

Papers for Preselection 1: Physical setting of river ecosystems

RESEARCH

GEOMORPHOLOGY

Rapid changes to global river suspended sediment flux by humans

R. van Nieuwenhuis^{1,2*}, Carl E. Renshaw¹, Francis J. Magilligan³

Rivers support indispensable ecological functions and human health and infrastructure. Yet limited river sampling hinders our understanding of consequential changes to river systems. Satellite-based estimates of suspended sediment concentration and flux for 414 major rivers reveal widespread global change that is directly attributable to human activity in the past half-century. Sediment trapping by dams in the global hydrologic north has contributed to global sediment flux declines to 49% of pre-dam conditions. Recently, intensive land-use change in the global hydrologic south has increased erosion, with river suspended sediment concentration on average 41.4% greater than in the 1980s. This north-south divergence has rapidly reconfigured global patterns in sediment flux to the oceans, with the dominant sources of suspended sediment shifting from Asia to South America.

River basins globally are experiencing increasing threats to their key roles in physical and ecological processes, including increased erosion from land use changes, sediment trapping by dam building, and the cascading hydrological and sedimentological effects of climate change (1). In many basins, the past and ongoing relative impacts of each of these changes remain unknown because of insufficient monitoring, and future projections are hindered by nonstationary watershed behavior, including changes without recent or well-noted precedents (2, 3). Given the divergent impacts of these different stressors—with land-use change dominantly increasing sediment flux, sediment trapping by dams dominantly decreasing sediment flux, and the effect of climate change on sediment flux uncertain—the temporal and global spatial variations in current and future net impacts are poorly constrained. We circumvented the global paucity of recent in situ river monitoring by using satellite analysis to investigate historic and ongoing changes in suspended sediment flux in 414 major rivers worldwide. We focused on sediment flux because of its essential role in maintaining riparian habitat and complexity, bolstering wetlands and deltas, delivering important nutrients to the oceans, and increasing coastal resilience to sea level rise. Because the major anthropogenic stresses to river functioning have both increased and decreased sediment flux, we found complex spatial and temporal variations in net in-lake rock the world's major rivers, with major, global-scale reconfigurations in the past several decades.

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SSC remains regionally consistent (Fig. 1 and fig. S4). However, our findings demonstrate in spatial and temporal detail the effects of direct human activity in altering suspended sediment transport, resulting in major changes to sediment transport in rivers and delivery of physical materials and nutrients to global estuaries and oceans. Decreasing sediment flux has been the prevailing global signal since the mid-20th century (Fig. 2), primarily because of dams (figs. S8 and S5), which are likely the dominant agent of riverine suspended sediment alteration in the past several centuries (4, 5). However, this global signal masks the extreme spatial variation in impacts. Widespread dam building in the 20th and 21st centuries has led to systematic declines in suspended sediment flux from rivers in the global hydrologic north, defined here geographically as north of ~20°N. Yet dam building is, at present, less pervasive in the global hydrologic south, defined here as south of ~20°N. There, intensive land-use change is driving rapidly increasing sediment fluxes. This strong north-south divergence is dramatically reshaping the pattern of sediment delivery to global oceans (Fig. 3). Until the 1990s, Asia was the leading continental exporter of suspended sediment to the oceans and, during the pre-dam peak, accounted for ~50% of all sediment exported to global oceans now, rivers in Asia export only ~2–10% of the global total.

The major Northern Hemisphere shift toward sediment retention in dammed reservoirs occurred in the 20th century. Of the rivers in this study, 58% (240 of 414) have one or more major dams (Fig. 4) (16), and 75% of those (187 of 240) have decreased sediment flux relative to pre-dam estimates largely made by Milliman and Farnsworth (1). These pre-dam data are from a range of years and reflect varying estimation and extrapolation approaches and sampling techniques and periods. However, although these metadata gaps can make constraint of uncertainty challenging, the estimates are by far the most comprehensive pre-dam inventory of suspended sediment flux made from direct measurements and are an essential point of comparison. In aggregate, we found that continental fluxes are reduced by 49 ± 26%. The rivers with major dams are not only comprehensively dammed. On average, reservoirs retain 102% of annual river discharge over the time this normalized reservoir capacity simply as “reservoir capacity”. Continental sediment flux is decreased by 1.8 ± 0.6% per percent increase in reservoir capacity ($P = 0.048$) (Fig. 5), a negative trend that is also present and significant for individual rivers ($P < 0.002$) (Fig. S10).

Dams have continued to reduce suspended sediment flux since 1984, although this effect has been strongly regional, focused where

we focused on 414 major rivers that flow into the oceans or major inland seas, are wider than ~50 m at their outlets, and have a drainage area of >20,000 km². Many of these rivers had suspended sediment observations during the period of interest, and some have no published suspended sediment data at all. Recent advances in computational resources (4) and digital archives of hydrologic data allow for improved analysis of satellite image archives to monitor global water quality (5, 6). We explained these advances to evaluate direct impacts of river suspended sediment concentration (SSC) and flux, using a suite of algorithms trained on more than 100,000 ground truth measurements from 340 diverse sites in North America, South America, and Taiwan (5). Applied to the entire Landsat-5 and 7 archive, these algorithms flux unrain—the temporal and global spatial variations in current and future net impacts are poorly constrained. We circumvented the global paucity of recent in situ river monitoring by using satellite analysis to investigate historic and ongoing changes in suspended sediment flux in 414 major rivers worldwide. We focused on sediment flux because of its essential role in maintaining riparian habitat and complexity, bolstering wetlands and deltas, delivering important nutrients to the oceans, and increasing coastal resilience to sea level rise. Because the major anthropogenic stresses to river functioning have both increased and decreased sediment flux, we found complex spatial and temporal variations in net in-lake rock the world's major rivers, with major, global-scale reconfigurations in the past several decades.

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Mapping the world's free-flowing rivers

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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. Here we assess the connectivity status of 12 million kilometers of rivers globally and identify those that remain free-flowing in their entire length. Only 37 per cent of rivers longer than 1,000 kilometers remain free-flowing over their entire length and 23 per cent flow uninterrupted to the ocean. Very long FFRs are largely restricted to remote regions of the Arctic and of the Amazon and Congo basins. In densely populated areas only few very long rivers remain free-flowing, such as the Irrawaddy and Salween. Dams and reservoirs and their up- and downstream propagation of fragmentation and flow regulation are the leading contributors to the loss of river connectivity. By applying a new method to quantify riverine connectivity and map FFRs, we provide a foundation for concerted global and national strategies to maintain or restore them.

Rivers are essential sources of environmental health, economic wealth and human well-being. For millennia, rivers have provided food, controlled water for domestic use and agriculture, sustained transportation corridors and, more recently, enabled power generation and industrial production¹. These goods and services generally require built infrastructure, and society has addressed this demand by constructing an estimated 2.8 million dams (with reservoir areas >10³ m²), regulating and creating over 500,000 km of rivers and canals for navigation and water diversion schemes².

As a result, rivers are exposed to sustained pressure from fragmentation and loss of river connectivity, constraining their capacity to flow unimpeded, affecting many fundamental processes and functions characteristic of healthy rivers³ and leading to the rapid decline of biodiversity and essential ecosystem services⁴. The capacity of rivers to flow freely is governed by the connectivity of pathways that enable the movement and exchange of water and of the organisms, sediments, organic matter, nutrients and energy that it conveys throughout the riverine environment. River connectivity extends in four dimensions: longitudinally (up- and downstream in the river channel), laterally (between the main channel, the floodplain and riparian areas), vertically (between the groundwater, the river and the atmosphere) and temporally (seasonality of flows)^{5–7}. River connectivity is also spatially and temporally dynamic, largely driven by the natural flow regime⁸, enabling and regulating hydrological, geomorphic and ecological processes in river networks and providing the aquatic medium for matter and species to move along the river and into adjacent habitats⁹. Humans have altered natural river connectivity in

multiple ways, either directly by placing structures into the longitudinal or lateral flow paths, such as dams and levees, or indirectly by altering the hydrological, thermal and sediment regimes of the river^{10–12}. Although it is inherently complex to quantify the value of services provided by FFRs or to measure the devaluing effect of impeding infrastructure, many examples exist that underline the importance of connectivity for the provision of natural riverine ecosystem functions and processes. For instance, floodplains are among the most productive and diverse riverine ecosystems globally¹³, and their disconnection from the upstream catchment or river channel alters ecosystem services such as natural flood storage, nutrient retention and flood-recession agriculture¹⁴. Built river infrastructure has also been linked to declines in terrestrial and freshwater species^{15–17} and sediment capture by dams can cause the alteration of the geomorphic dynamics of rivers and the shrinking of river deltas worldwide¹⁸.

