical requirements that arise under the constraints imposed by river dynamics—every spanning tree is exactly a local minimum of total energy dissipation. It is remarkable that dynamically accessible configurations, the local optima, stabilize into diverse metastable forms that are nevertheless characterized by universal statistical features. Such universal features explain very well the statistics of, and the linkages among, the scaling features measured for fluvial landforms across a broad range of scales regardless of geology, exposed lithology, vegetation, or climate, and differ significantly from those of the ground state, known exactly. Results are provided on the emergence of criticality through adaptative evolution and on the yet-unexplored range of applications of the OCN concept.

trees and networks | adaptive evolution | feasible optimality | erosional mechanics | river network patterns

A drainage basin of a river is the region from which rainfall becomes runoff flowing downhill and aggregating to form the river streams. Branching river networks in runoff-generating areas are naturally fractal (1)—there are basins within basins within basins, all of them looking alike. Fluvial landforms show deep similarities of the parts and the whole across up to six orders of magnitude despite the great diversity of their drivers and controls—geology, exposed lithology, vegetation, and climate (2). Observational data reveal the fine detail and large-scale patterns of fluvial landforms. Such data have been used to characterize river basins across our planet (2). River networks are spanning trees: spanning, because there is a route for water to flow from every location of the basin to the main stream; and a tree, because of the absence of loops. The scaling associated with the observed spanning trees is a topic of great interest (3–25). Remarkably, one observes approximate universality in the set of scaling exponents even though one is considering nonequilibrium conditions. As characteristic of conventional critical phenomena, the exponents were found not to be independent of each other. Rather, each of them can be derived through scaling relations postulating the knowledge of geometrical constraints. In addition, as is common in any good detective novel, our story comes with unexpected twists. The first surprise was that the observational exponents do not fall into any known standard universality class of spanning or directed trees with equal weight. A pivotal step in the story came through the notion of optimal channel networks (OCNs). This was directly inspired by the notable success of variational principles in physics. As water flows downhill, it loses potential energy. Could it be that nature selected those spanning trees for which the total energy dissipation was a minimum? Remarkably, numerical simulations compared with data suggested that this was likely the case. In a puzzling twist, it was found that one could solve OCNs exactly and the resulting exponents associated with the global minimum did not match either the observational data or the numerical simulations. The puzzles were resolved through a study of the dynamics of erosion sculpting the landscape. It was shown that the simplest dynamical equation, under reparametrization invariance, predicted that river networks were necessarily trees and had no loops. Even more interestingly, one could show that every local minimum of the OCN functional is a stationary solution of the general landscape evolution equation. The above observations suggested that the adaptation of the fluvial landscape to the geological and climatic environment corresponds to the dynamical settling of optimal structures into suboptimal niches of their fitness landscape and that feasible optimality, i.e., the search for optima that are accessible to the dynamics given the initial conditions, might apply to a broad spectrum of problems in nature. The puzzle was solved: The statics and dynamics of river networks had been collected in a neat package. It all fit in and a surprising outcome was the robust statistical features of the dynamically accessible minima.

This Inaugural Article provides technical details and references for the various steps of the development of the theory, explores results on the role of heterogeneity, and reviews recent developments and applications of the OCN concept in a variety of fields.

Scaling Fluvial Landscapes: Comparative Geomorphology

Accurate descriptions of the fluvial landscape across scales stem from digital terrain maps, i.e., discretized elevation fields $\{z_i\}$ on a lattice of pixels of unit area. The drainage network is determined by assigning to each site i a drainage direction through steepest

Significance

Our focus is on a rich interdisciplinary problem touching on earth science, hydrology, and statistical mechanics—an understanding of the statics and dynamics of the network structures that we observe in the fluvial landscape, and their relation to evolution and selection of recurrent patterns of self-organization. It is an exemplar of how diverse ideas, numerical simulation, and elementary mathematics can come together to help solve the mystery of understanding a ubiquitous pattern of nature.

Author contributions: A.R., R.R., J.R.B., A.M., and I.R.-I. designed research; A.R., R.R., and I.R.-I. performed research; A.R., R.R., A.M., and I.R.-I. analyzed data; and A.R. wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

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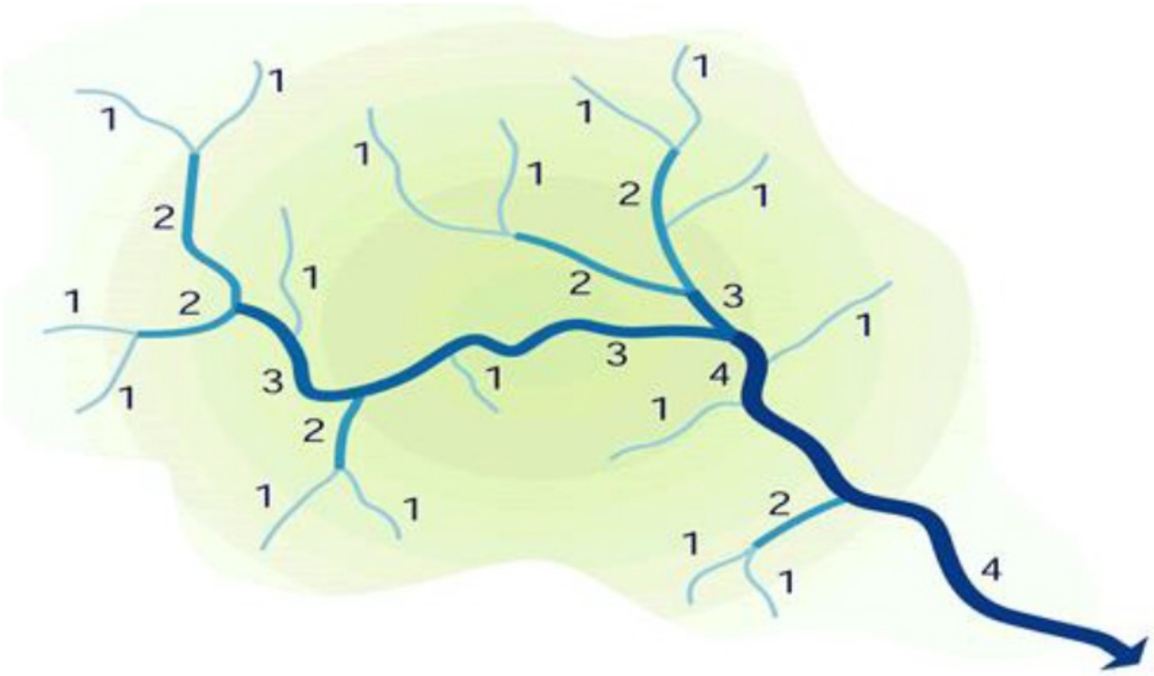
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1322700111/-/DCSupplemental.

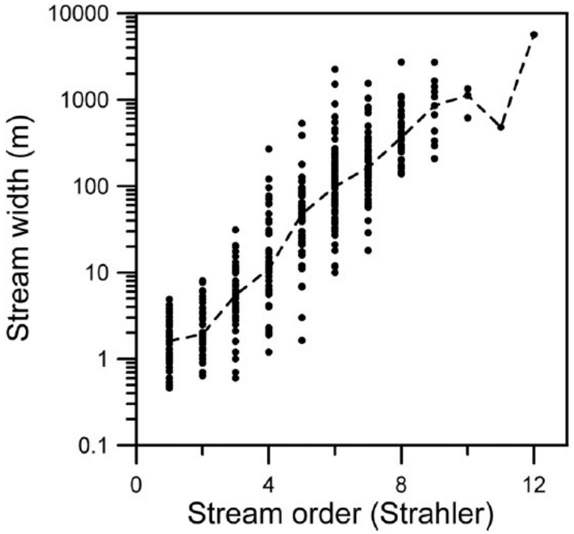
Describing river networks

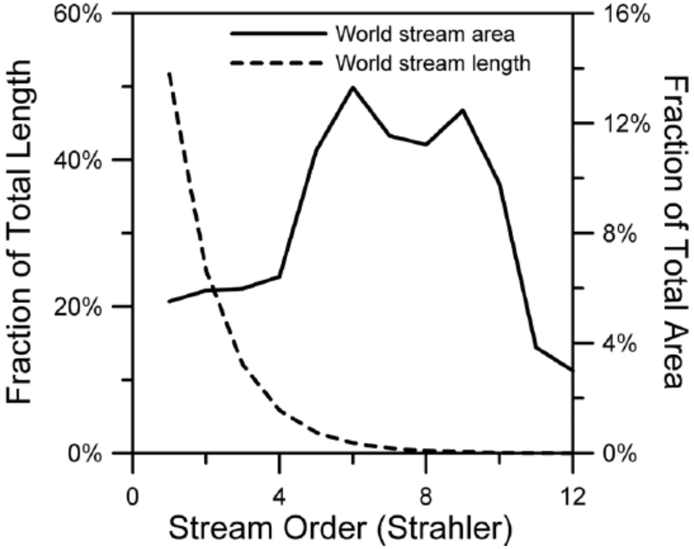


Article

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]





Strahler order

- 662'000 km^2, 0.45 % of the continental land surface
- around 35% of global stream length and number is made up of streams smaller than Strahler order 6

Order (ω)	n_ω	$\bar{l}_\omega$ (km)	Total length (km)	Width (m)	Area (km^2)
1	28 550 000	1.6	45 660 000	0.8	36 500
2	6 000 000	3.7	22 061 000	1.8	39 200
3	1 260 000	8.5	10 660 100	3.7	39 600
4	264 000	19.5	5 151 100	8.3	42 500
5	55 500	44.8	2 489 000	29.3	72 800
6	11 700	103.2	1 202 700	73.3	88 100
7	2450	237.4	581 200	131.5	76 400
8	515	546.2	280 800	264.5	74 300
9	110	1256.7	135 700	608.5	82 600
10	23	2891.7	65 600	988.5	64 900
11	5	6653.8	31 700	803.0	25 400
12	1	6437.0	6440	3079.0	19 800

Quantifying global river surface area

Use Landsate imagery for streams and rivers near annual mean discharge (from 3693 gaging stations), validate against field surveys

Rivers with channels wider than 90 meters — still numerous headwaters missing

Global river and stream surface area at mean annual discharge is 773,000 ± 79,000 square kilometers (0.58 ± 0.06%) of Earth’s non-glaciated land surface

Surface area matters for…

RIVER NETWORKS

Global extent of rivers and streams

George H. Allen*† and Tamlin M. Pavelsky

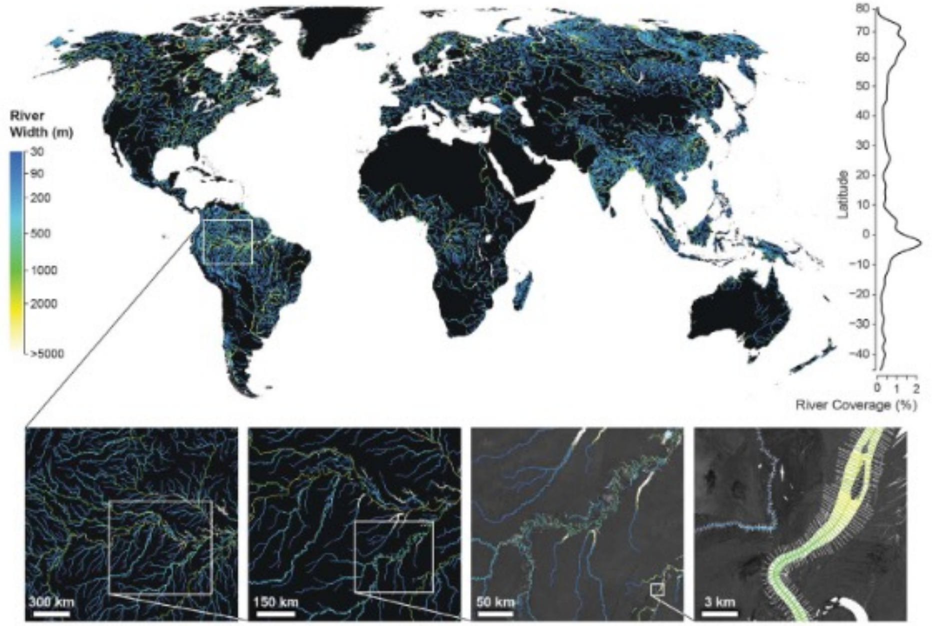
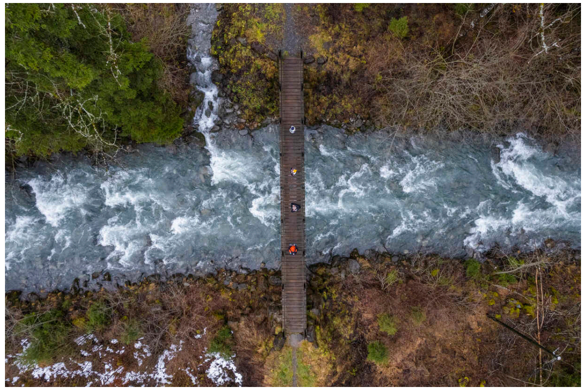


Fig. 1. The Global River Widths from Landsat (GRWL) Database contains more than 58 million measurements of planform river geometry. The line plot on the right shows observed river coverage as a percentage of land area by latitude, and the bottom insets show GRWL at increasing zoom. The rightmost inset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

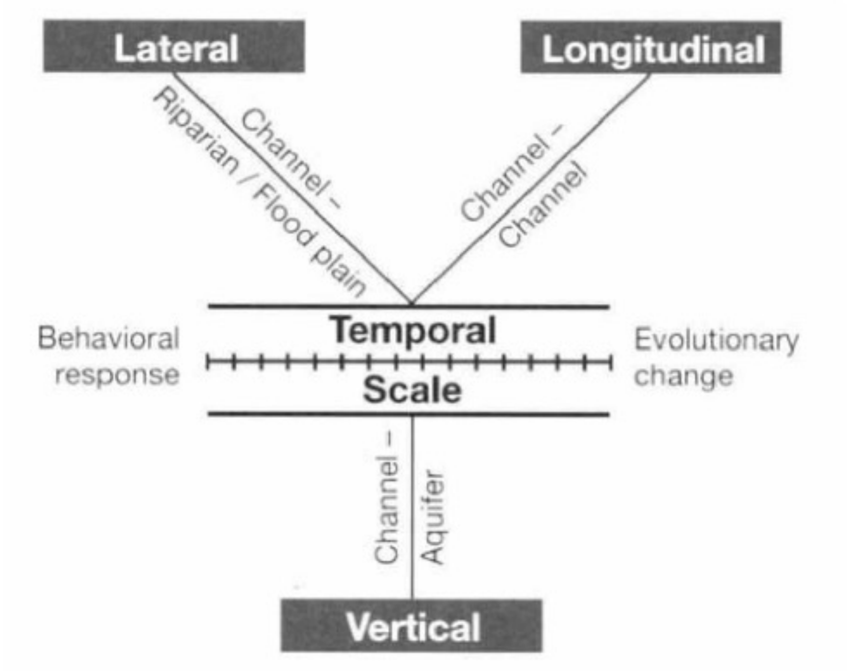
Why would changes in width, area and depth matter?