Although advances in the identification and quantification of pathways that enable the movement and exchange of water and of the organisms, sediments, organic matter, nutrients and energy that it conveys throughout the riverine environment. River connectivity extends in four dimensions: longitudinally (up- and downstream in the river channel), laterally (between the main channel, the floodplain and riparian areas), vertically (between the groundwater, the river and the atmosphere) and temporally (seasonality of flows)^{5–7}. River connectivity is also spatially and temporally dynamic, largely driven by the natural flow regime⁸, enabling and regulating hydrological, geomorphic and ecological processes in river networks and providing the aquatic medium for matter and species to move along the river and into adjacent habitats⁹. Humans have altered natural river connectivity in

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Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks

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ABSTRACT

Hydrologic connections link hillslopes to channel networks, streams to lakes, subsurface to surface, land to atmosphere, terrestrial to aquatic, and upstream to downstream. These connections can develop across vertical, lateral, and longitudinal dimensions and span spatial and temporal scales. Each of these dimensions and scales are interconnected, creating a mosaic of nested hydrologic connections and associated processes. In turn, these interacting and nested processes influence the transport, cycling, and transformation of organic material and inorganic nutrients through watersheds and along fluvial networks. Although hydrologic connections span dimensions and spatiotemporal scales, relationships between connectivity and carbon and nutrient dynamics are rarely evaluated within this framework. The purpose of this paper is to provide a cross-disciplinary view of hydrologic connectivity—highlighting the various forms of hydrologic connectivity that control fluxes of organic material and nutrients—and to help stimulate integration across scales and dimensions, and collaboration among disciplines.

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1. Introduction

Hydrologic connectivity is a broad term that has been used in various contexts by numerous researchers, but its meaning often differs among disciplines (Bracken et al., 2013; Michardides and Chappell, 2009). The different meanings are due in part to the varying influence that hydrologic connectivity has on a wide variety of watershed processes of physical (Ambrose, 2004; Fryer et al., 2007) and biological (Amoros and Borrette, 2002) importance (Table 1). Water connects hillslopes to channel networks, streams to lakes, subsurface to surface, land to atmosphere, terrestrial to aquatic, and upstream to downstream. Through these myriad hydrologic connections water is the medium that facilitates (in large part) the movement of energy, solutes, and particulates through and across the land.

Hydrologic connectivity can be established via surface or subsurface pathways and occurs along four dimensions: these are lateral, vertical, and longitudinal spatial dimensions, and the fourth dimension is time (Ward, 1980; Ward and Stanford, 1983). While this conceptual framework is useful for organizing the way we envision hydrologic connectivity, in reality connections are not simply in one direction or another but typically span multiple dimensions. Hydrologic connections in each direction operate across temporal scales from seconds to millennia (Ward, 1988) and spatial scales from submeter to thousands of kilometers (Harvey and Arp, 1996). Accordingly, hydrologic connections and

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Article

Global prevalence of non-perennial rivers and streams

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Flowing waters have a unique role in supporting global biodiversity, biogeochemical cycles and human societies^{1–4}. Although the importance of permanent water ecosystems is well-recognized, the prevalence, value and fate of non-perennial rivers and streams that periodically cease to flow tend to be overlooked, if not ignored^{5–7}. This oversight contributes to the degradation of the main source of water and livelihood for millions of people⁸. Here we predict that 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. Leveraging global information on the hydrology, climate, geology and surrounding land cover of the Earth's river network, we show that non-perennial rivers occur within all climates and biomes, and on every continent. Our findings challenge the assumptions underpinning foundational river concepts across scientific disciplines⁹. To understand and adequately manage the world's flowing waters, their biodiversity and functional integrity, a paradigm shift is needed towards a new conceptual model of rivers that includes flow intermittence. By mapping the distribution of non-perennial rivers and streams, we provide a stepping stone towards addressing this grand challenge in freshwater science.

Almost every river network on Earth includes channels that periodically cease to flow. From Himalayan snow-fed creeks to occasionally water-filled Sahara wadis, river flow cessation is naturally prevalent worldwide. Yet the global extent of intermittent rivers and ephemeral streams (IRES) is largely unknown. IRES vary widely in size and flow duration, encompassing all non-perennial watercourses—from large, sparse intermittent rivers with nearly continuous channel flow to mostly dry streams that only flow after intense rainfall (see Extended Data Table 1 for additional definitions and IRES terminology). IRES are pivotal components of the landscape, critically contributing to the biodiversity¹⁰. Management frameworks also need to be adapted to conserve entire non-perennial river networks and streams have become intermittent in the past 50 years owing to water abstractions, climate change and land-use transitions, including sections of cooler rivers such as the Nile, Indus, Yellow and Colorado^{11,12}. Given continued global change, an increasingly large proportion of the global river network is expected to seasonally cease to flow over the coming decades¹³.

Despite their prevalence, IRES are frequently mismanaged owing to a lack of recognition¹⁴, or altogether excluded from management actions and conservation laws¹⁵. As a result, non-perennial rivers and streams are being degraded at an alarming rate¹⁶. Recent attempts to further remove IRES from environmental legislation and national water governance systems (for example, in the USA¹⁷), if implemented, would be spatially and temporally variable (Dunne and Black, 1970a, 1970b; Dunne and Leopold, 1978; Hewlett, 1982; Hewlett and Hibbert, 1967). Certain hillslopes in a watershed may remain connected to the channel

where their already inadequate protection. The long-standing neglect of IRES is partly the result of their continued omission from scientific research. Most freshwater science has focused on the functioning and conservation of perennial water bodies, and only recently has riverine flow cessation become its own subject of study¹⁸. Consequently, science-based methods for managing these unique ecosystems, such as biomonitoring tools and protocols, are still limited or absent¹⁹. Management frameworks also need to be adapted to conserve entire non-perennial river networks and streams have become intermittent in the past 50 years owing to water abstractions, climate change and land-use transitions, including sections of cooler rivers such as the Nile, Indus, Yellow and Colorado^{11,12}. Given continued global change, an increasingly large proportion of the global river network is expected to seasonally cease to flow over the coming decades¹³.

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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.



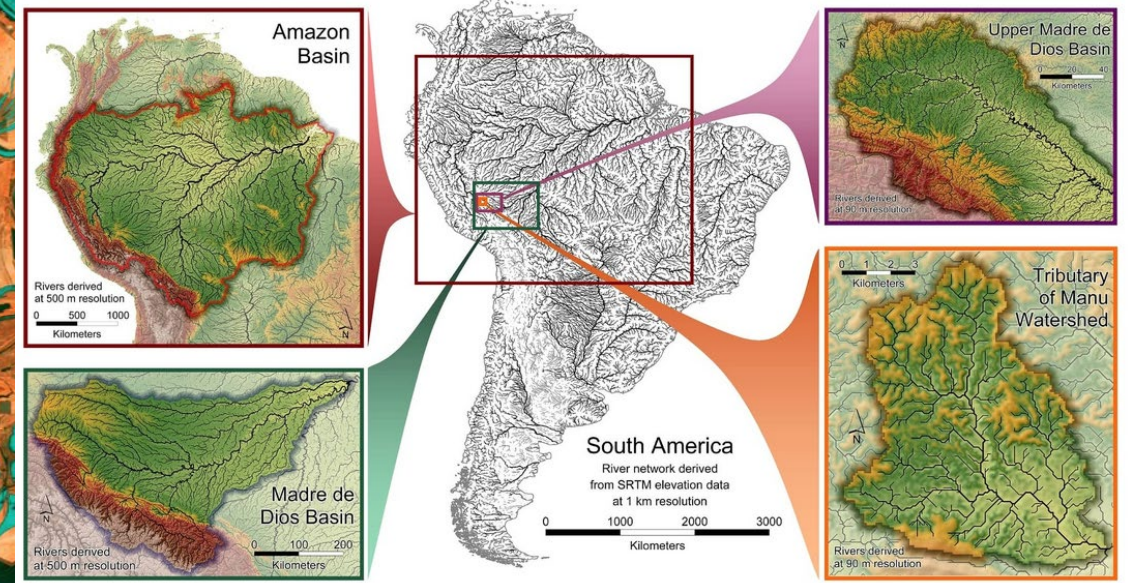
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The core data products of HydroSHEDS v1 are:

- 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)

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: there is a route for water to flow from every location of the basin to the main stream;*
- *Trees: absence of loops.*



INAUGURAL ARTICLE

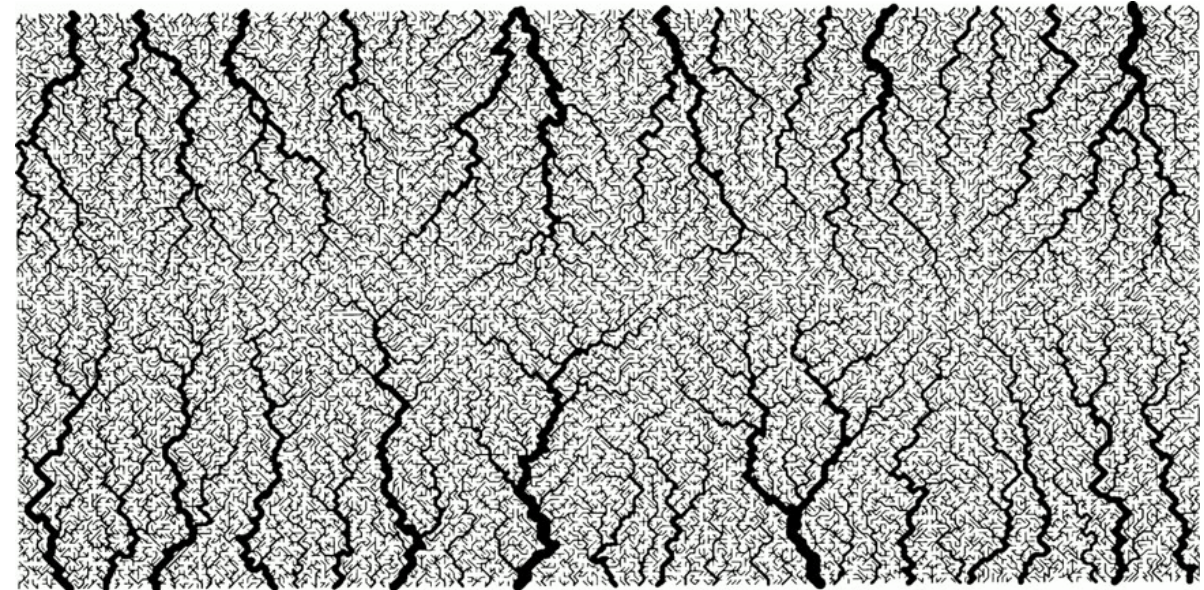
Evolution and selection of river networks: Statics, dynamics, and complexity