- Connectivity with terrestrial environmentand terrestrial subsidies
- Flow regime
- Sediment composition and hydraulics
- Gas exchange
- Energetics and biology
- Land use

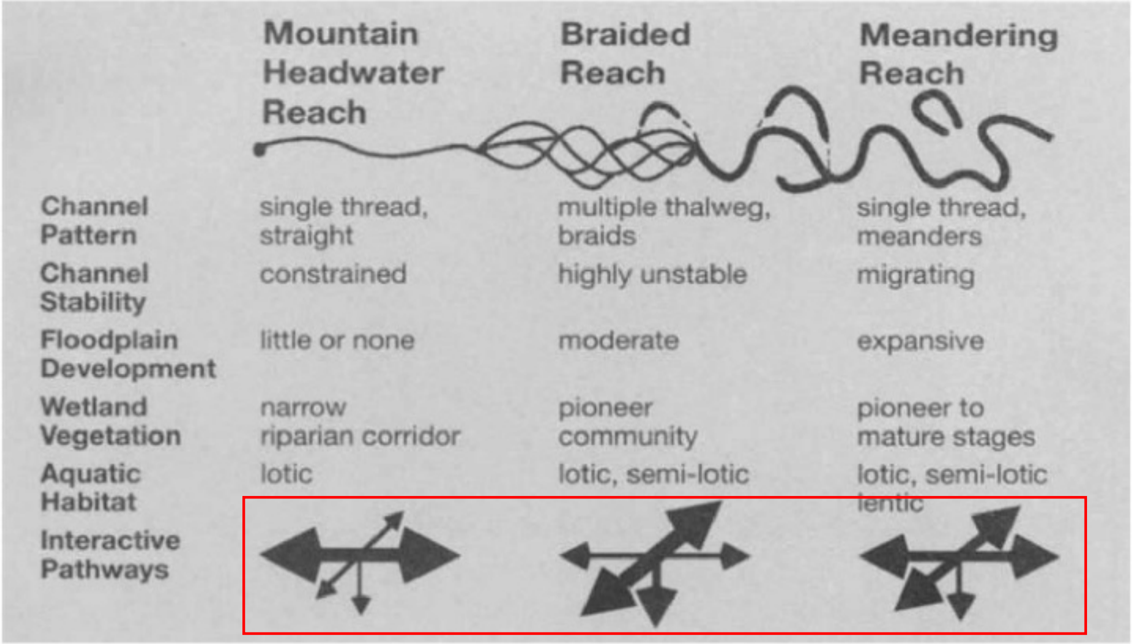
Downstream change of river dimensions

The four-dimensional nature of stream and river ecosystems



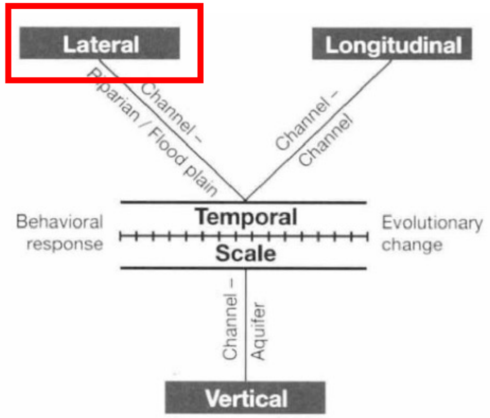
An Expansive Perspective of Riverine Landscapes: Pattern and Process Across Scales

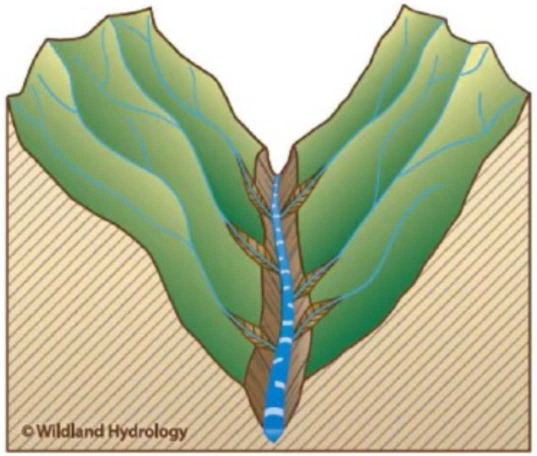
James V. Ward*

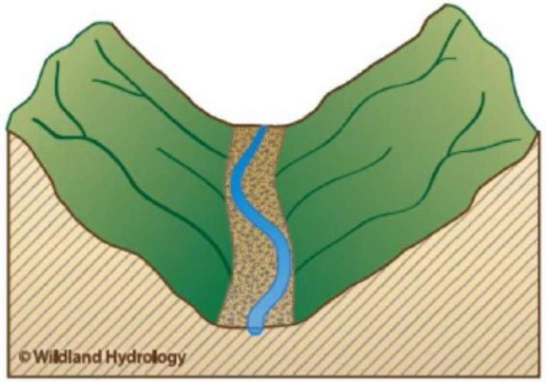


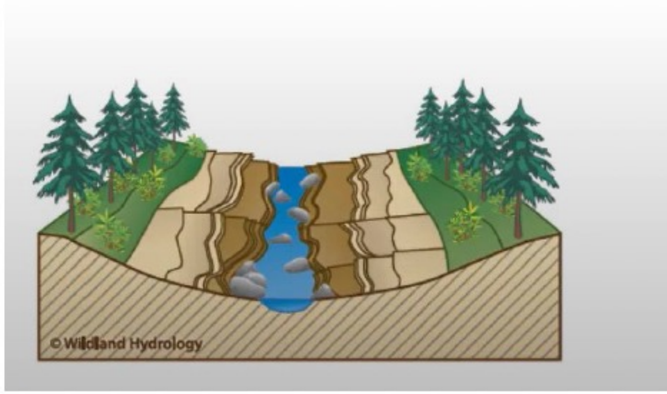
The four-dimensional nature of stream and river ecosystems

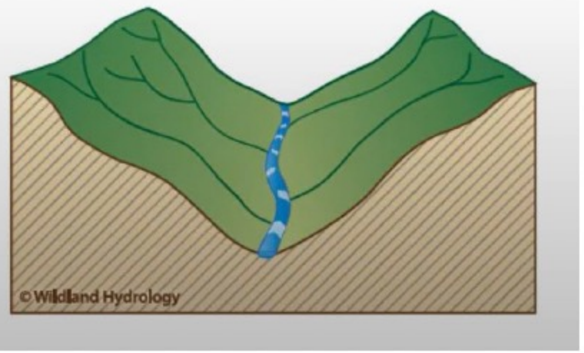
- Lateral







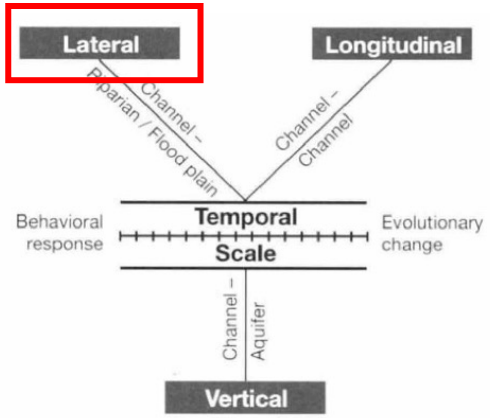


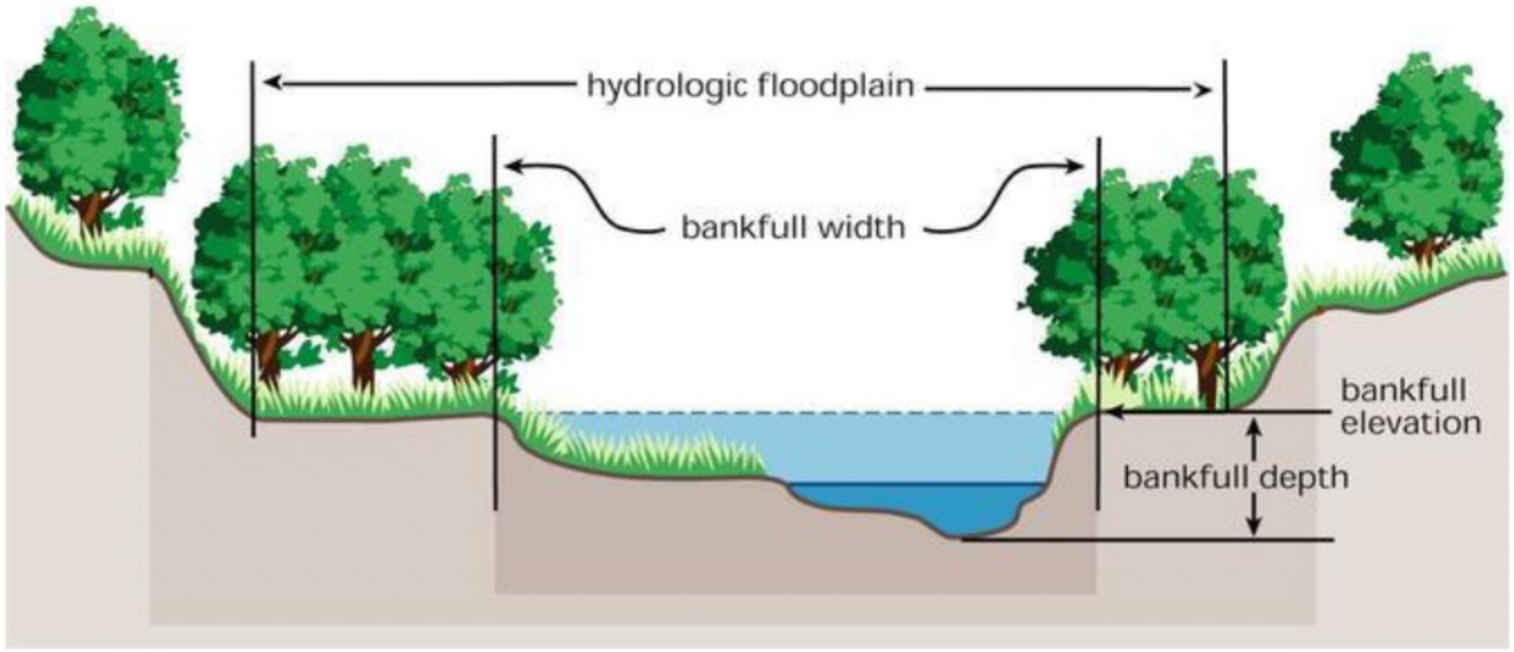


- Geology (e.g., erodibility) and related geomorphology (e.g., slope)are first-order controls on the lateral dimension
- Land use as well

The four-dimensional nature of stream and river ecosystems

- Lateral

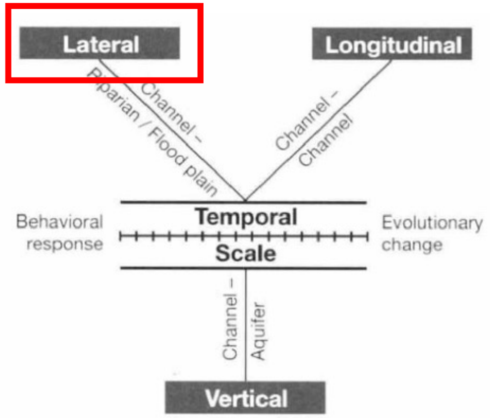


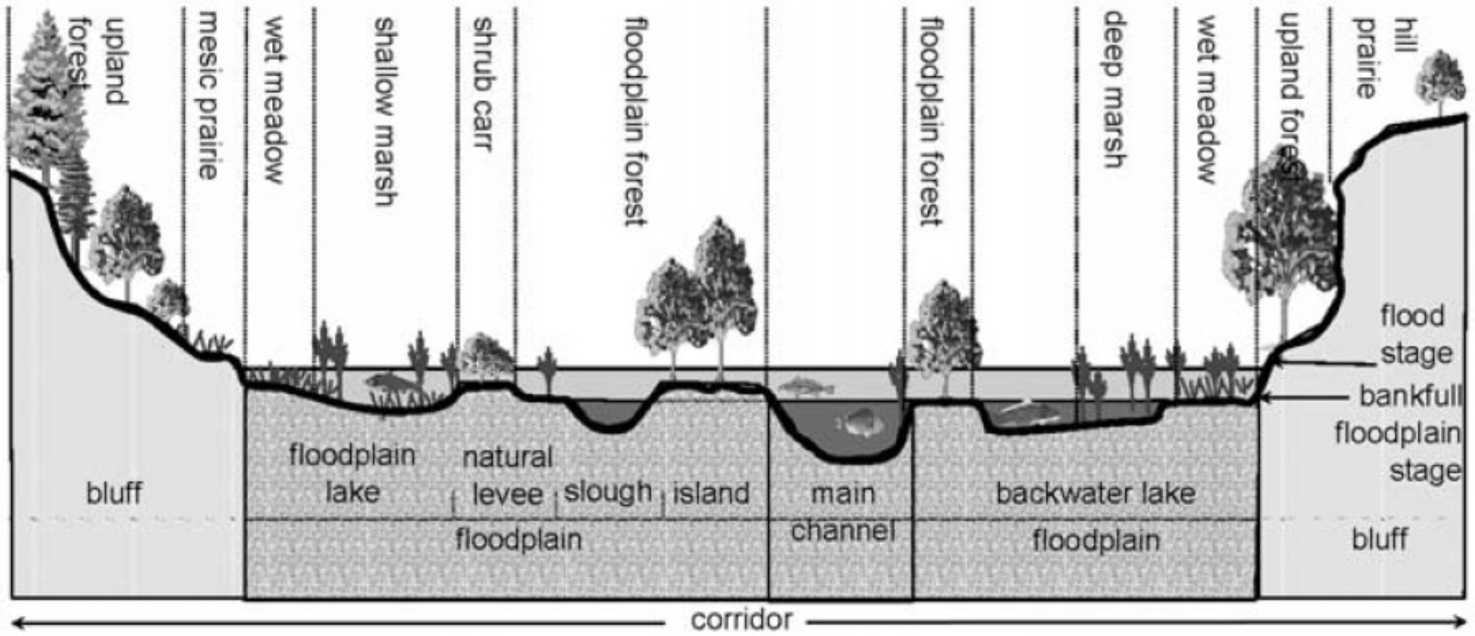


- Active channel within ‘bankfull width’
- Floodplain beyond ‘bankfull width’
- Innundation: over-topping of banks

The four-dimensional nature of stream and river ecosystems

- Lateral





RIPARIAN ECOTONE: A FUNCTIONAL DEFINITION AND DELINEATION FOR RESOURCE ASSESSMENT

E. S. VERRY [1]*, C. A. DOLLOFF [2] and M. E. MANNING [3]

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[2] USDA Forest Service, Southern Research Station, Blacksburg, VA, U.S.A.;
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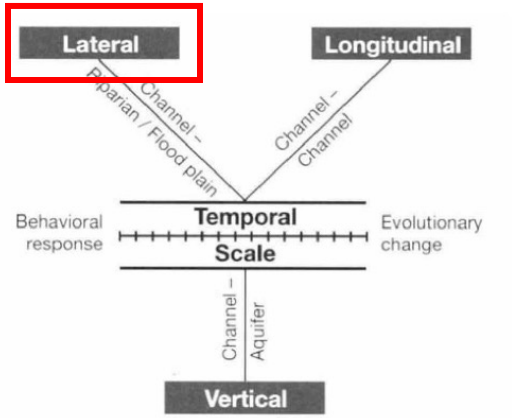
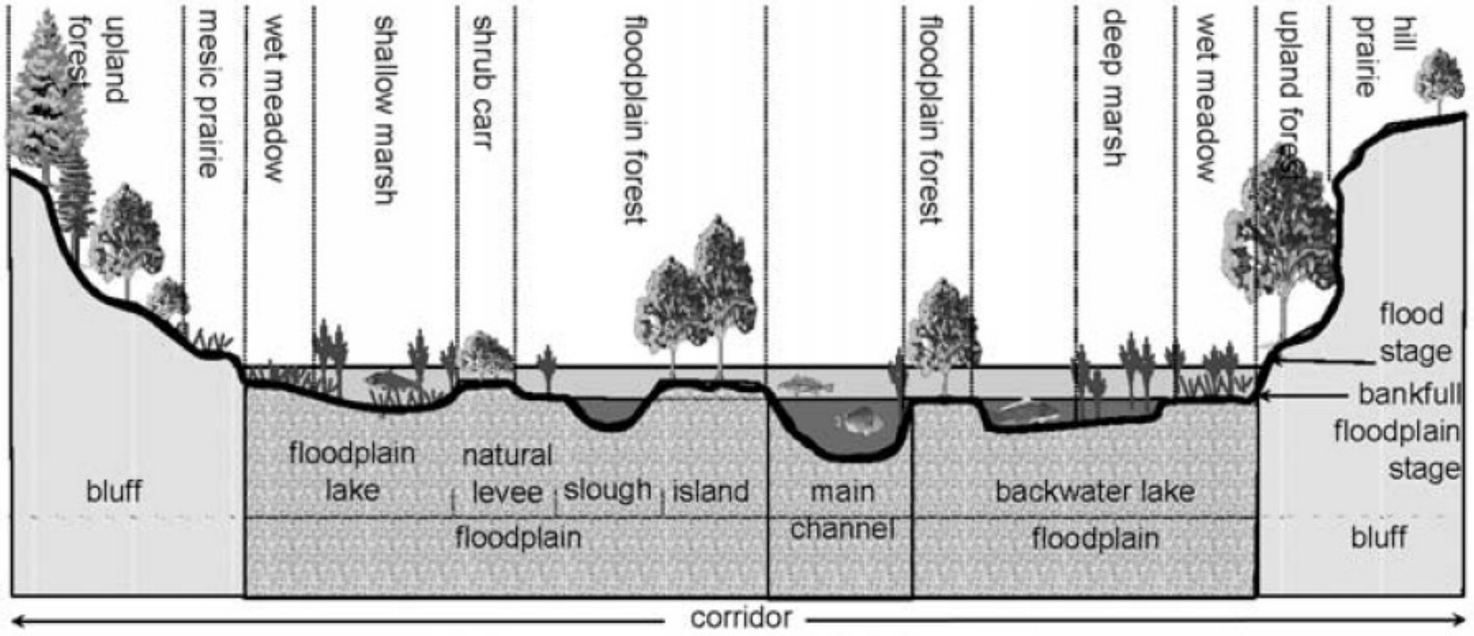
(author for correspondence, e-mail: sverry@fs.fed.us; fax: 218 326 7123)*

- The river corridor
- Riparian zone: stabilisation of banks, filtration, shade and thermal regime, energy subsidies…
- An aquatic-terrestrial ecotone (ecological transition zone promoting biodiversity)

The four-dimensional nature of stream and river ecosystems

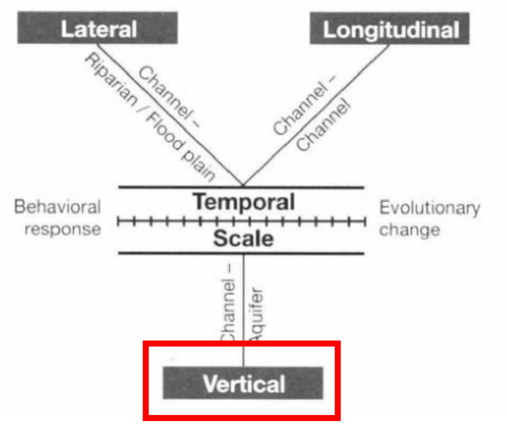
- Lateral



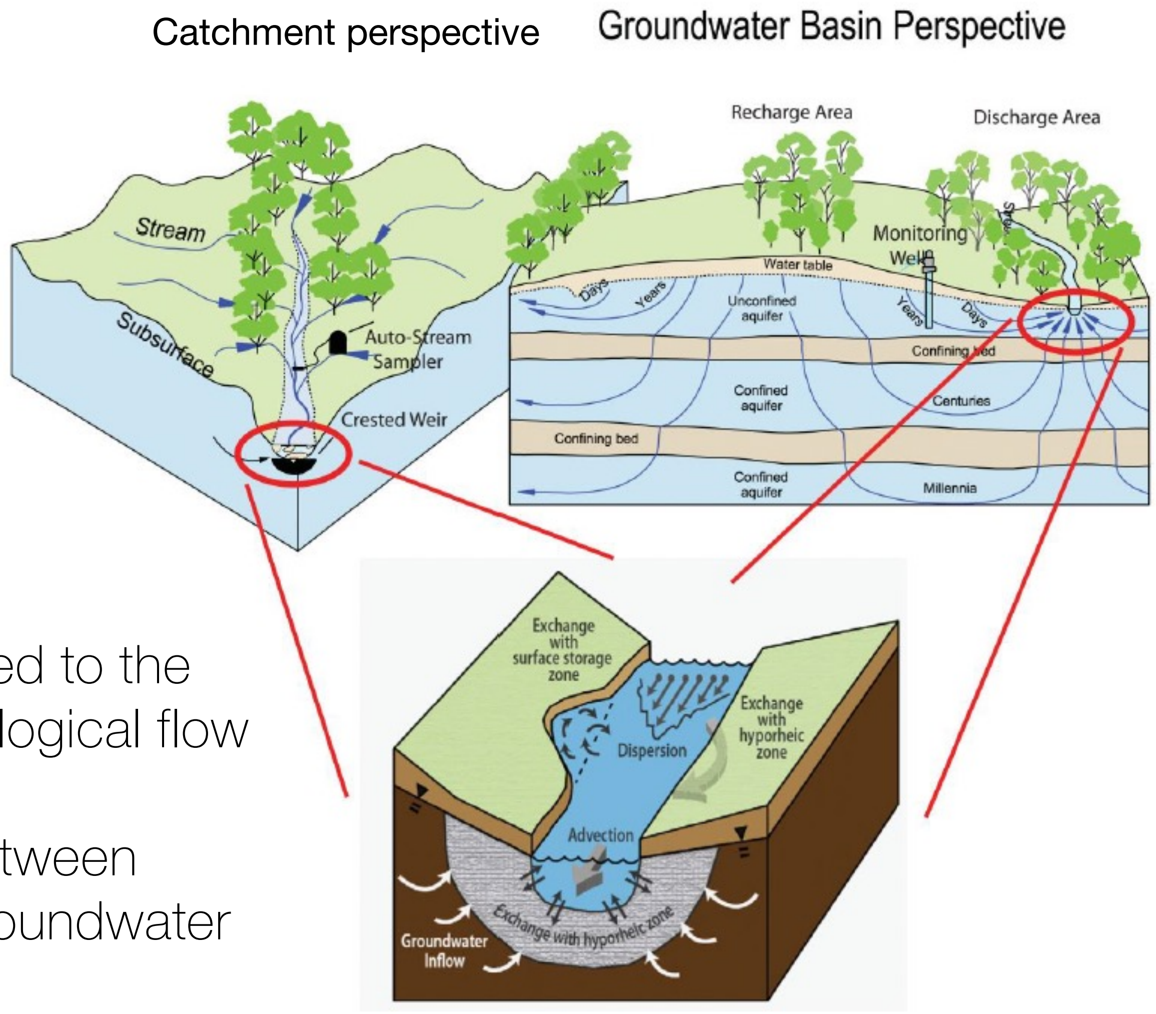


The four-dimensional nature of stream and river ecosystems

- Vertical



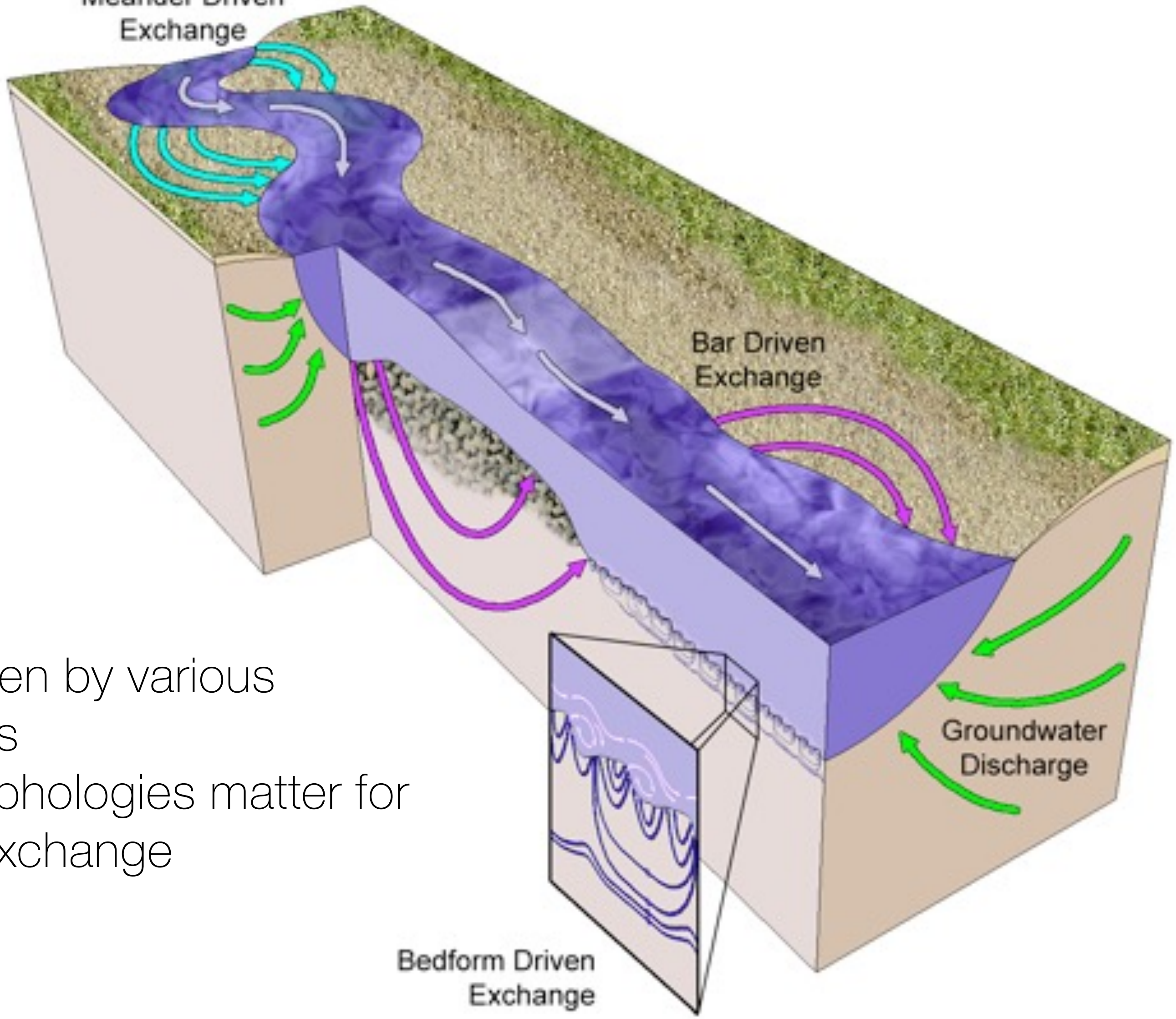
Catchment perspective

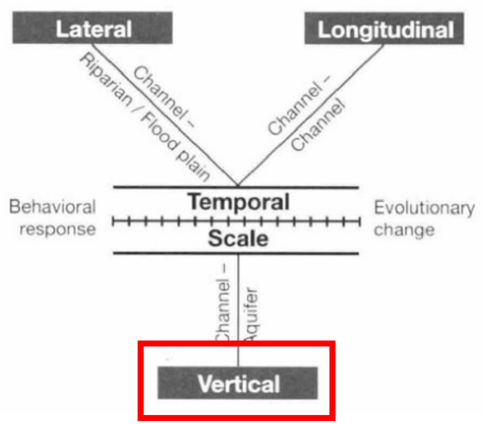


- Streams and rivers connected to the catchment via vertical hydrological flow paths
- Hydrodynamic exchange between surface water and parent groundwater through the hyporheic zone

The four-dimensional nature of stream and river ecosystems

- Vertical

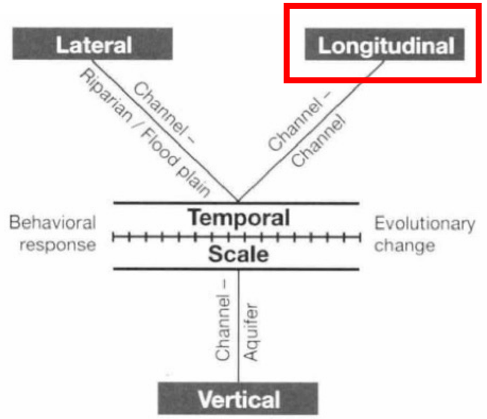


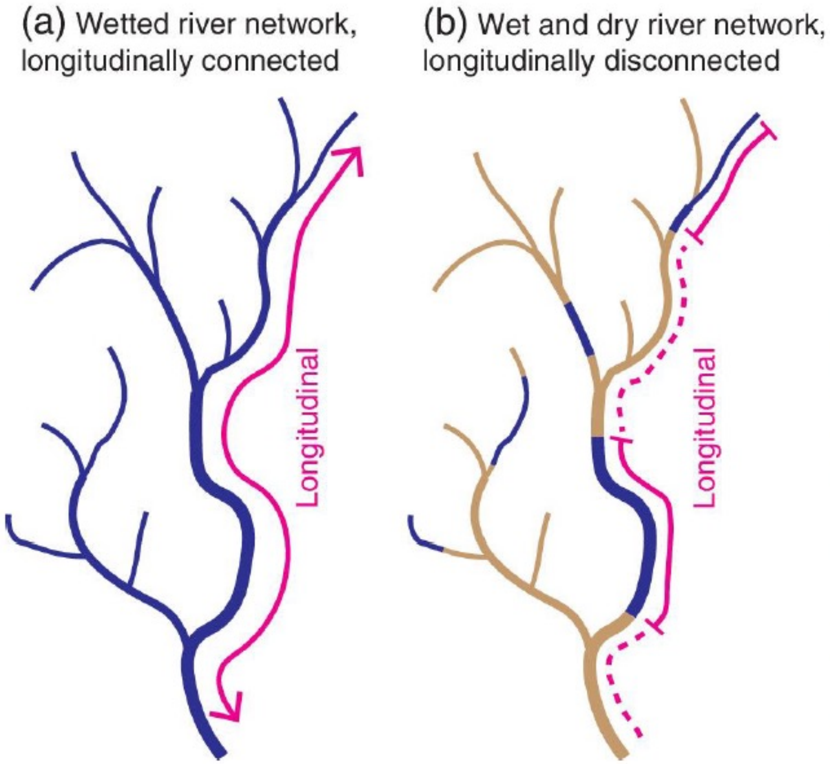


- Vertical flow driven by various bedform features
- Diverse geomorphologies matter for hydrodynamic exchange

The four-dimensional nature of stream and river ecosystems

- Longitudinal



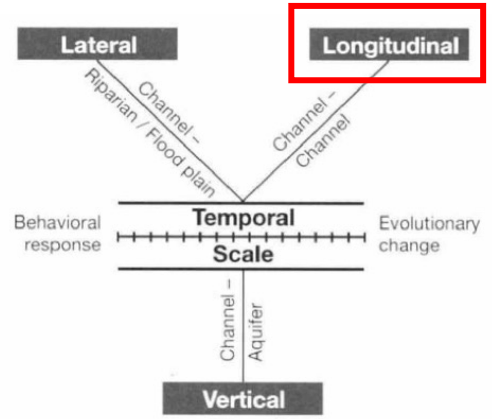


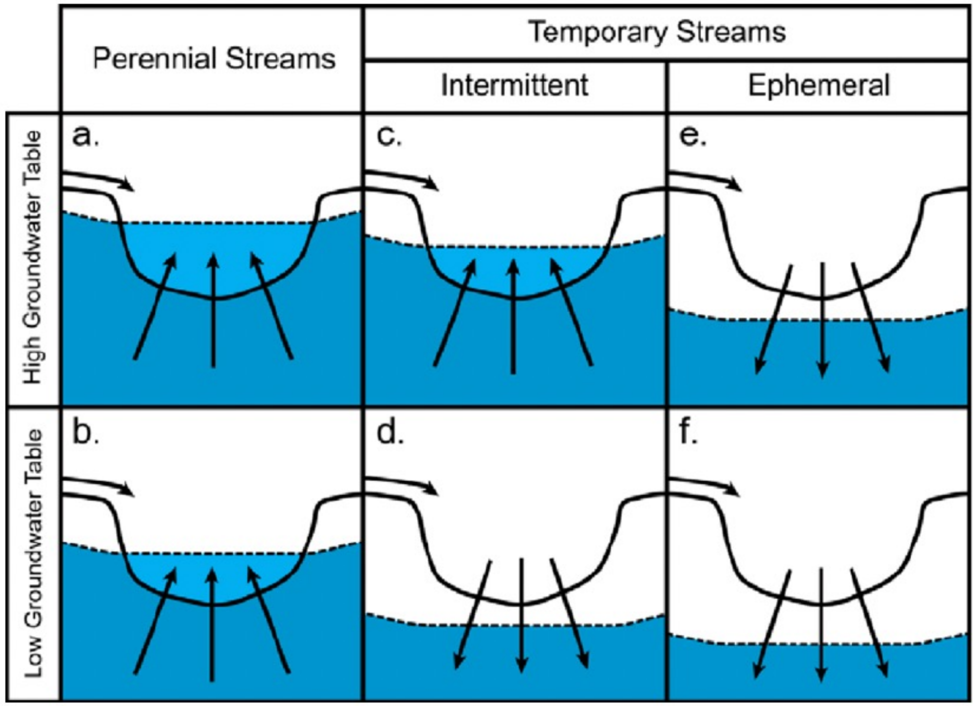


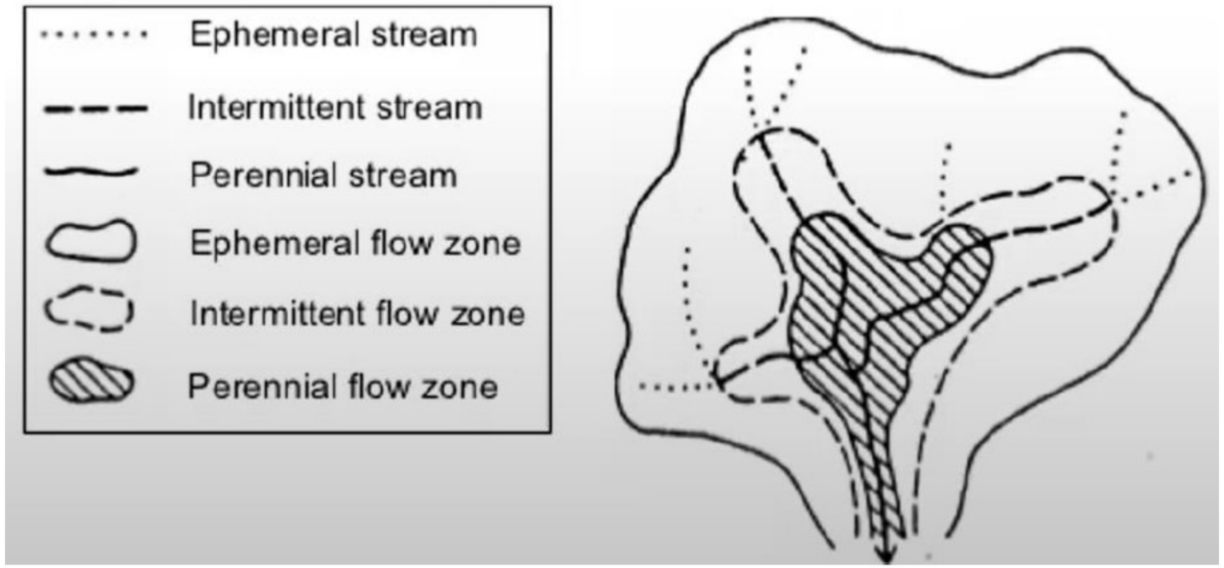
- The longitudinal distribution of flow
- Discharge increases downstream as the size of the drainage basin increases
- Flow is continuous or interrupted

The four-dimensional nature of stream and river ecosystems

- Longitudinal



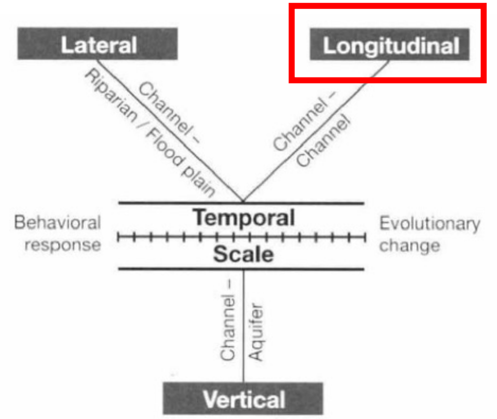




- Perennial: always flowing — gaining streams
- Intermittent: seasonally flowing — gaining and losing streams
- Epheremal: randomly flowing (after rain, snow melt) — losing streams