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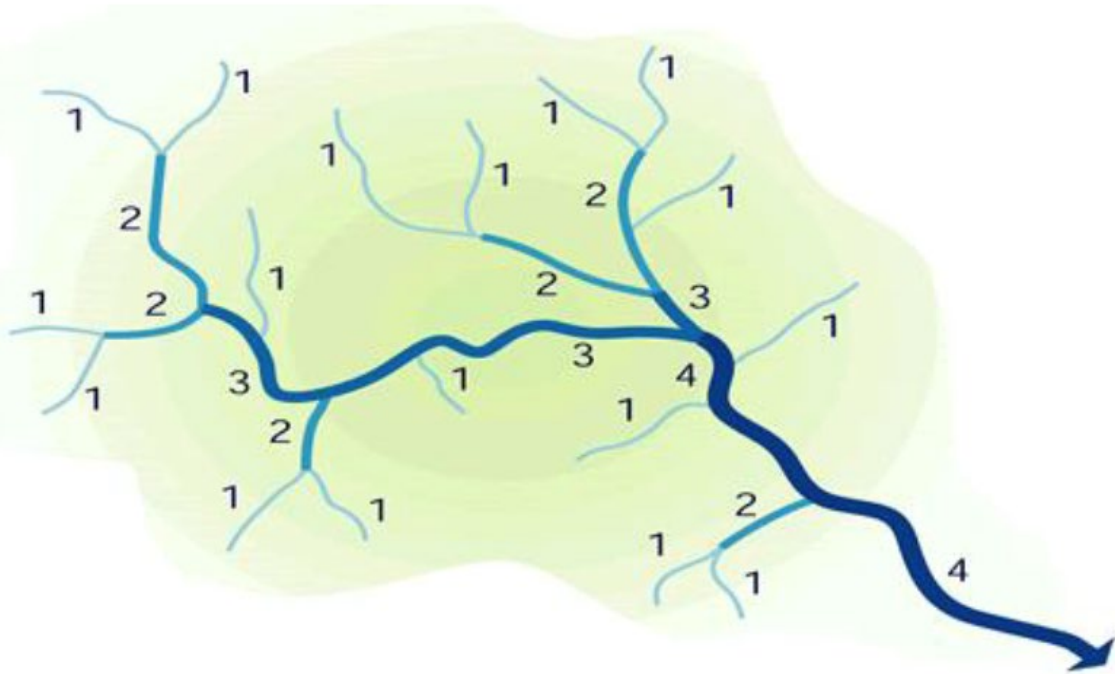
Contributed by Andrea Rinaldo, December 27, 2013 (sent for review November 30, 2013)

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



Picture from: Rinaldo, A., Rodriguez-Iturbe, I., and Rigon, R. "Channel networks." *Annual review of earth and planetary sciences* 26.1 (1998): 289-327.

Describing river networks

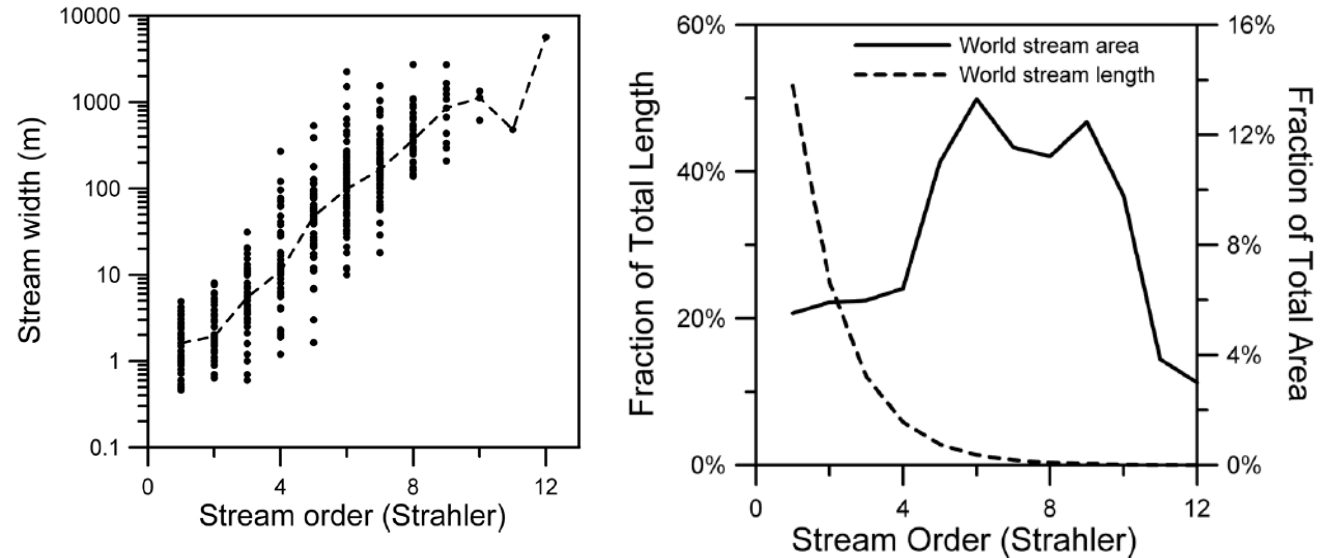


Strahler order

- 662'000 km², 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

Global abundance and size distribution of streams and rivers

J.A. Downing¹, J.J. Cole², C.M. Duarte³, J.J. Middelburg⁴, J.M. Melack⁵, Y.T. Prairie⁶, P. Kortelainen⁷, R.G. Striegl⁸, W.H. McDowell⁹, and L.J. Tranvik¹⁰



Order (ω)	n_{ω}	\bar{l}_{ω} (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 Landsat 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 $773,000 \pm 79,000$ square kilometers ($0.58 \pm 0.06\%$) 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

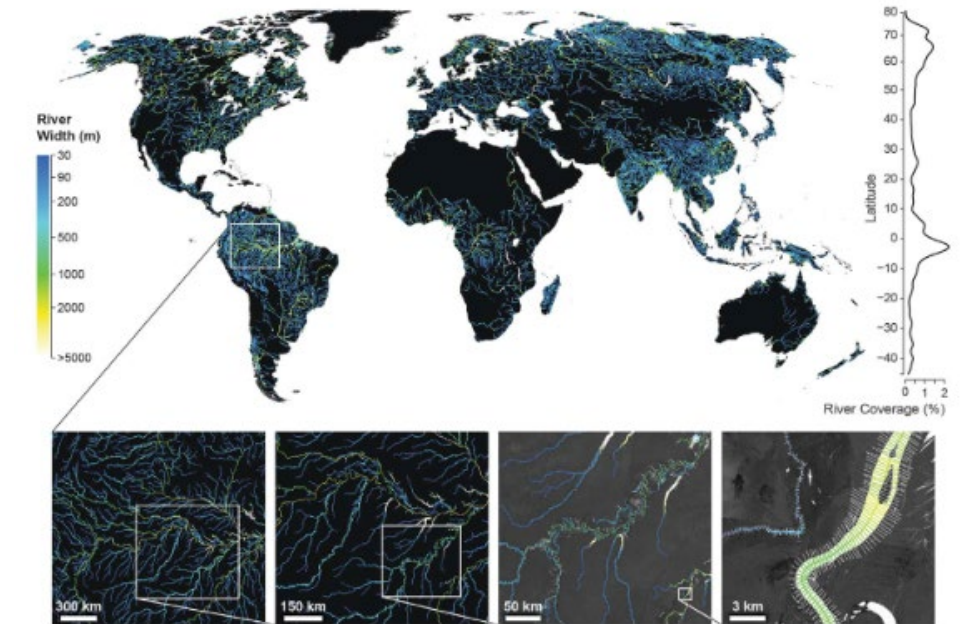
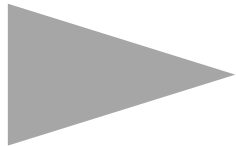
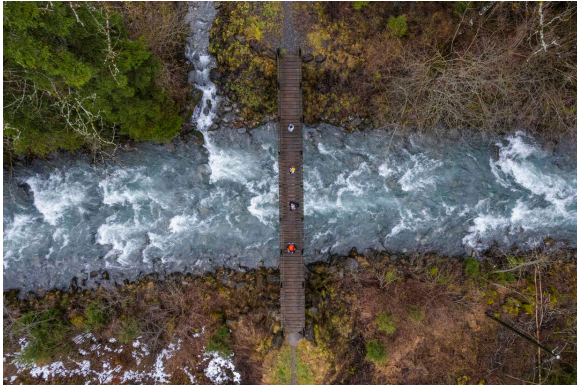
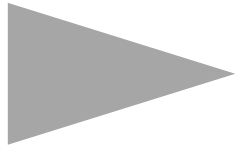


Fig. 1. The Global River Widths from Landsat (GRWL) Database contains more than 58 million measurements of planform river geometry. The line plot on the right shows observed river coverage as a percentage of land area by latitude, and the bottom insets show GRWL at increasing zoom. The rightmost inset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

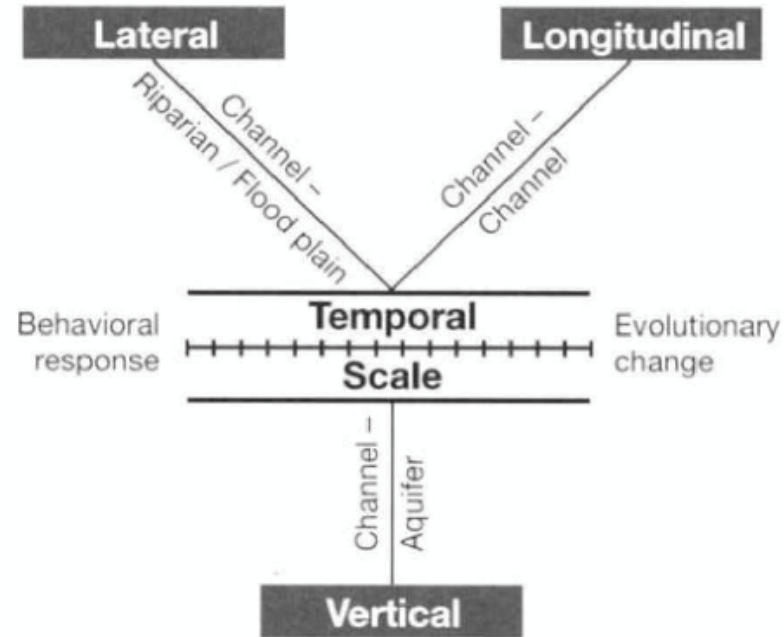
Why would changes in width, area and depth matter?



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

Downstream change of **River Dimensions**

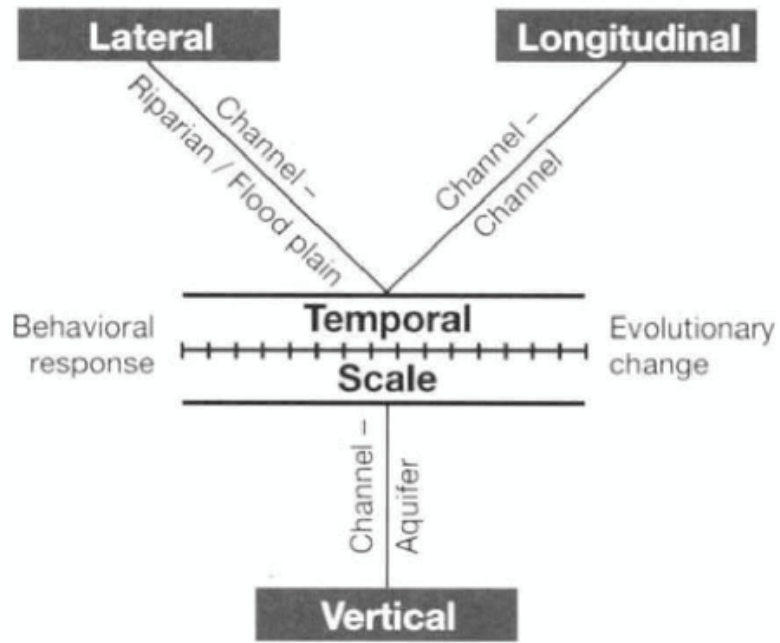
The four-dimensional nature of stream and river ecosystems






The four-dimensional nature of stream and river ecosystems

An Expansive Perspective of Riverine Landscapes: Pattern and Process Across Scales¹⁾

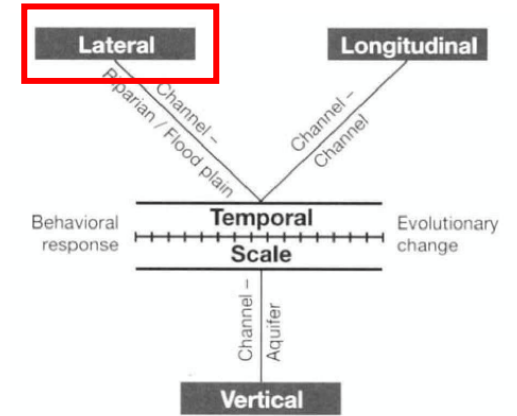
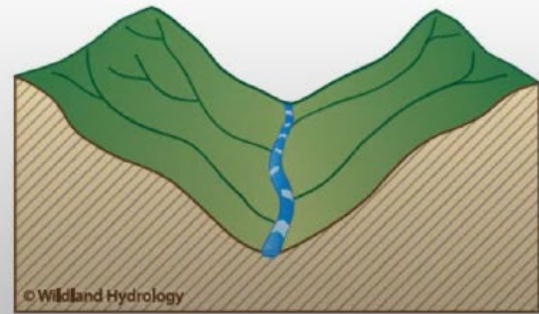
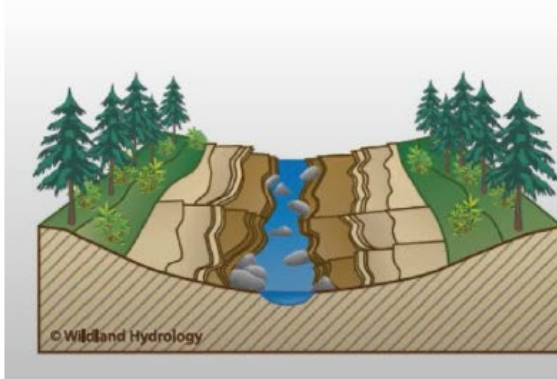
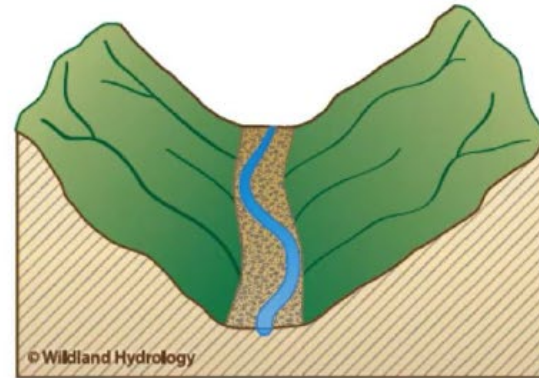
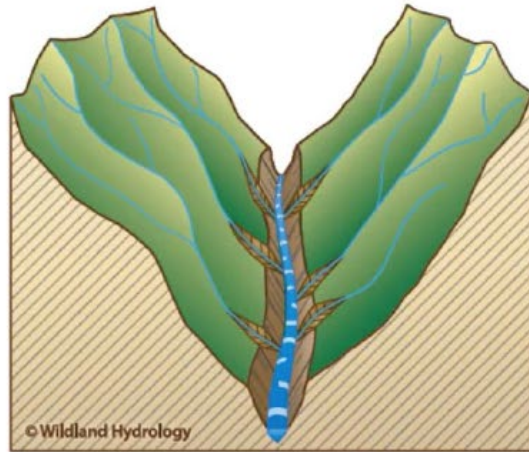
James V. Ward*



	Mountain Headwater Reach	Braided Reach	Meandering Reach
Channel Pattern	single thread, straight	multiple thalweg, braids	single thread, meanders
Channel Stability	constrained	highly unstable	migrating
Floodplain Development	little or none	moderate	expansive
Wetland Vegetation	narrow riparian corridor	pioneer community	pioneer to mature stages
Aquatic Habitat	lotic	lotic, semi-lotic	lotic, semi-lotic
Interactive Pathways			