The four-dimensional nature of stream and river ecosystems

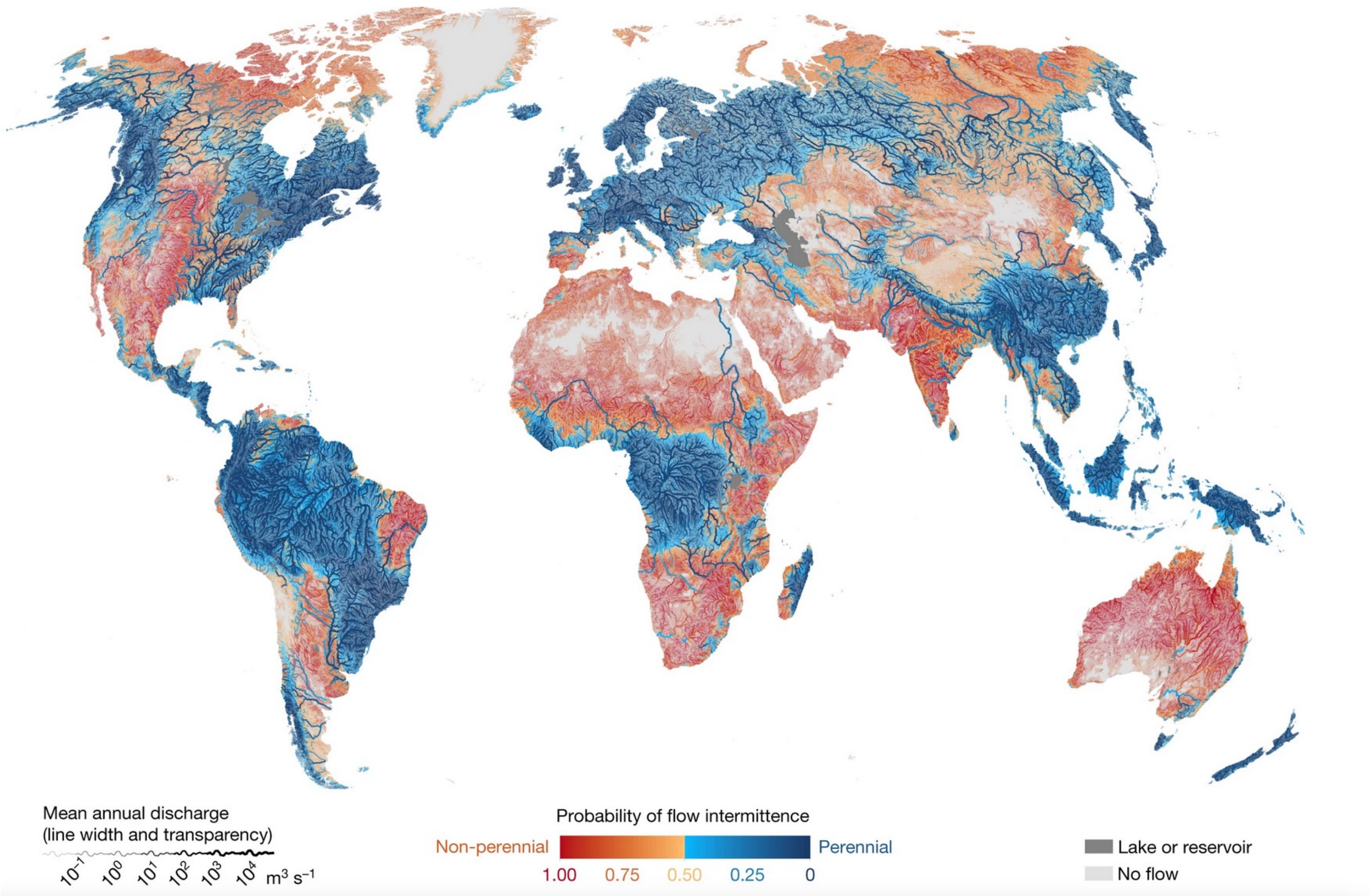
- Longitudinal



Article

Global prevalence of non-perennial rivers and streams

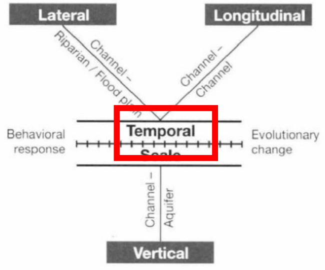
Mathis Loïc Messager[1,2], Bernhard Lehner[1], Charlotte Cockburn[1,7], Nicolas Lamouroux[2], Hervé Pella[2], Ton Snelder[3], Klement Tockner[4,5], Tim Trautmann[6], Caitlin Watt[1,8] & Thibault Datry[2]



Water ceases to flow for at least one day per year along 51–60 per cent of the world's rivers by length, demonstrating that non-perennial rivers and streams are the rule rather than the exception on Earth

The four-dimensional nature of stream and river ecosystems

- Temporal- River network contraction and expansion

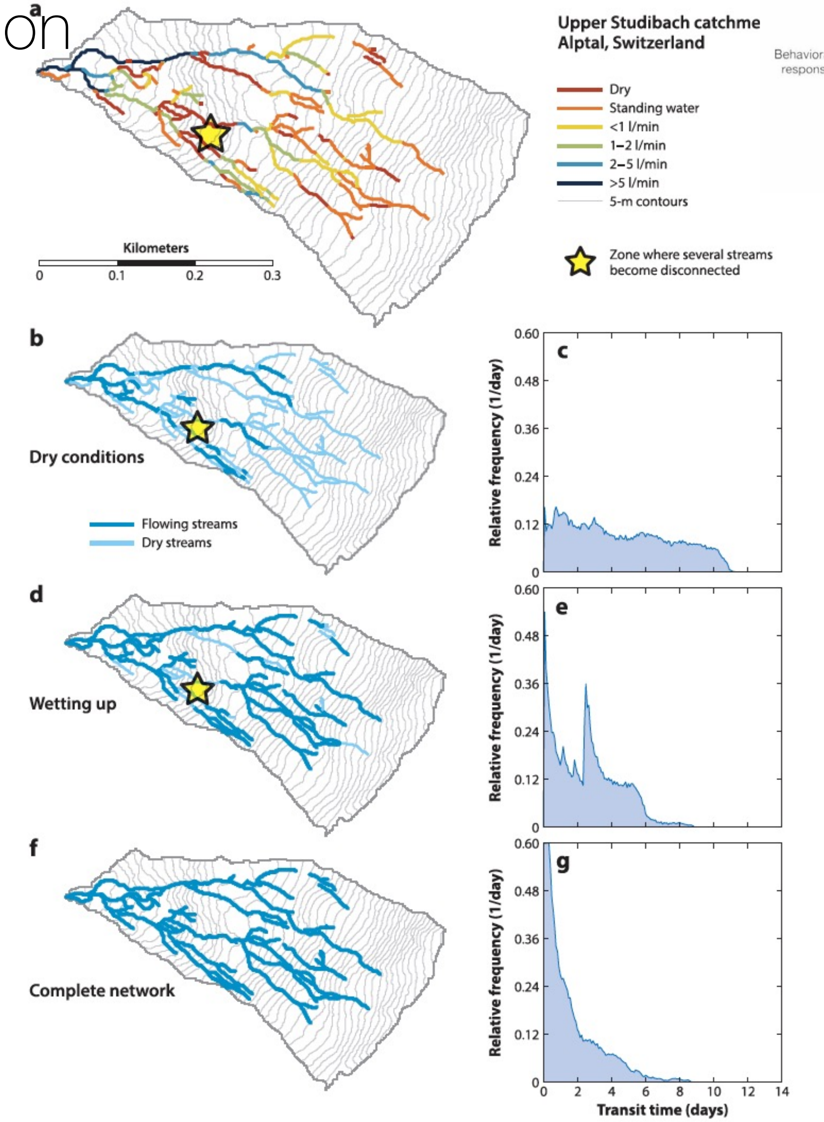


- Stream networks dynamically extend and retract, and connect and disconnect, both seasonally and during storm events, as the landscape wets up and dries out

- As the flowing stream network expands, it comes closer to each point on the landscape. This accelerates the runoff response at the catchment scale because hydraulic signals propagate faster along flowing channels than through hillslope soils or bedrock

- Expansion of the stream network shortens the average transit time and changes its distribution

- The onset of flow in previously dry or disconnected stream sections can flush out sediment and organic matter, leading to high sediment and nutrient fluxes to downstream reaches



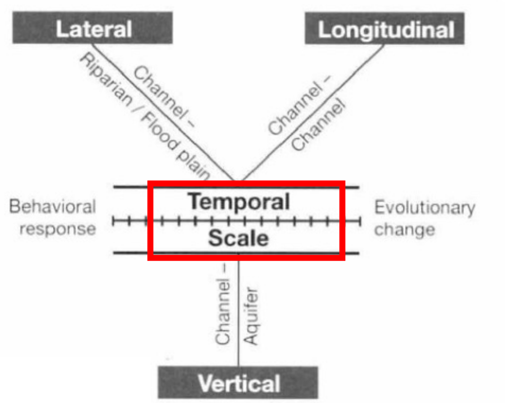
Network contraction and disconnection in the Upper Studibach catchment, Alptal, Switzerland. (*a*) Map of flow states and estimated flow rates on November 2, 2016, highlighting the variability in flows across the stream network, including gaining and losing reaches, as well as the dry sections that cause disconnections. Data collected by Rick Assendelft. (*b*–*g*) Maps of the flowing stream network (*dark blue*) during contrasting wetness conditions (*left panels*), and calculated transit time distributions (*right panels*) assuming a subsurface velocity through the soil of 5×10^{-4} m s^{-1} and a surface velocity in the stream of 0.5 m s^{-1}. As the flowing stream network expands, the distances to the stream become shorter, resulting in a shorter transit time and a less uniform transit time distribution because many more points in the landscape are now close to a flowing stream. Figure adapted from van Meerveld et al. (2019) (CC BY 4.0).

Annual Review of Earth and Planetary Sciences
Instructive Surprises in the Hydrological Functioning of Landscapes

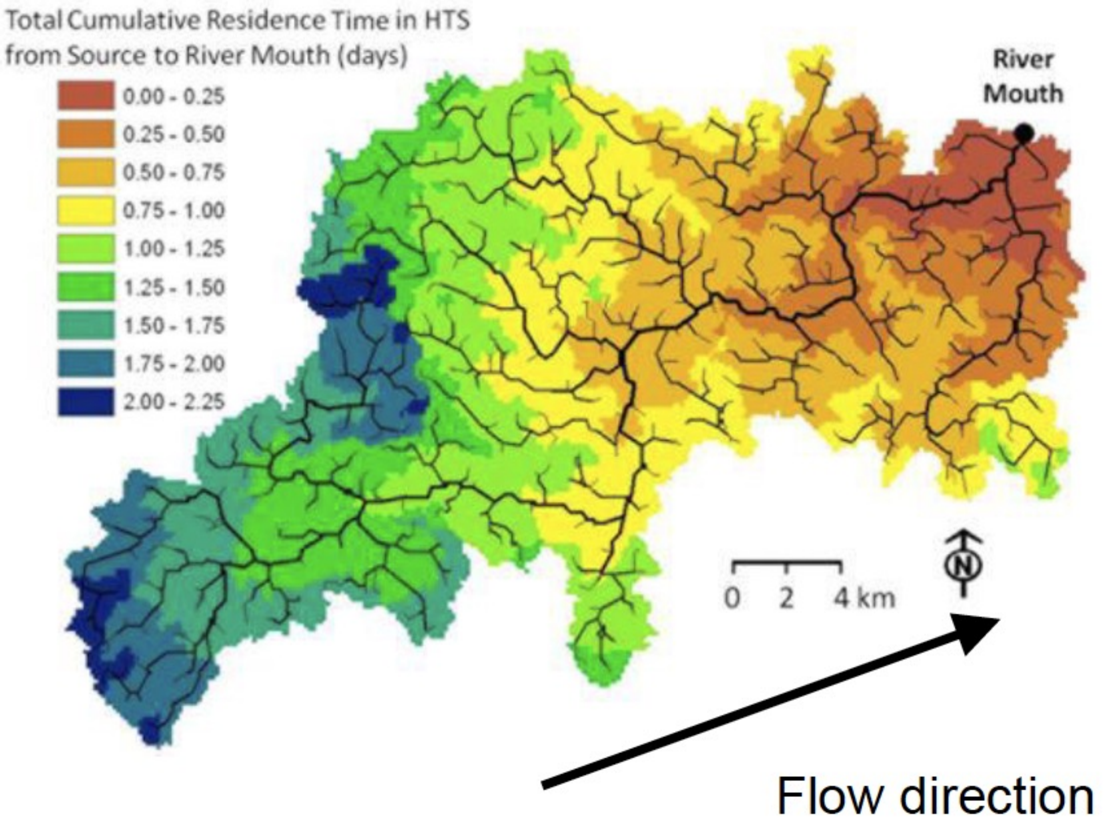
James W. Kirchner,[1,2,3] Paolo Benettin,[4] and Ilja van Meerveld[5]

The four-dimensional nature of stream and river ecosystems

- Temporal — Residence times

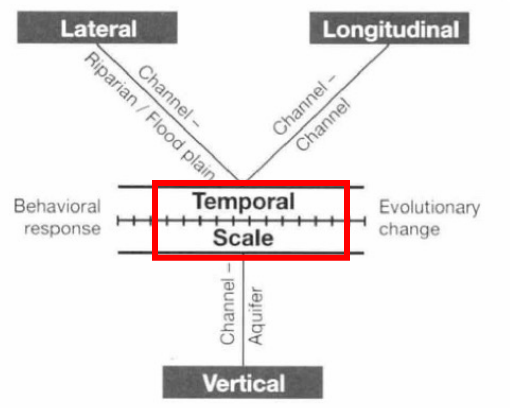


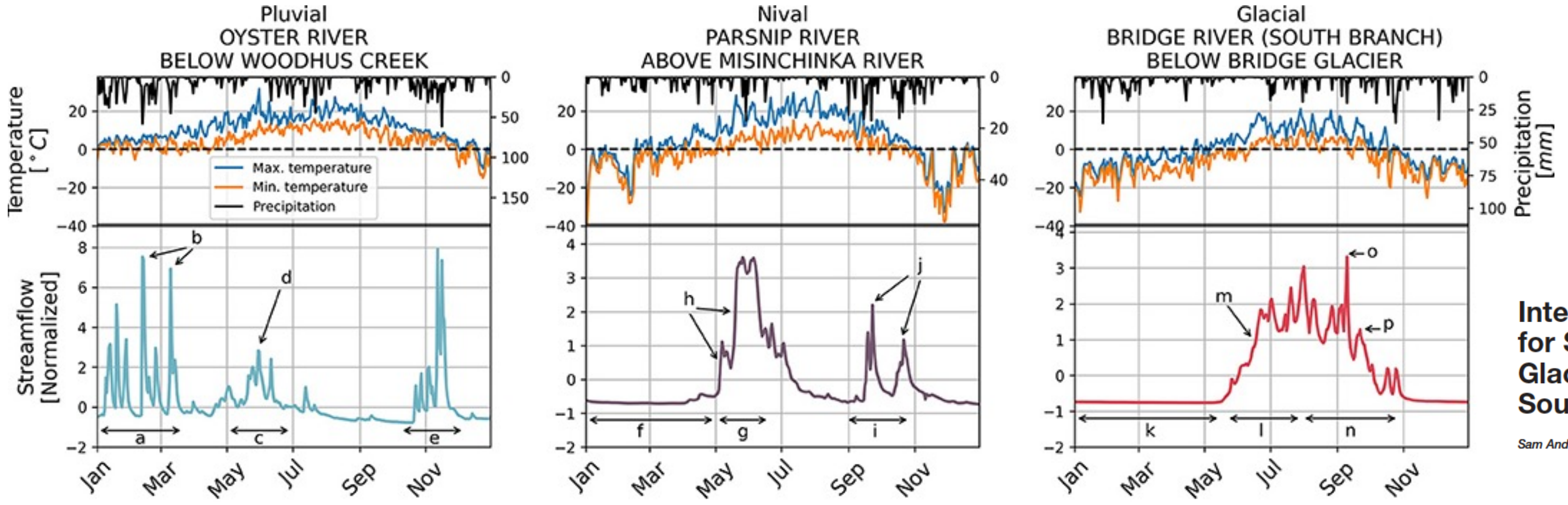
- Residence times of water decrease downstream
- Linked to hydrodynamic exchange
- Consequences for ecosystem processes and biogeochemistry



The four-dimensional nature of stream and river ecosystems

- Temporal — Flow regimes





Interpreting Deep Machine Learning for Streamflow Modeling Across Glacial, Nival, and Pluvial Regimes in Southwestern Canada

Sam Anderson and Valentina Radić*

Despite similar climate (precipitation and temperature) streams exhibit different flow regimes

- Pluvial
- Nival
- Glacial

Flow regimes differ in inter-annual predictability, which is important for system phenology

The four-dimensional nature of stream and river ecosystems

- Temporal — Flow regimes

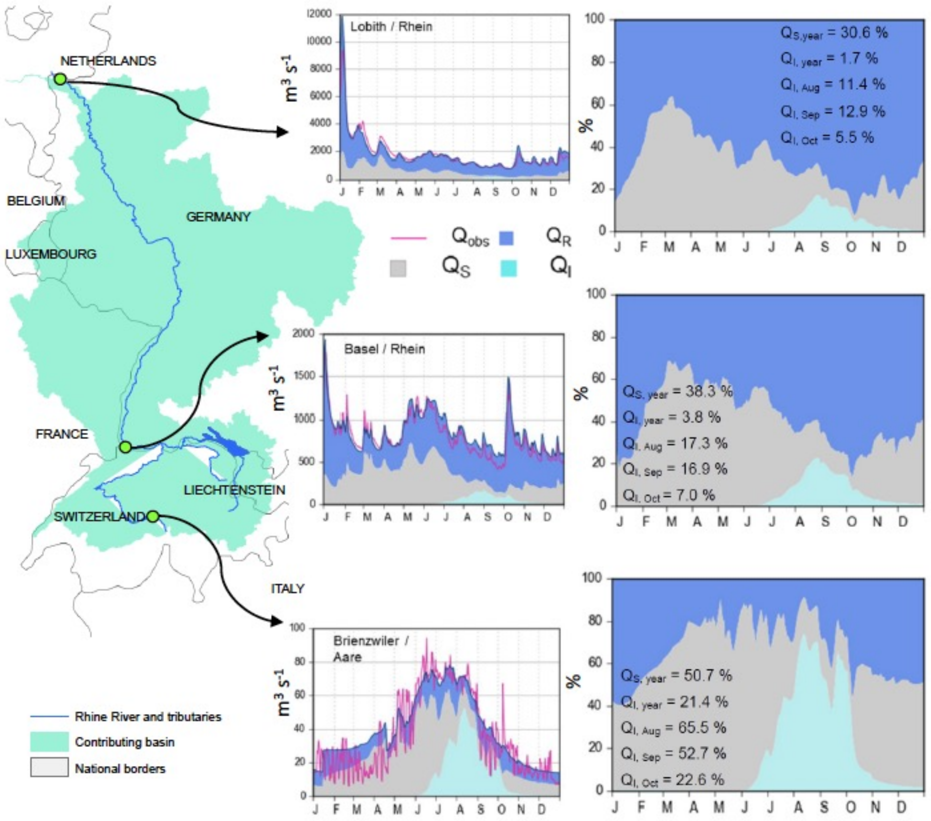
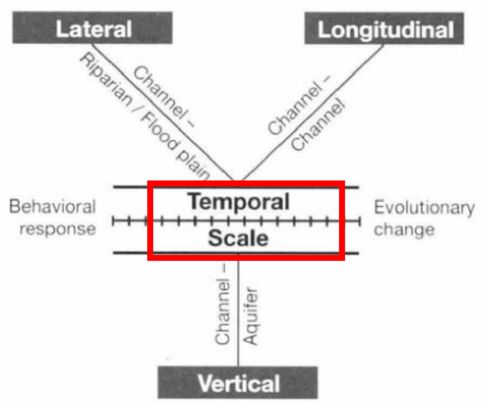


Figure 2.2: The role of ice melt along the Rhine River during drought conditions according to the CHR project. Absolute and relative estimated contributions of rain, snowmelt and ice melt to runoff are presented at the locations of Brienzwiler, Basel and Lobith in year 2003. Q_{obs}: Observed discharge, Q_R: Rain component, Q_S: Snow component, Q_I: Ice component. Adapted from Stahl et al. (2017).



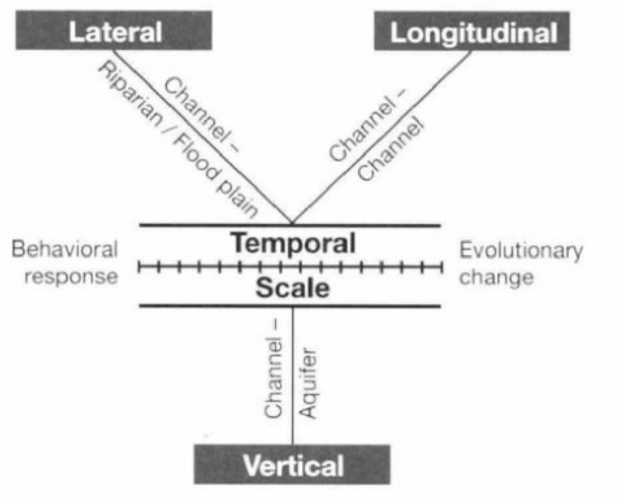
- Different annual flow regimes
- Contributions from rain, snowmelt and glacier ice
- Relative importance from these contributions changes downstream

Glaciers

HYDRO-CH2018 SYNTHESIS REPORT CHAPTERS: "FUTURE CHANGES IN HYDROLOGY"

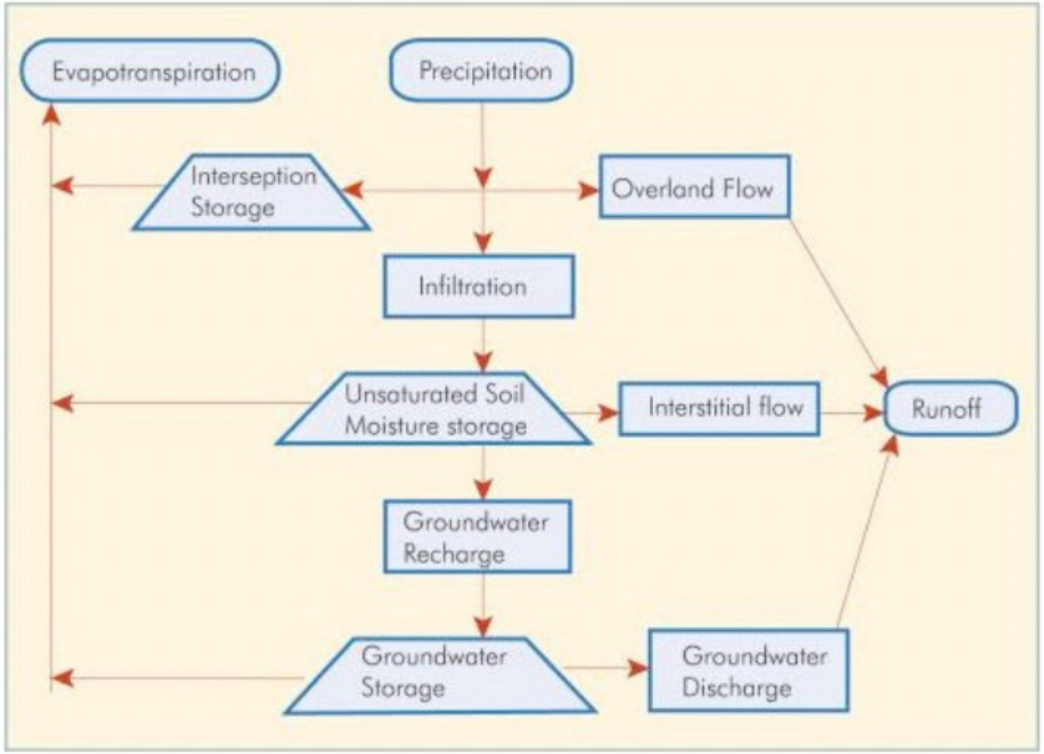
A. AYALA, D.FARINOTTI, M. STOFFEL, AND M. HUSS

EPFL



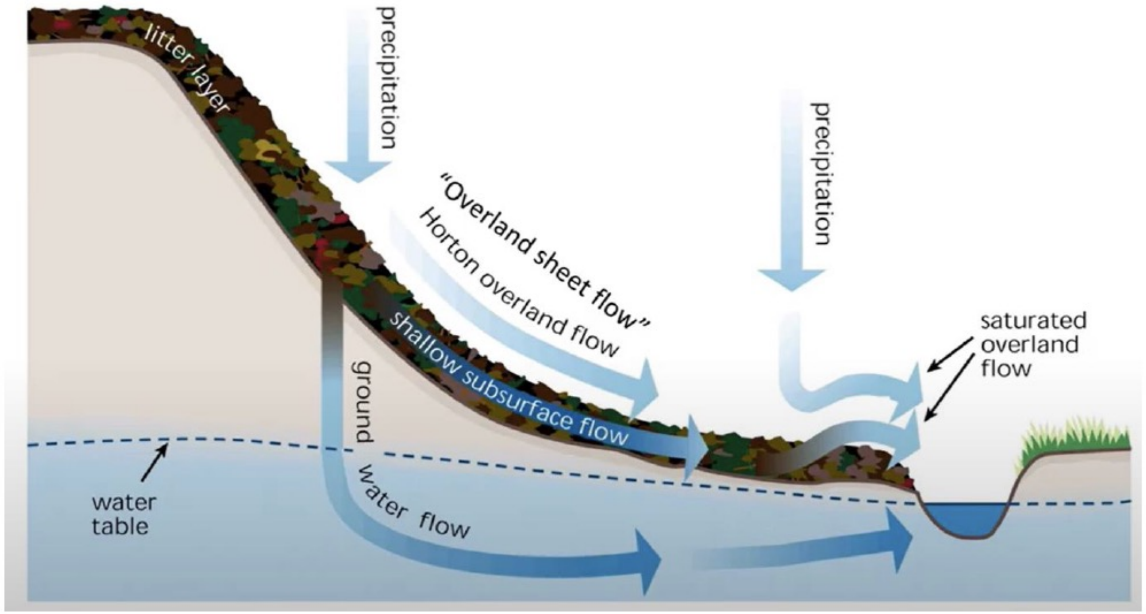
- Runoff generation
- Flow regimes
- Consequences for ecosystem functioning

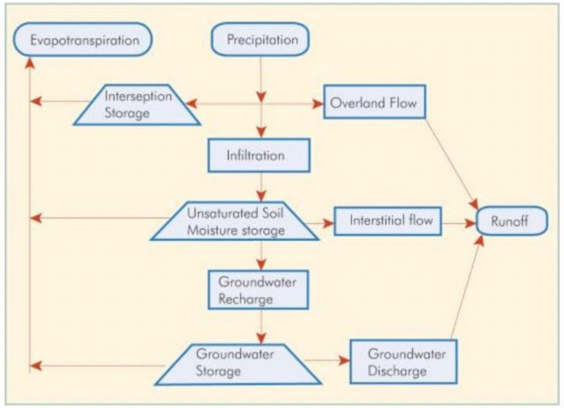
How is runoff produced and what are (some of) its consequences?



- Precipitation: Input into the catchment
- Runoff & evapotranspiration: Outputs from the catchment
- Overland and interstitial flow, as well as groundwater discharge affect runoff dynamics at short scales (compared to annual flow regimes)
- Contributions of each depend on precipitation events, geology, vegetation cover, soil texture, slope, land use etc

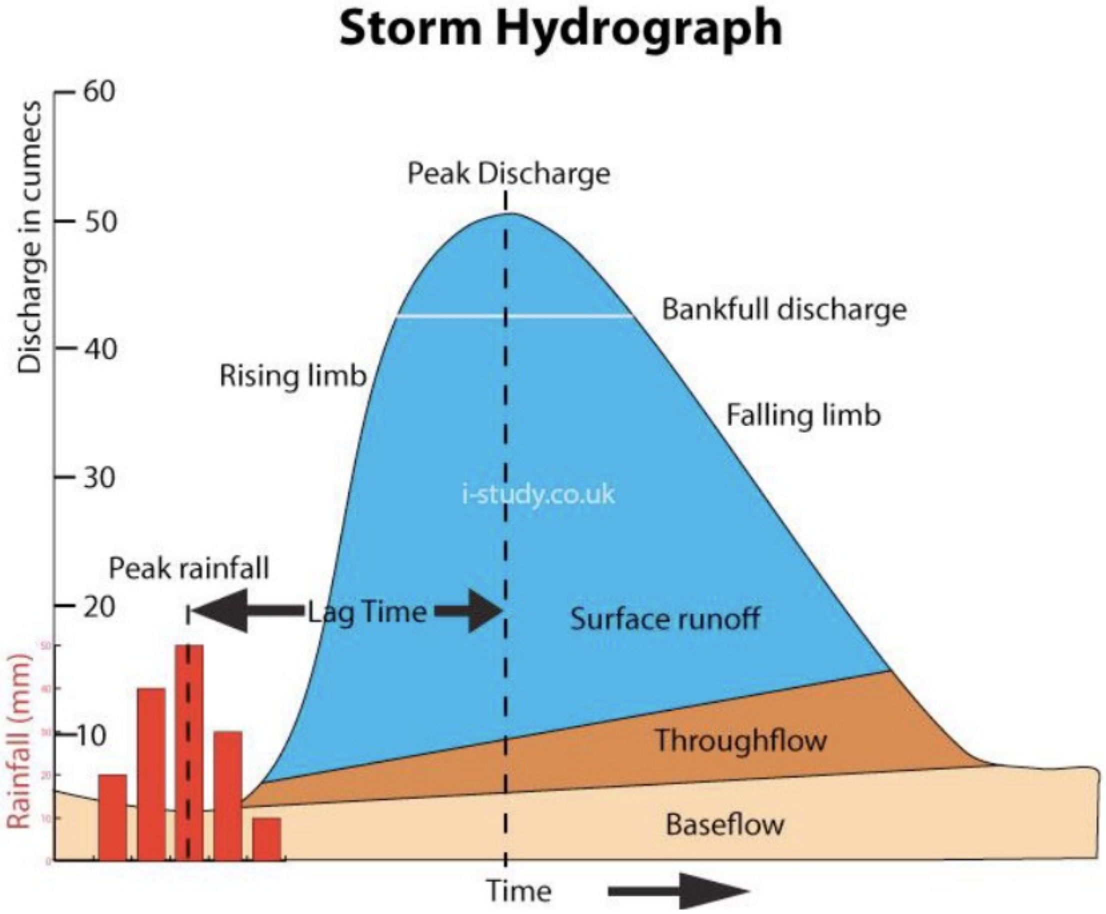
How does runoff generate and what are (some of) its consequences?

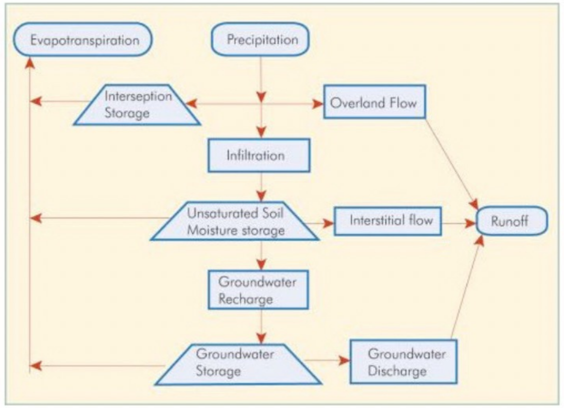




- Different flow paths mobilize different waters (e.g., age, chemistry, temperature)
- Organic matter, nutrients, contaminants etc

How does runoff generate and what are (some of) its consequences?

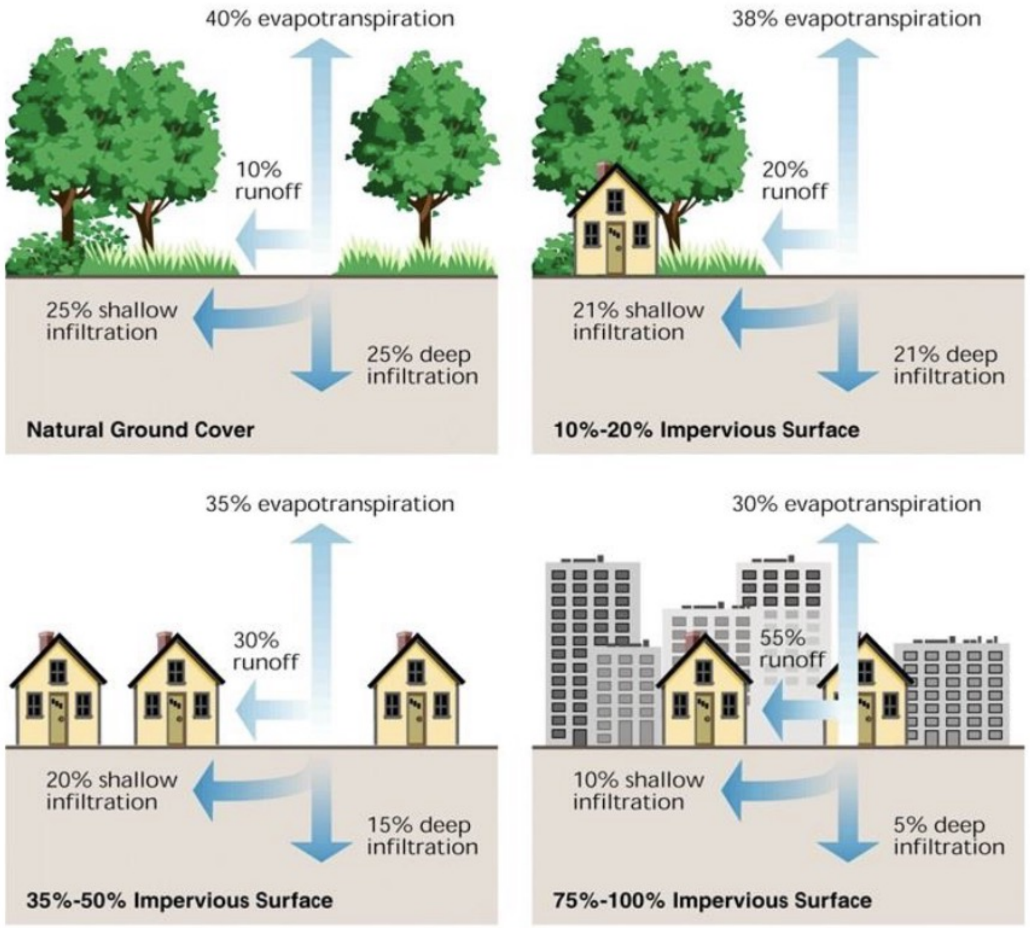


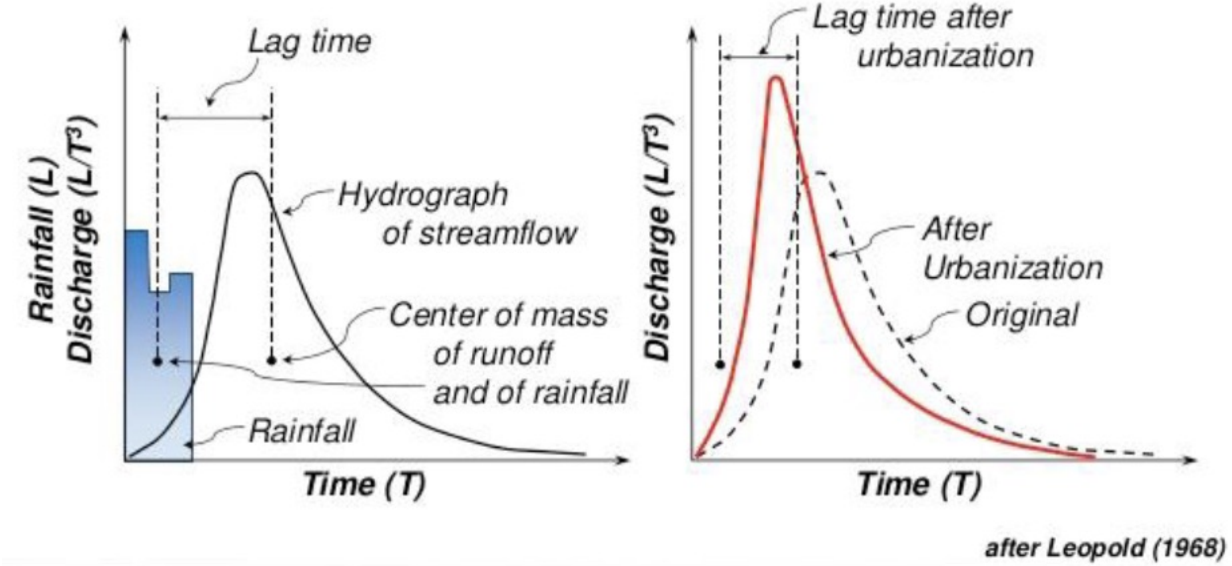


Hydrograph separation

- Baseflow (from groundwater)
- Throughflow (interstitial flow)
- Surface runoff (overland flow)

How does runoff generate and what are (some of) its consequences?