The four-dimensional nature of stream and river ecosystems

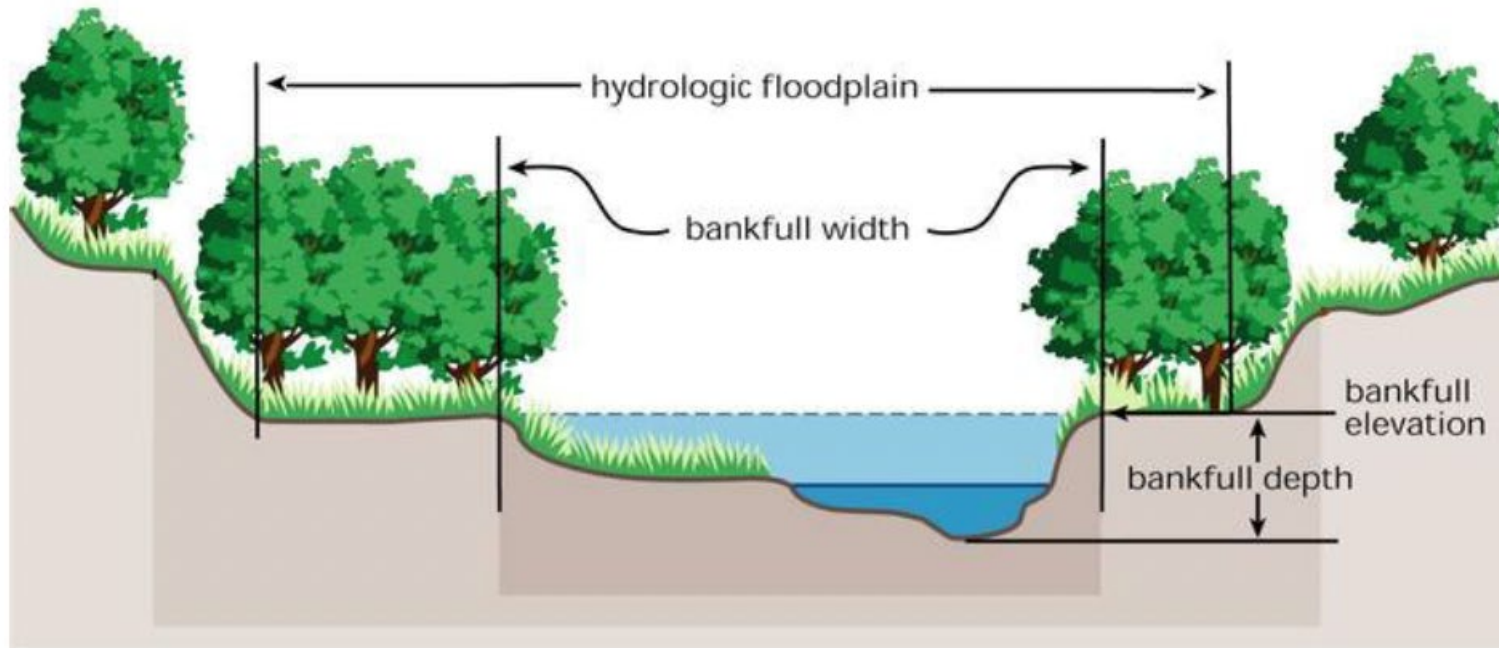
1) Lateral



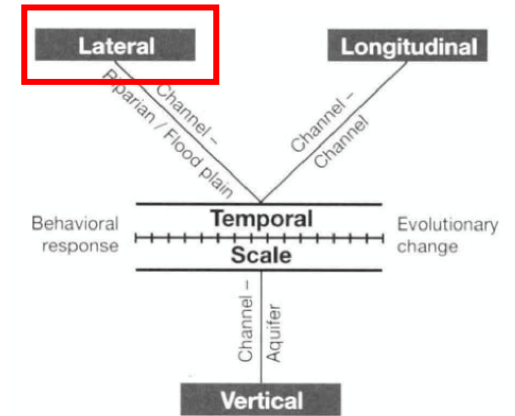
- Geology (e.g., erodibility) and related geomorphology (e.g., slope) are first-order controls on the lateral dimension
- Land use as well

The four-dimensional nature of stream and river ecosystems

1) Lateral

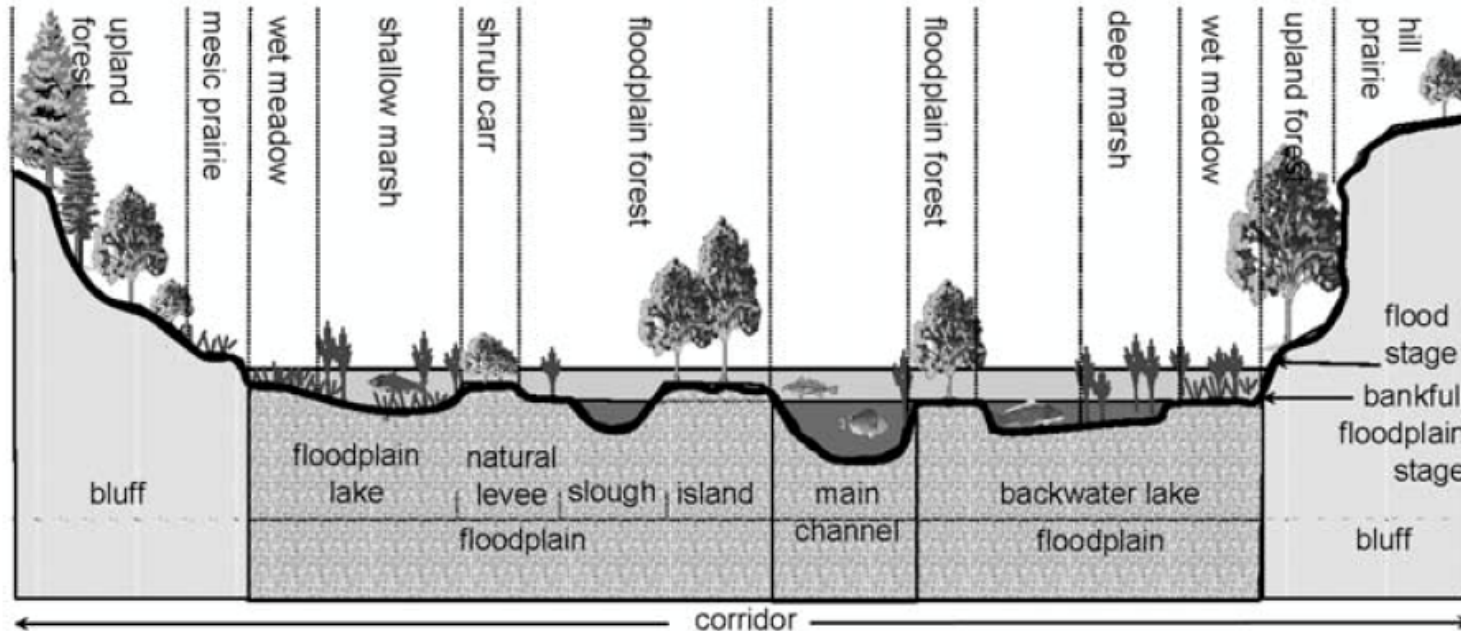
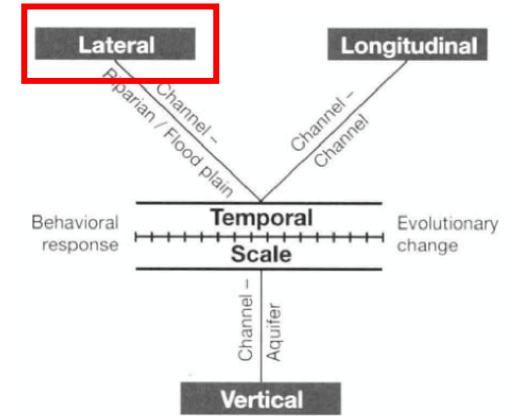


- Active channel within 'bankfull width'
- Floodplain beyond 'bankfull width'
- Innundation: over-topping of banks



The four-dimensional nature of stream and river ecosystems

1) Lateral



RIPARIAN ECOTONE: A FUNCTIONAL DEFINITION AND DELINEATION FOR RESOURCE ASSESSMENT

E. S. VERRY^{1*}, C. A. DOLLOFF² and M. E. MANNING³

¹Research Hydrologist, Ecology and Management of Riparian/Aquatic Ecosystems, USDA Forest Service, North Central Research Station, Grand Rapids, Minnesota, U.S.A.;

²USDA Forest Service, Southern Research Station, Blacksburg, VA, U.S.A.;

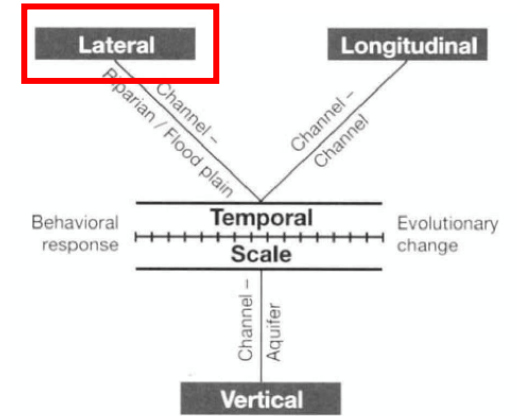
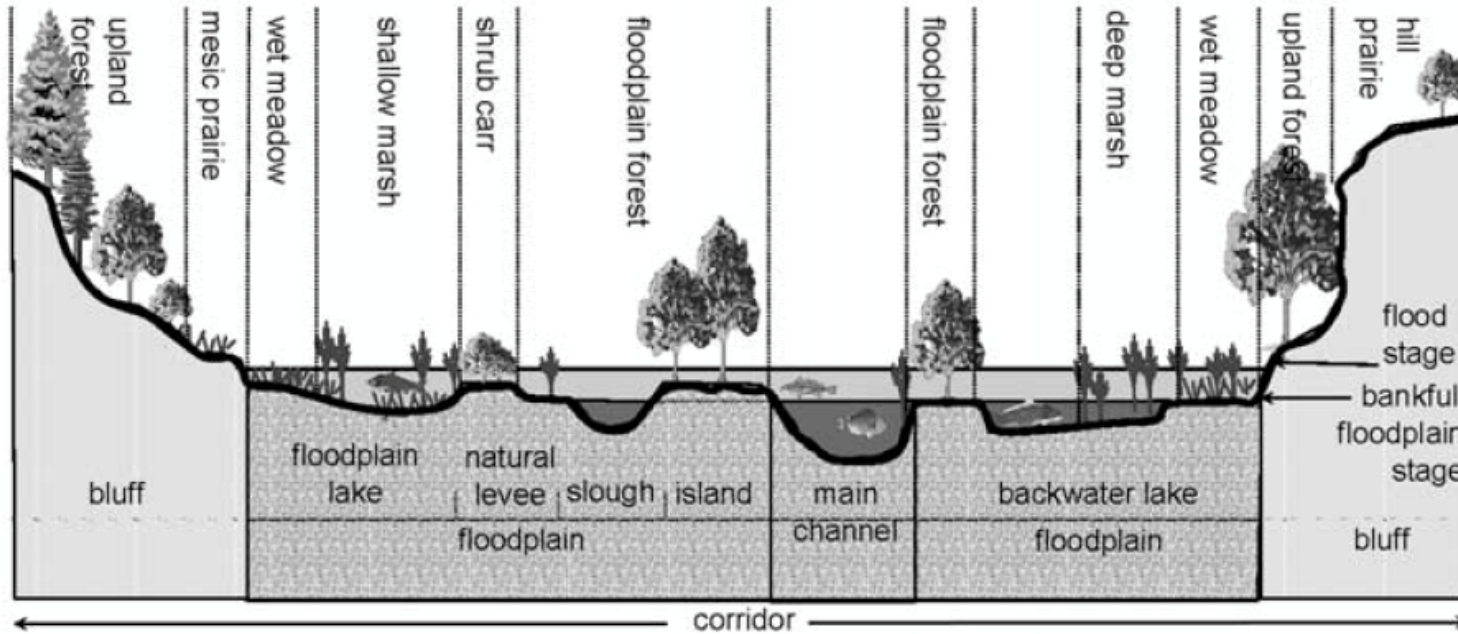
³Riparian Ecologist, Region I, USDA Forest Service, Missoula, MT, U.S.A.