- Elevated impermeabilisation increases runoff
- Reduces lag time between peak precipitation and peak discharge
- Augments peak discharge

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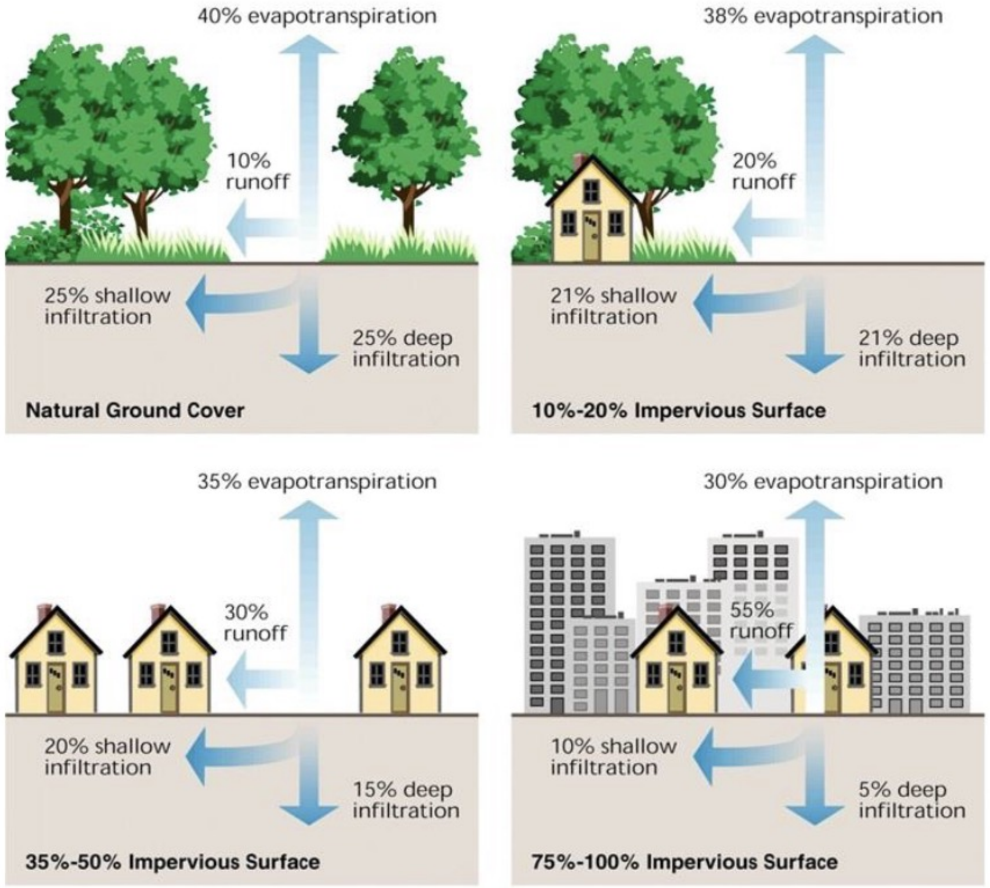
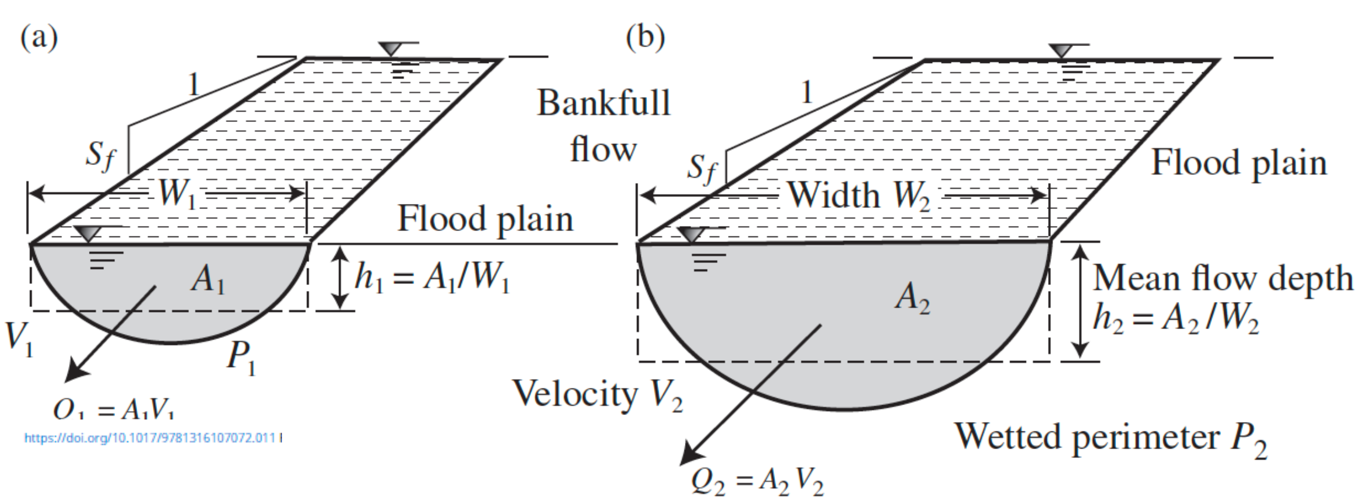
Innundation in central and eastern Europe



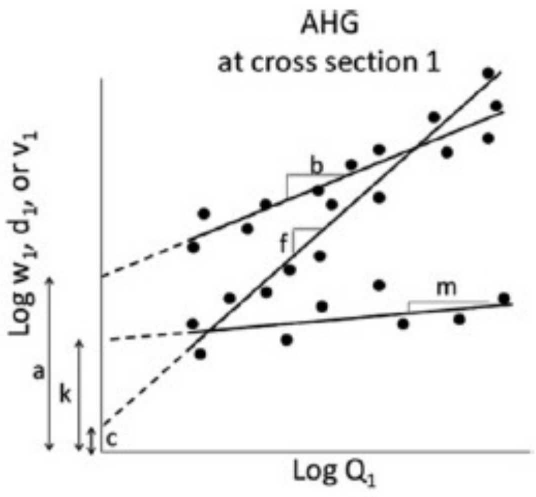
Catchment impermeabilisation, hydrological response curves and reduced residence times

What about river channelization (straightening and deepening channels)?

Hydraulic geometry



https://doi.org/10.1017/9781316107072.011



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 indicate rate of increase of w, d and v with increasing Q

Continuity equation, $Q = wdv$,

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

$$Q = ack\,Q^{b+f+m}$$

the exponents are constrained to 1 (that is, $b+f+m = 1$)

The consequences of which are…..

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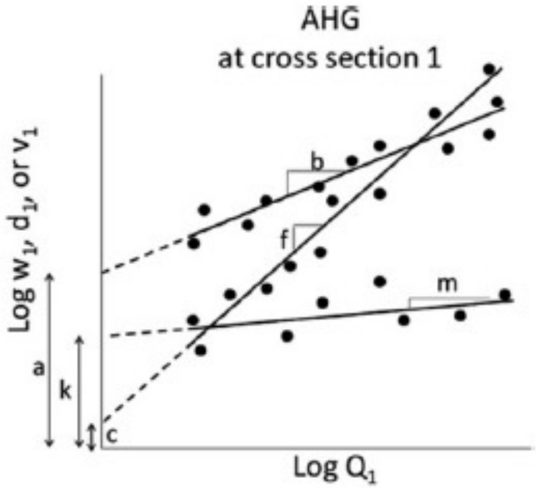
Hydraulic geometry

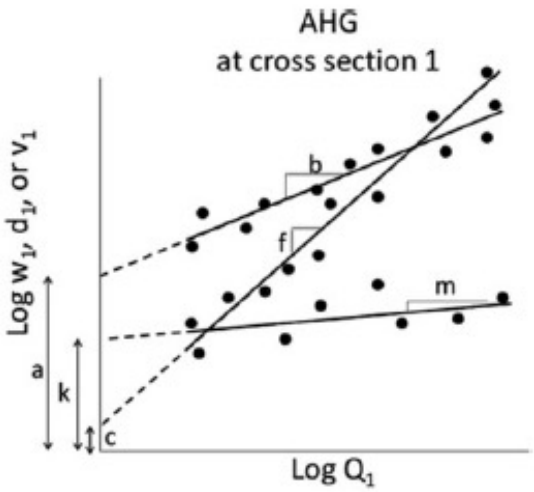


depth

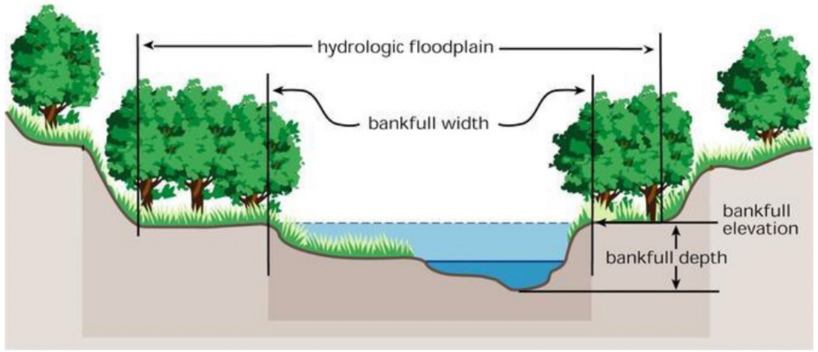
velocity

Elevated response in depth and velocity for channels that are constrained in width

Hydraulic geometry

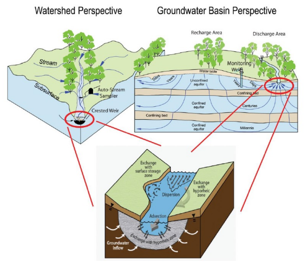


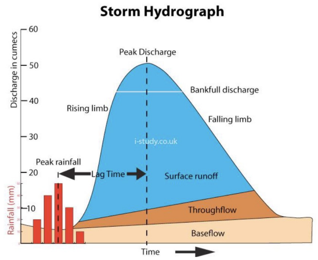
Elevated response in width — can lead to over-topping of the river banks — creating innundations



Hydrological flow paths, reconnecting our streams and rivers

Towards restoration and risk management





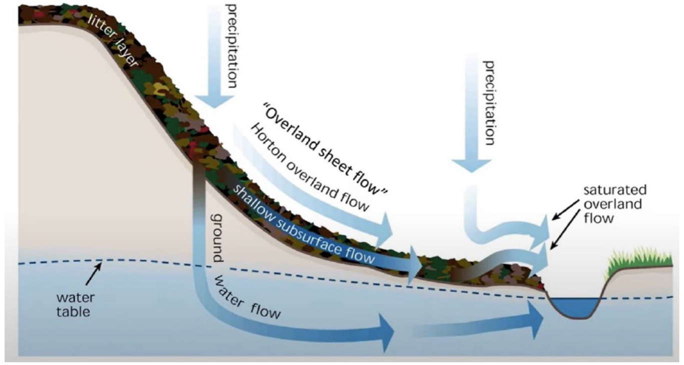
Areas next to rivers hold potential for cost-effective flood protection and improving the health of an entire river ecosystem. According to a European Environment Agency (EEA) briefing published today, restoring European floodplains closer to their natural state would contribute to the achievement of several European Union policies. Estimates suggest that 70-90 % of Europe's floodplain area is ecologically degraded.

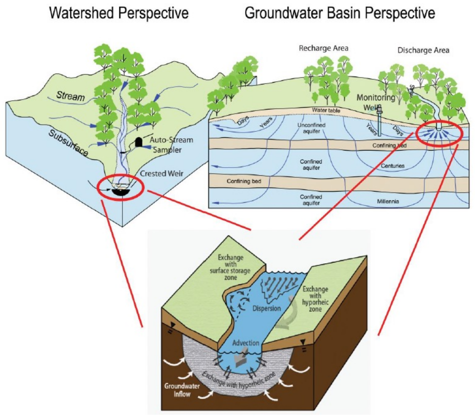
Published 19 Nov 2018 — Last modified 19 Nov 2018 — 1 min read — Photo: © Suleyman Uzumcu, WaterPIX /EEA PDF

News > Restoring floodplains would ...

The EEA briefing 'Why should we care about floodplains?' analyses the potential benefits of restoring natural areas next to rivers that are covered by water during floods. According to the analysis, these areas can deliver valuable cultural and ecosystem services, including a cost-effective alternative to structural flood protection.

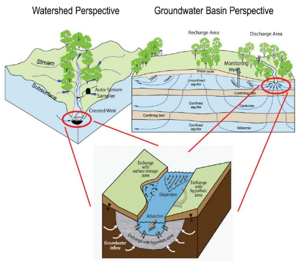
How do various flow paths of water through the landscape affect streamwater chemistry?

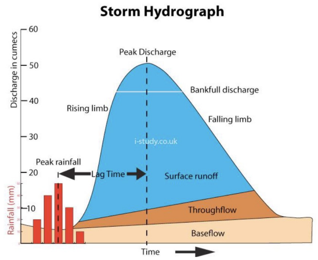


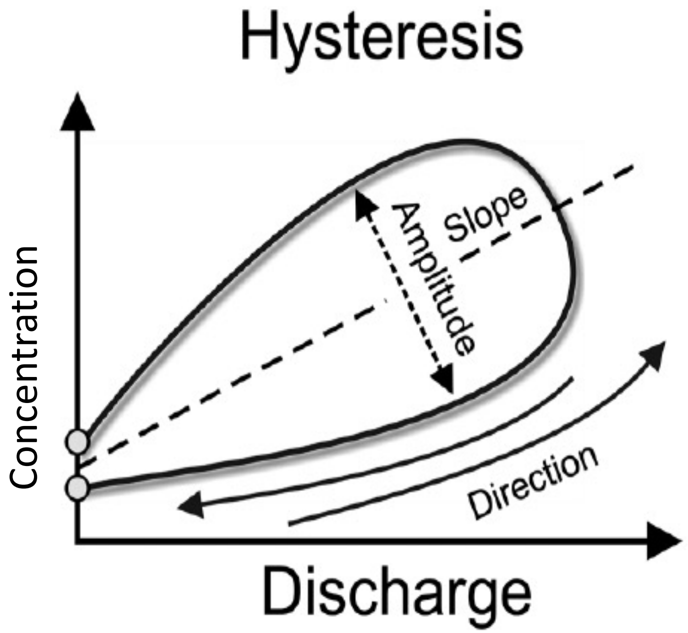


Hydrological flow paths and the chemical birth of water

Hysteresis loops







- The steeper the slope of the hysteresis loop (solid line), the higher the solute gradient between terrestrial solute source areas and the stream — that is high terrestrial inputs

- A clockwise direction of change over the course of the event indicates that solute sources are spatially connected to each other and proximal to the stream

- A counter-clockwise direction indicates solute sources are spatially disconnected from each other and distal from the stream

- The greater the loop amplitude, the greater the hydrological expansion into terrestrial solute sources

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Contents lists available at ScienceDirect

Journal of Hydrology

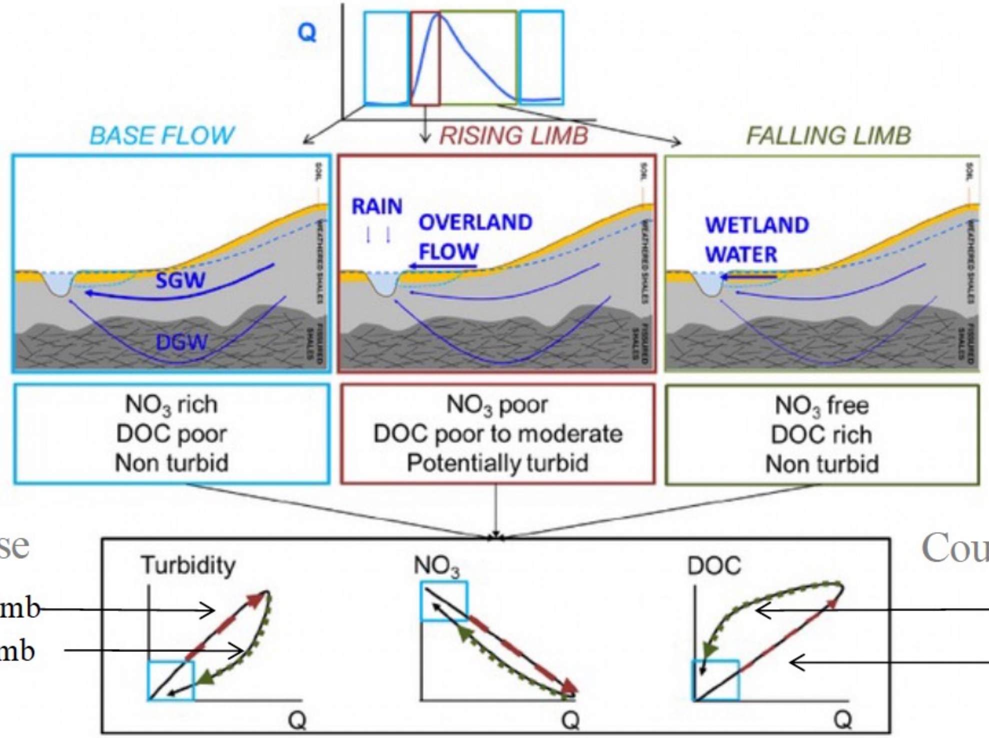
journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Seasonal variability of stream water quality response to storm events captured using high-frequency and multi-parameter data