(* 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)

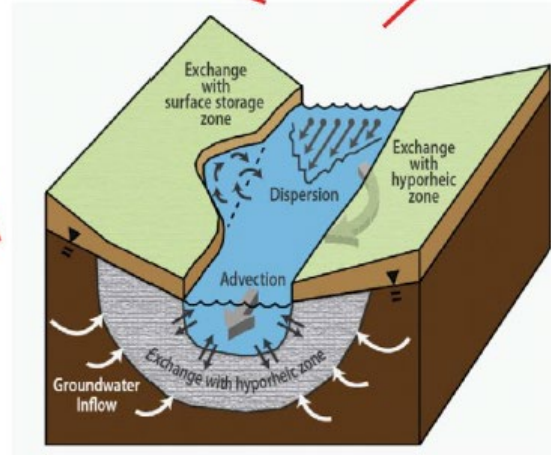
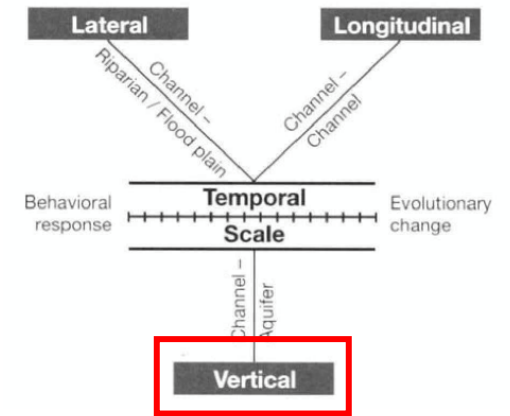
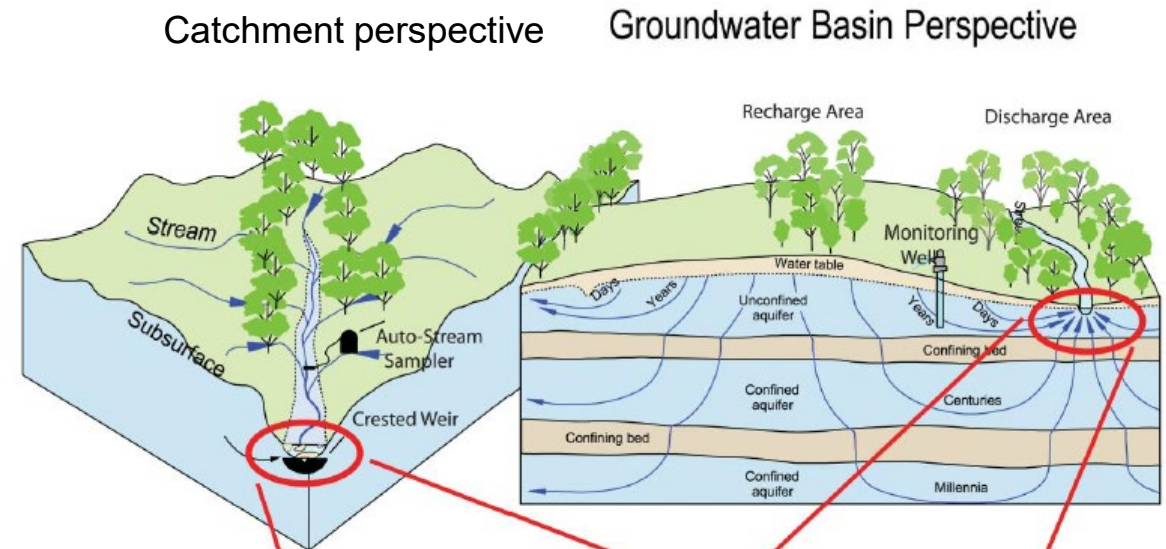
The four-dimensional nature of stream and river ecosystems

1) Lateral



The four-dimensional nature of stream and river ecosystems

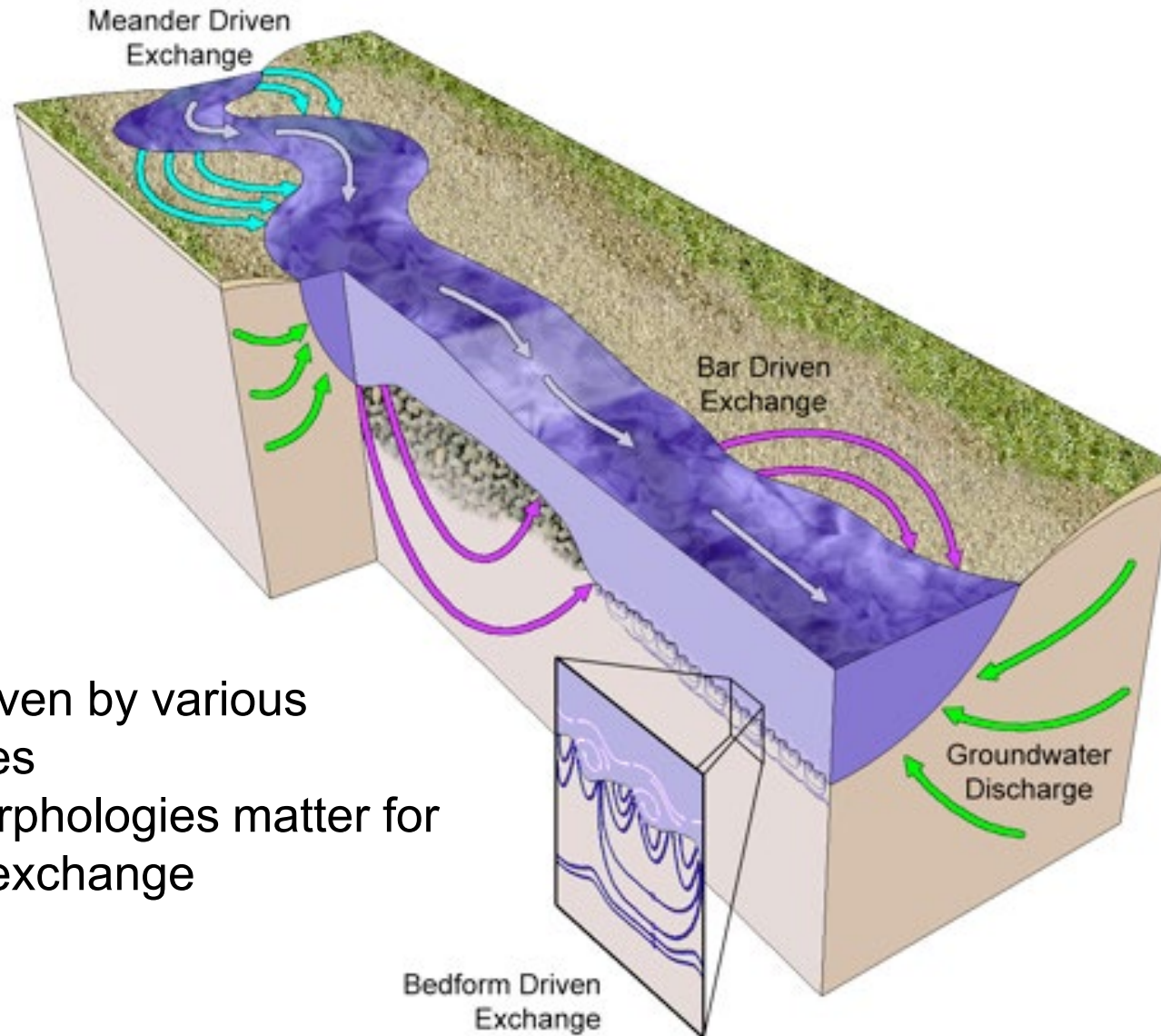
2) Vertical



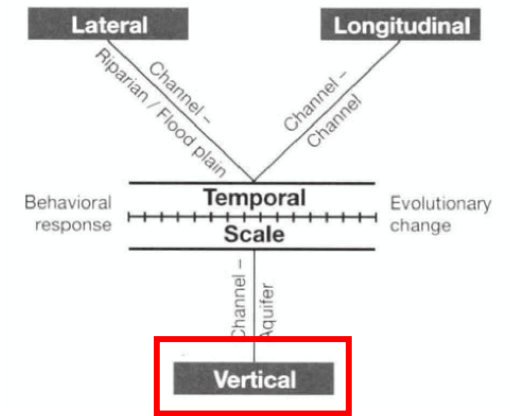
- Streams and rivers connected to the catchment via vertical hydrological flow paths
- Hydrodynamic exchange between surface water and parent groundwater through the hyporheic zone