O. Fovet [a,*], G. Humbert [a], R. Dupas [a], C. Gascuel-Odoux [a], G. Gruau [b], A. Jaffrezic [a], G. Thelusma [a], M. Faucheux [a], N. Gilliet [a], Y. Hamon [a], C. Grimaldi [a]

SGW: shallow groundwater
DGW: deep groundwater



Clockwise

Rising limb

Decreasing limb

Counterclockwise

Decreasing limb

Rising limb

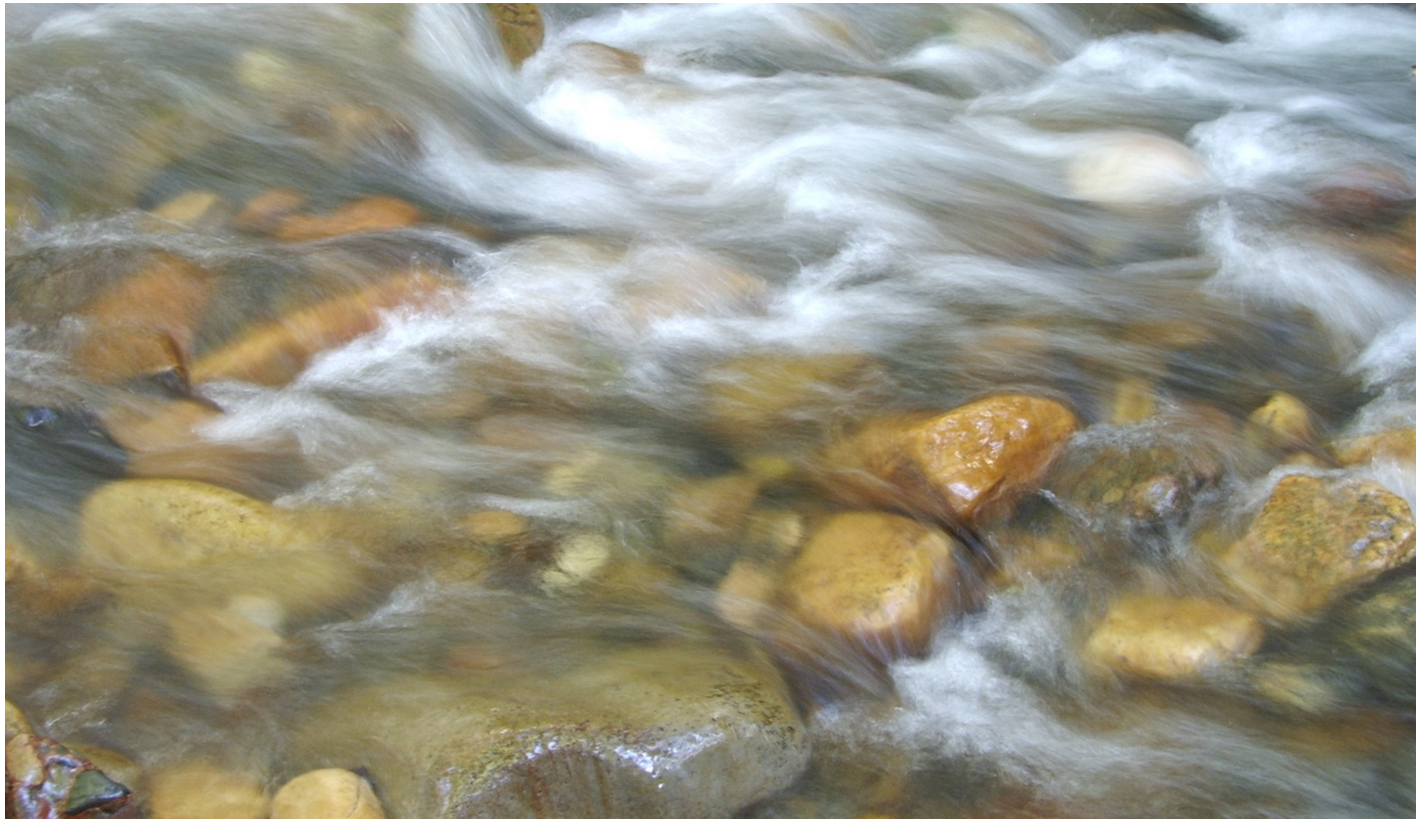
Fig. 4. Sketch of the successive dominant flow paths and related properties regarding their chemical composition. SGW: shallow groundwater; DGW: deep groundwater. Such a succession leads to the typical observed hysteretic patterns: Clockwise Tu-Q with accretion, Clockwise NO3-Q with dilution and Anticlockwise DOC-Q with accretion.

Mobilisation of sediments

Diluting effect on NO_3-rich groundwater

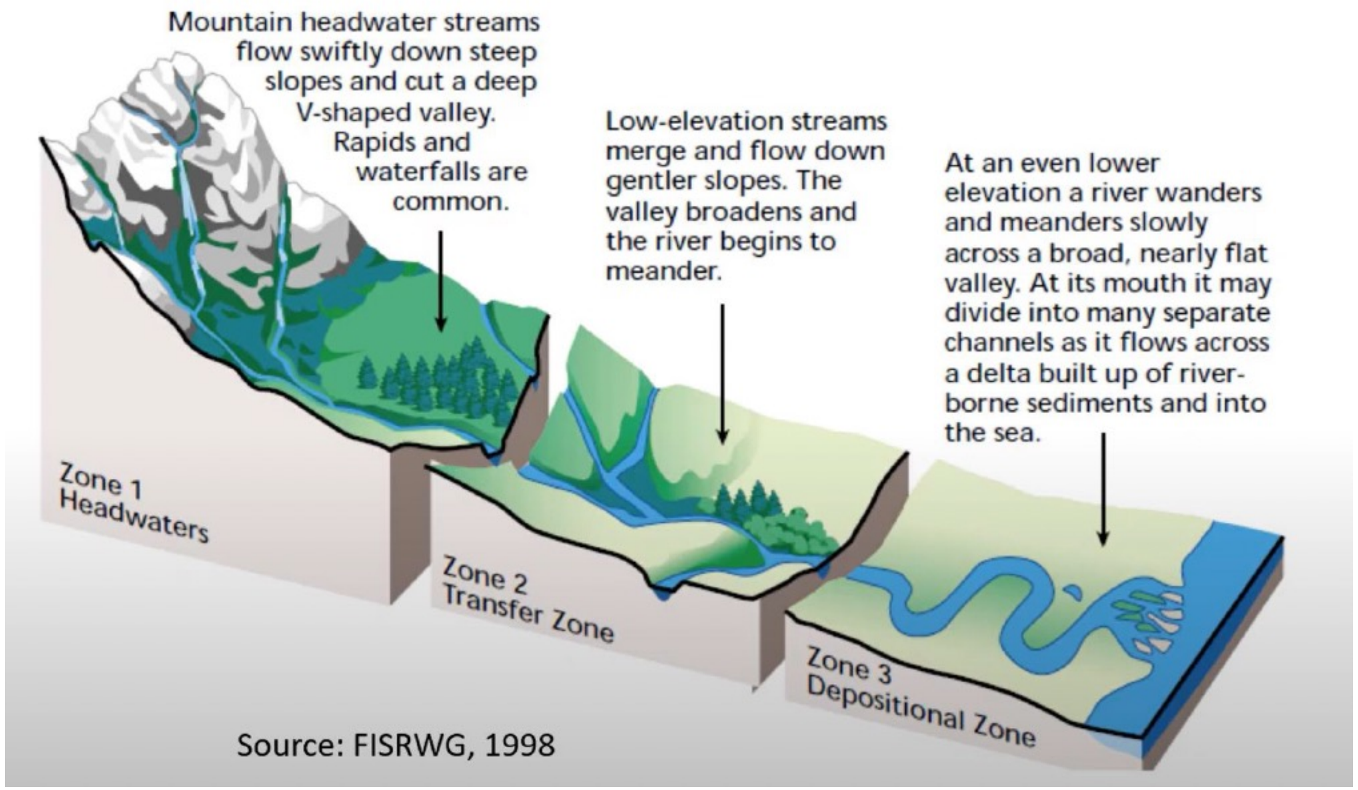
Mobilisation of DOC from sources other than sediments and NO_3

Spatial heterogeneity of streams and rivers



Spatial heterogeneity of streams and rivers

[spanning catchments and biomes — hence elevational gradients]

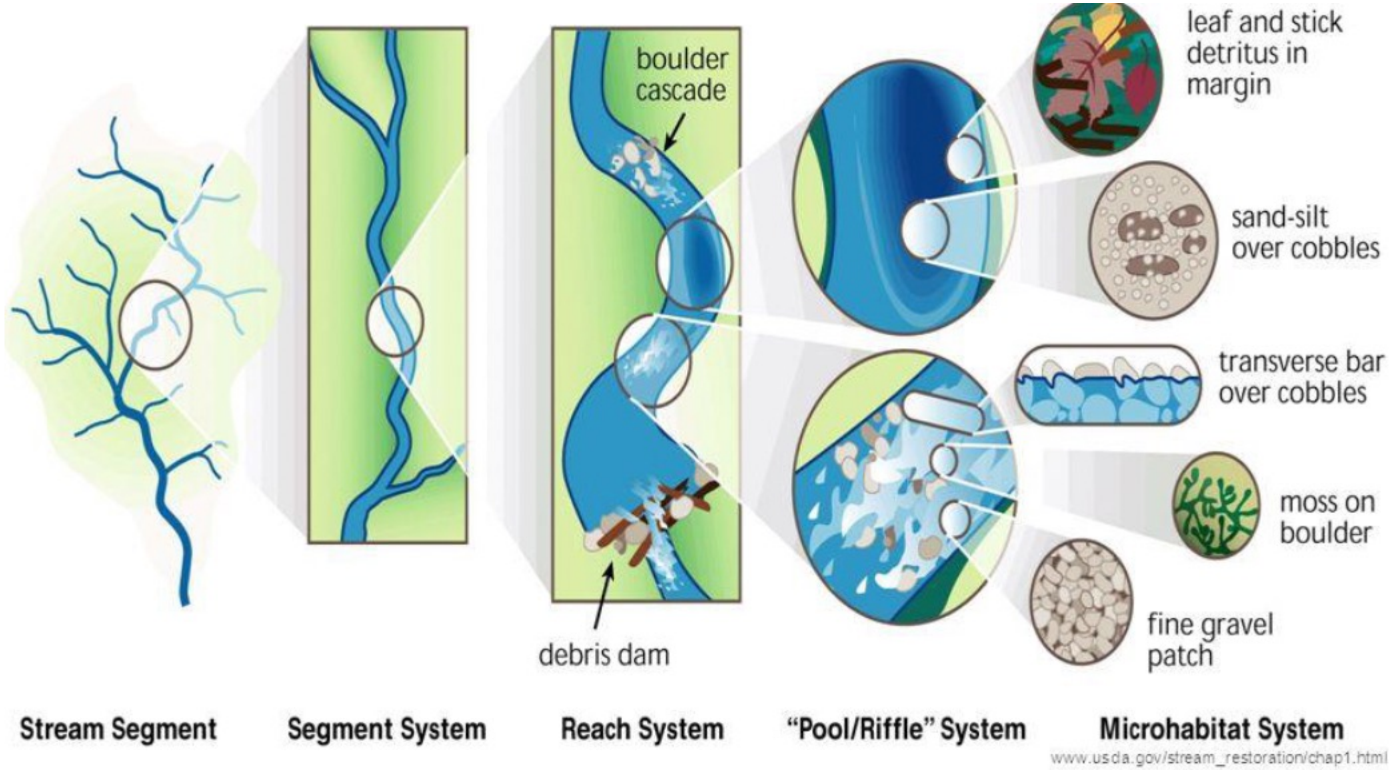


Landscape-scale spatial heterogeneity

- Gradients in terrain and geomorphology
- Gradients in contributing area (see hydraulic geometry)
- Gradients in land cover (use)

Spatial heterogeneity of streams and rivers

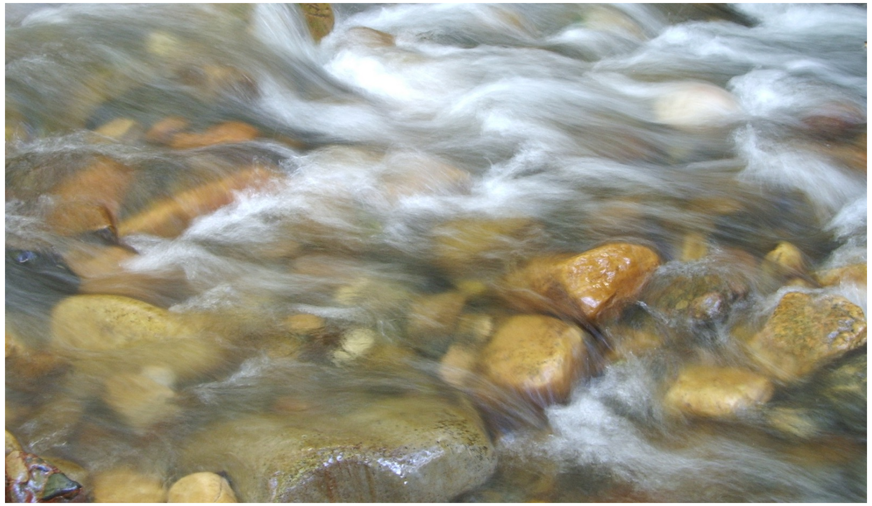
From networks to microhabitats



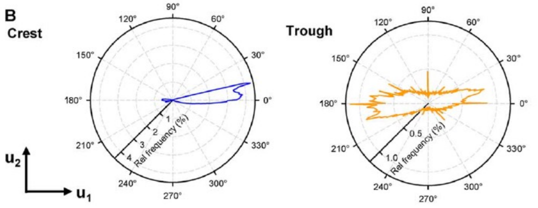
- Cross-scale spatial heterogeneity — at the interface beween geomorphology and hydraulics — from the reach to microhabitats
- Critical for biodiversity and ecosystem functioning

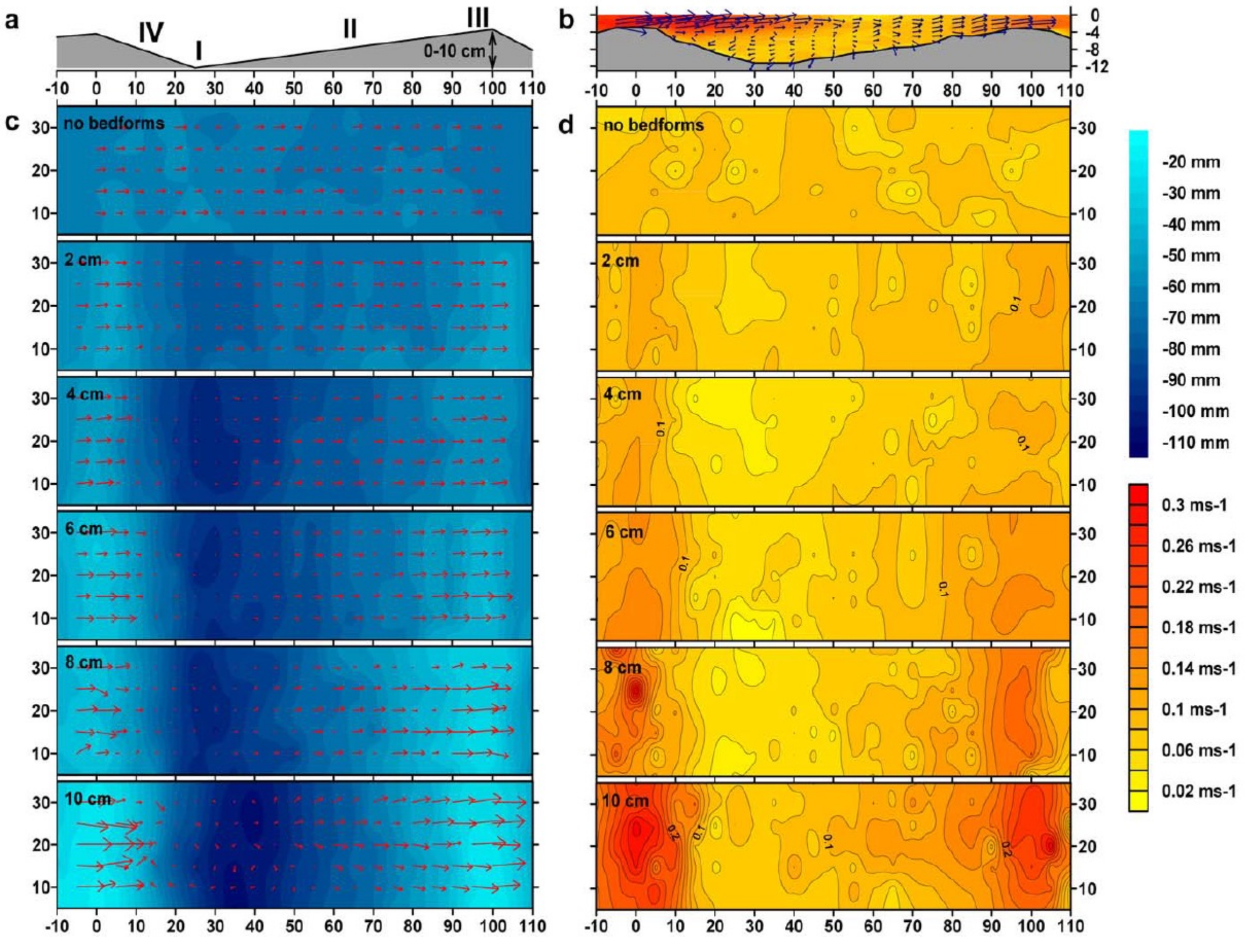
Small-scale hydraulic heterogeneity Microhabitats