The four-dimensional nature of stream and river ecosystems

2) Vertical

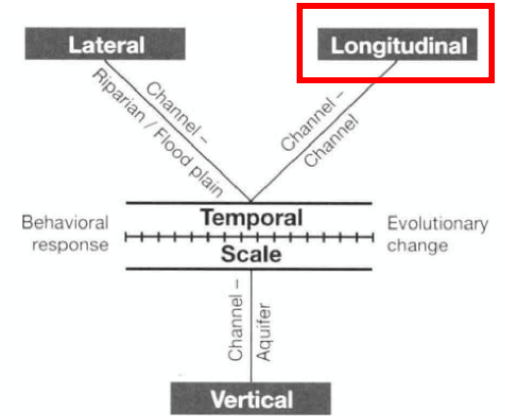


- Vertical flow driven by various bedform features
- Diverse geomorphologies matter for hydrodynamic exchange

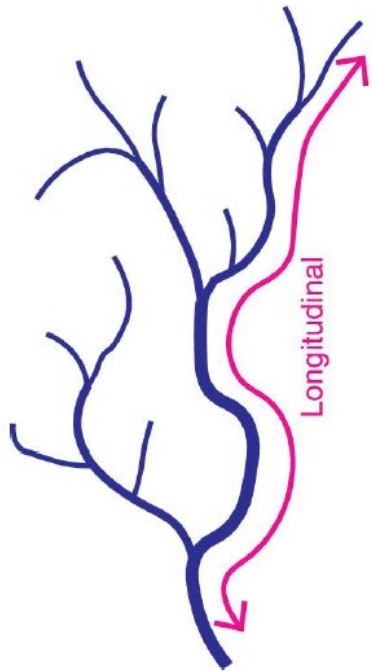


The four-dimensional nature of stream and river ecosystems

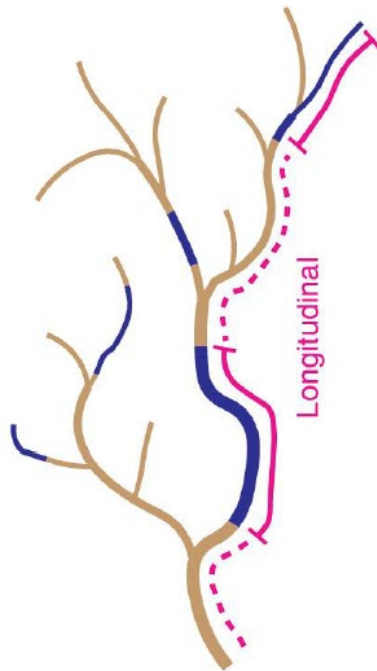
3) Longitudinal



(a) Wetted river network, longitudinally connected



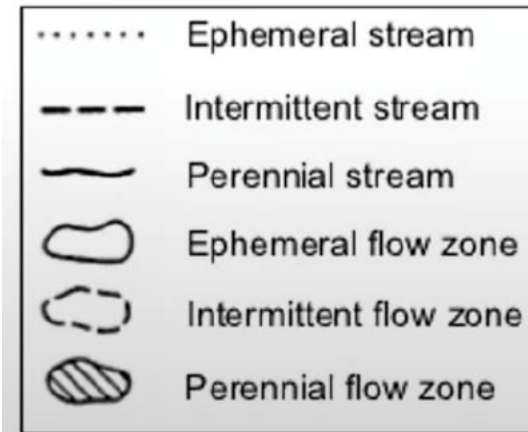
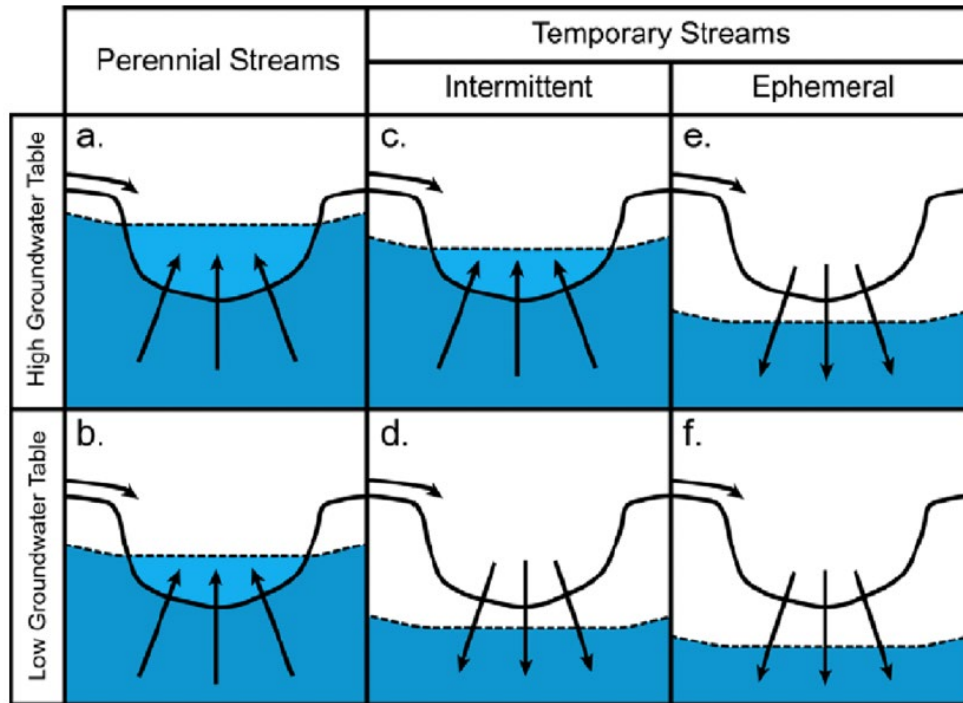
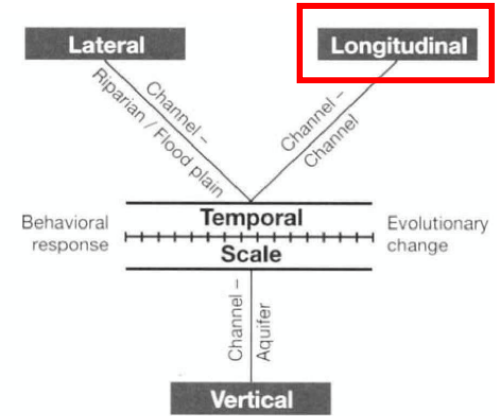
(b) Wet and dry river network, longitudinally disconnected



- 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

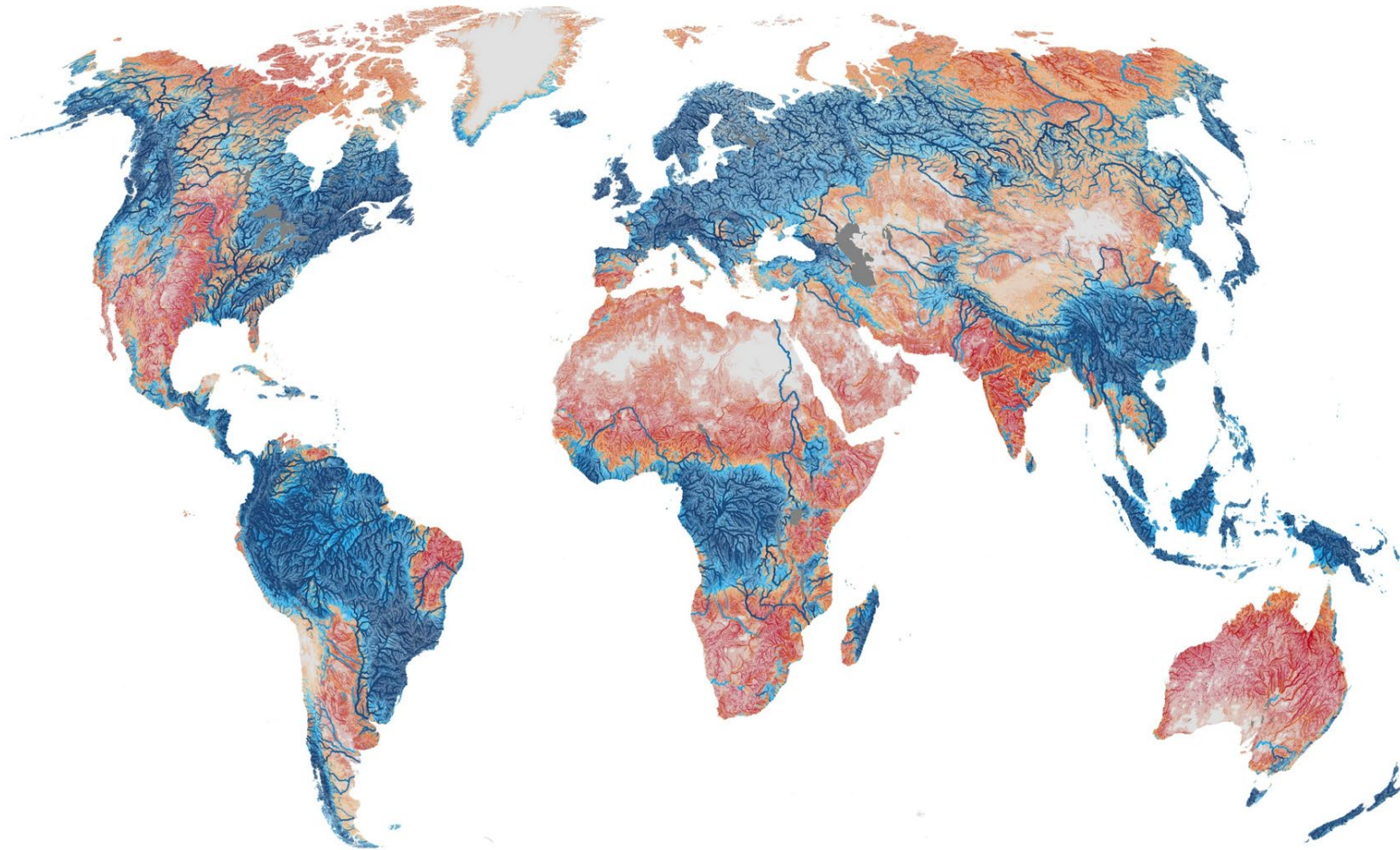
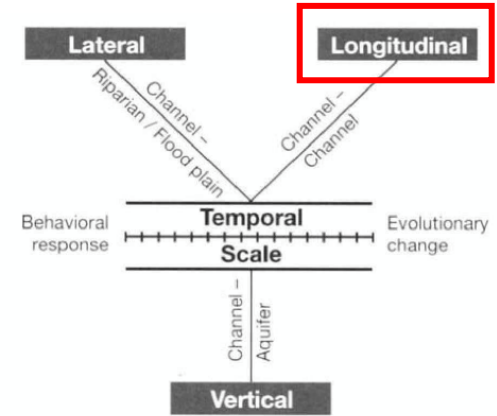
3) Longitudinal