- Roughness structures and non-compressibility of water induce flow structures
- Turbulence-related phenomena (e.g., transport, shear forces, uplift, gas transfer) affect life and biogeochemistry in streams and rivers



Bedforms

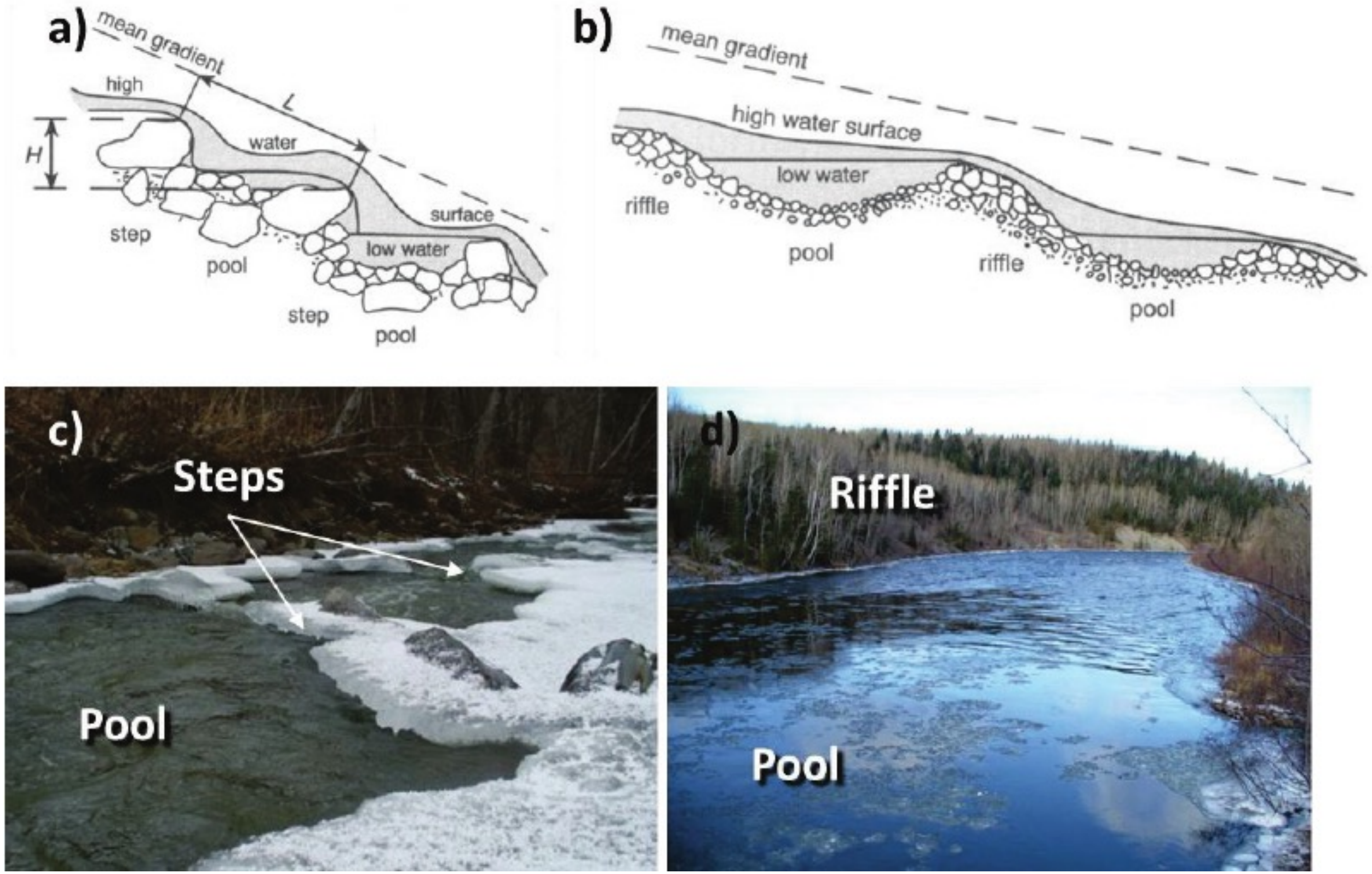




Water depth distributions

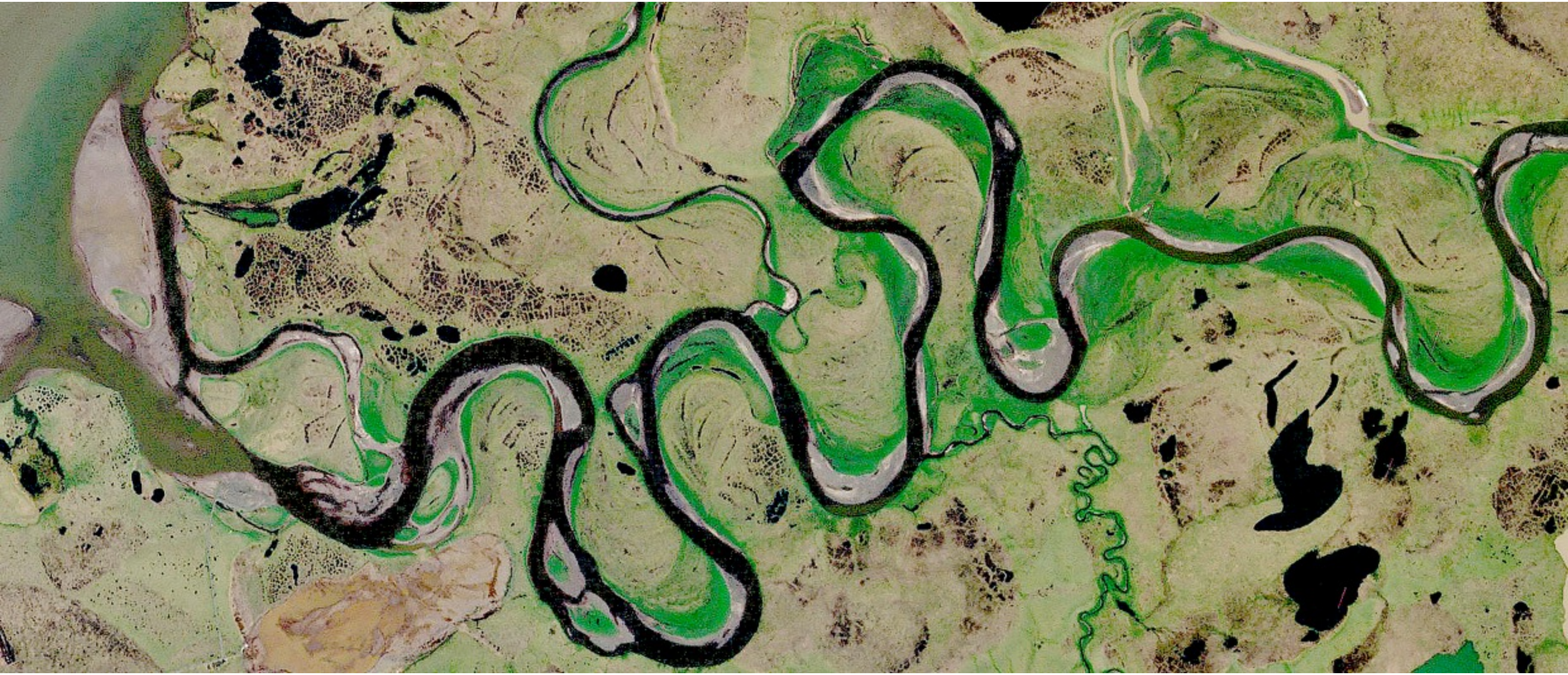
Three-dimensional flow velocity distributions

Reach-scale satial heterogeneity
Step-pool and riffle-pool sequences

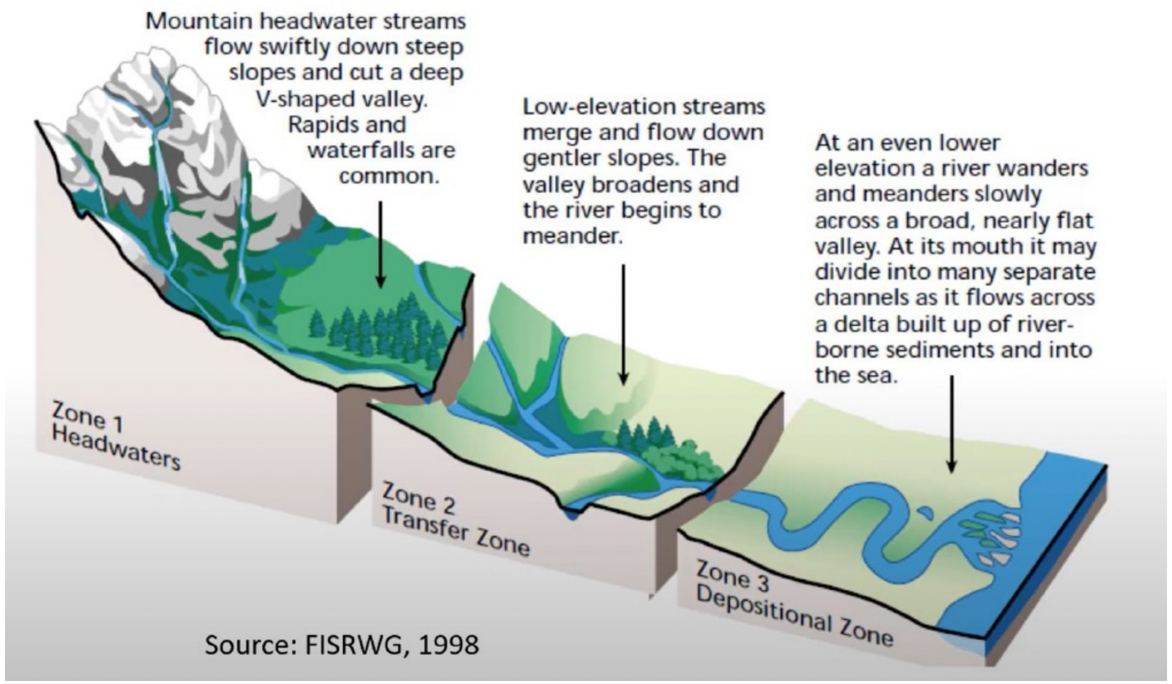


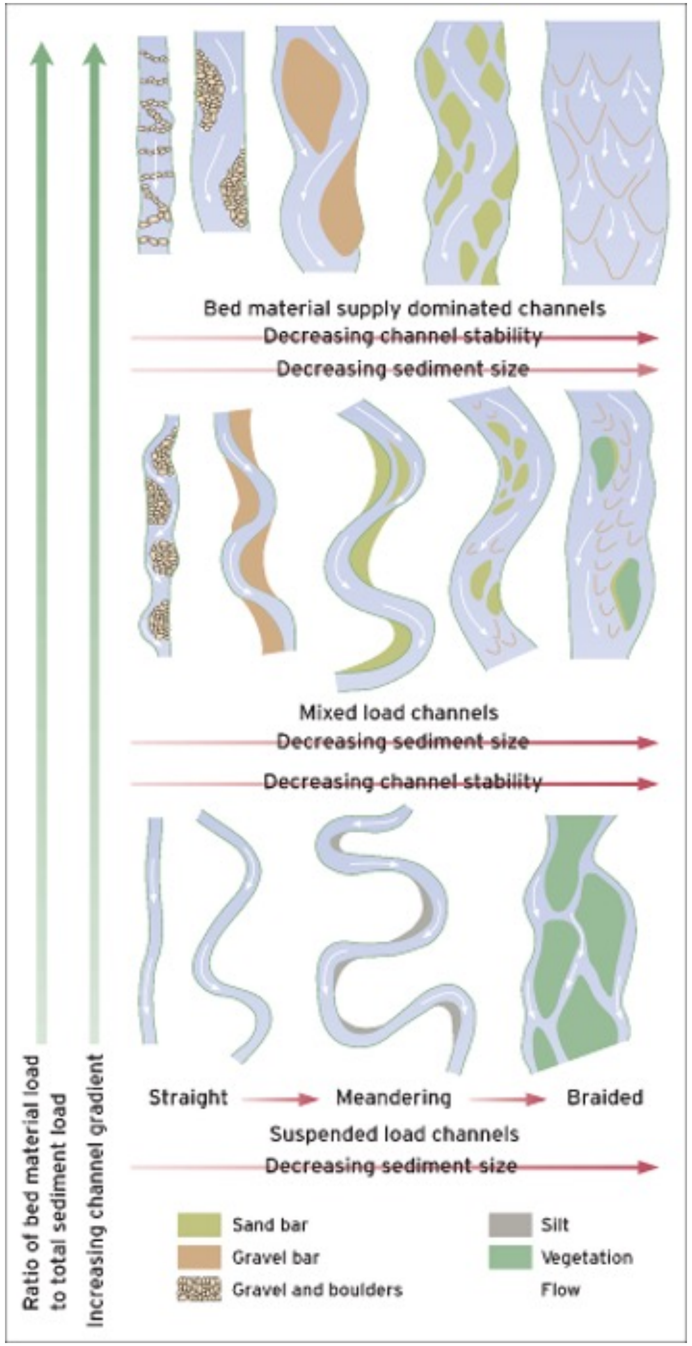
Elevated slope: step-pool
Reduced slope: riffle-pool

- Differences in water depth, velocity, residence time (continuity equation Q=vhw)
- Consequences for microhabitat formation and hydrodynamic exchange



From braided to meandering streams and rivers

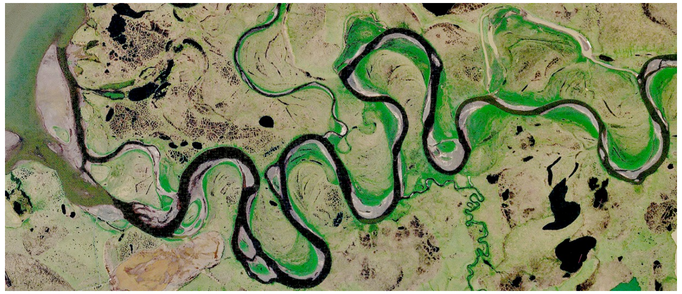


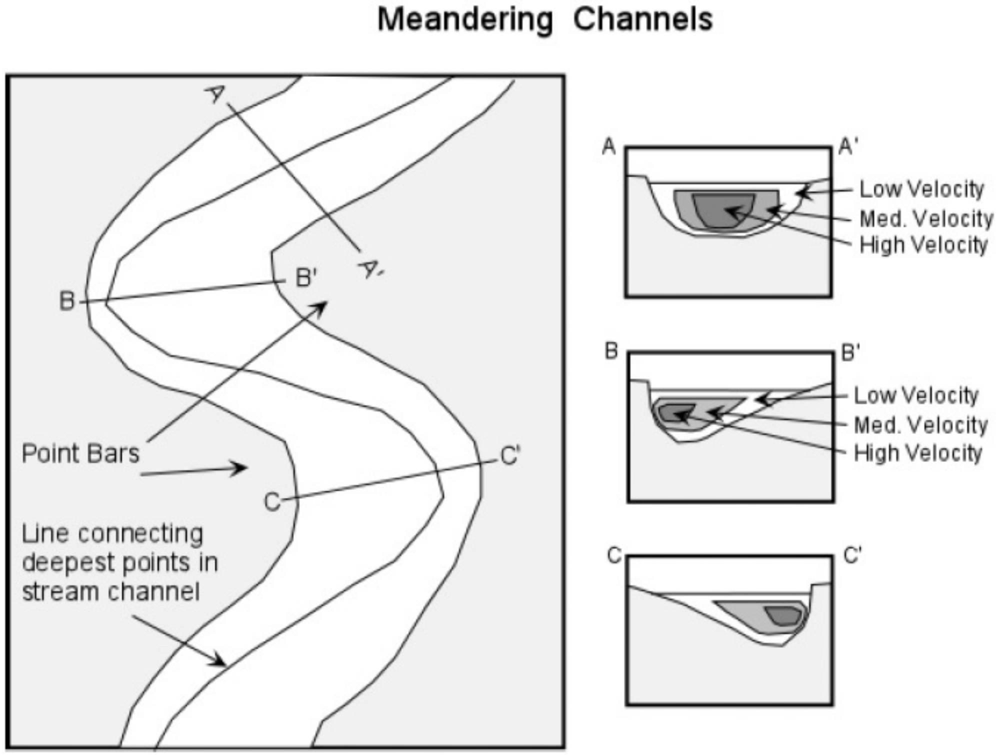


- Slope and energy
- Channel and bed stability
- Sediment load and size distribution

<u>Consequences</u>: connectivity, residence times, vegetation, biodiversity and ecosystem functioning

Meander formation





- Interplay between downstream directed sequences of erosion and deposition
- Sediment erosion of an outer bend and deposition of this material on inner bends downstream
- Depending on in-channel velocity distributions
- Stability of parent material

Next week:

Hydrodynamic exchange and consequences