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

The four-dimensional nature of stream and river ecosystems

3) Longitudinal



Mean annual discharge
(line width and transparency)
 10^{-1} 10^0 10^1 10^2 10^3 10^4 $\text{m}^3 \text{s}^{-1}$

Probability of flow intermittence
Non-perennial 1.00 0.75 0.50 0.25 0 Perennial

■ Lake or reservoir
■ No flow

Article

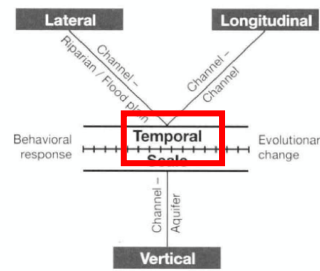
Global prevalence of non-perennial rivers and streams

Mathis Loïc Messager^{1,2}, Bernhard Lehner², Charlotte Cockburn¹, Nicolas Lamouroux², Hervé Pella², Ton Snelder², Klement Tockner^{4,5}, Tim Trautmann⁶, Caitlin Watt⁴ & Thibault Datry²

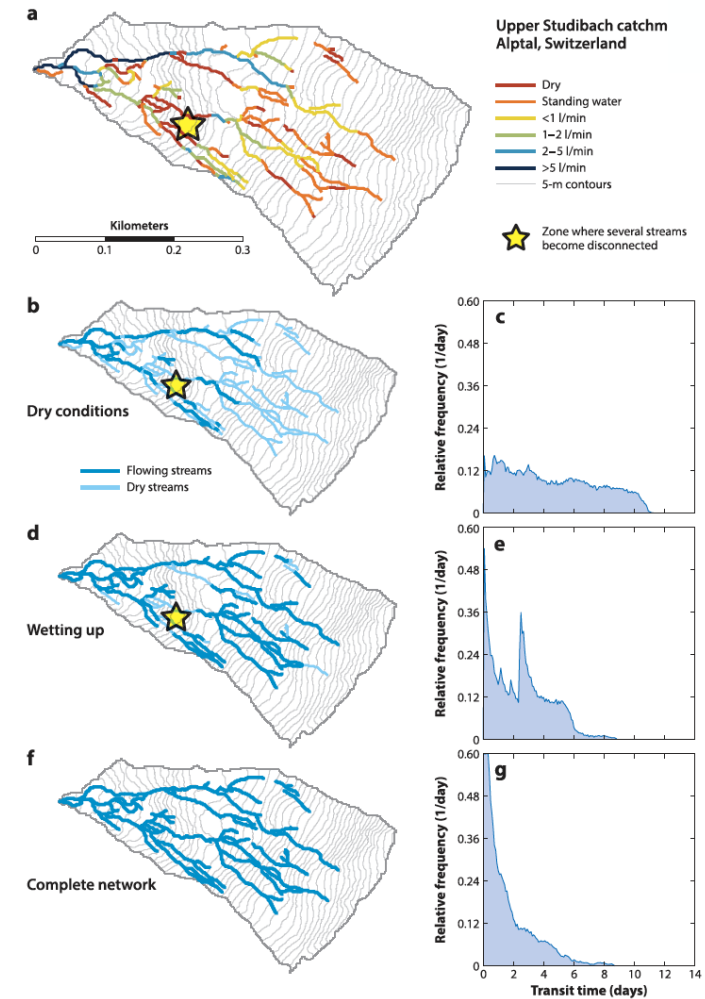
Water ceases to flow for at least one day per year along 51–60 per cent of the world’s rivers by length, demonstrating that non-perennial rivers and streams are the rule rather than the exception on Earth

The four-dimensional nature of stream and river ecosystems

4) 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 $5 \times 10^{-4} \text{ m s}^{-1}$ 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).

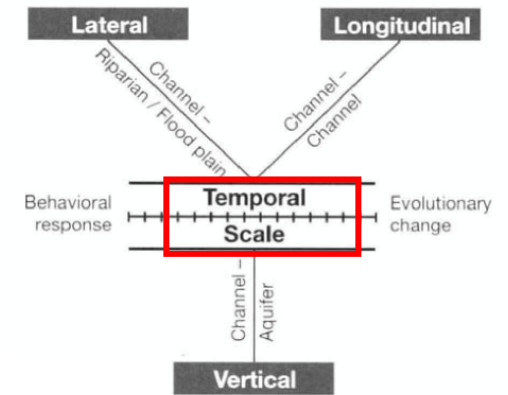
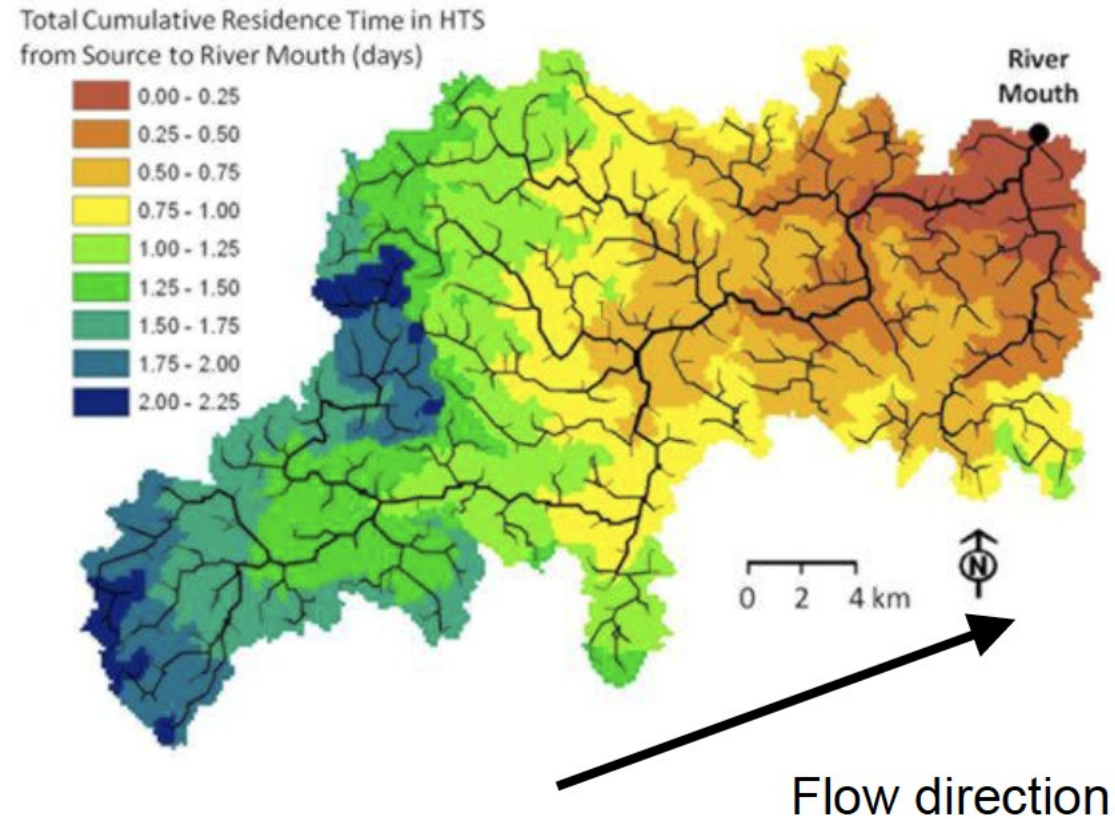
Annual Review of Earth and Planetary Sciences
 Instructive Surprises in the
 Hydrological Functioning of
 Landscapes

James W. Kirchner,^{1,2,3} Paolo Benettin,⁴
 and Ilja van Meerveld⁵

The four-dimensional nature of stream and river ecosystems

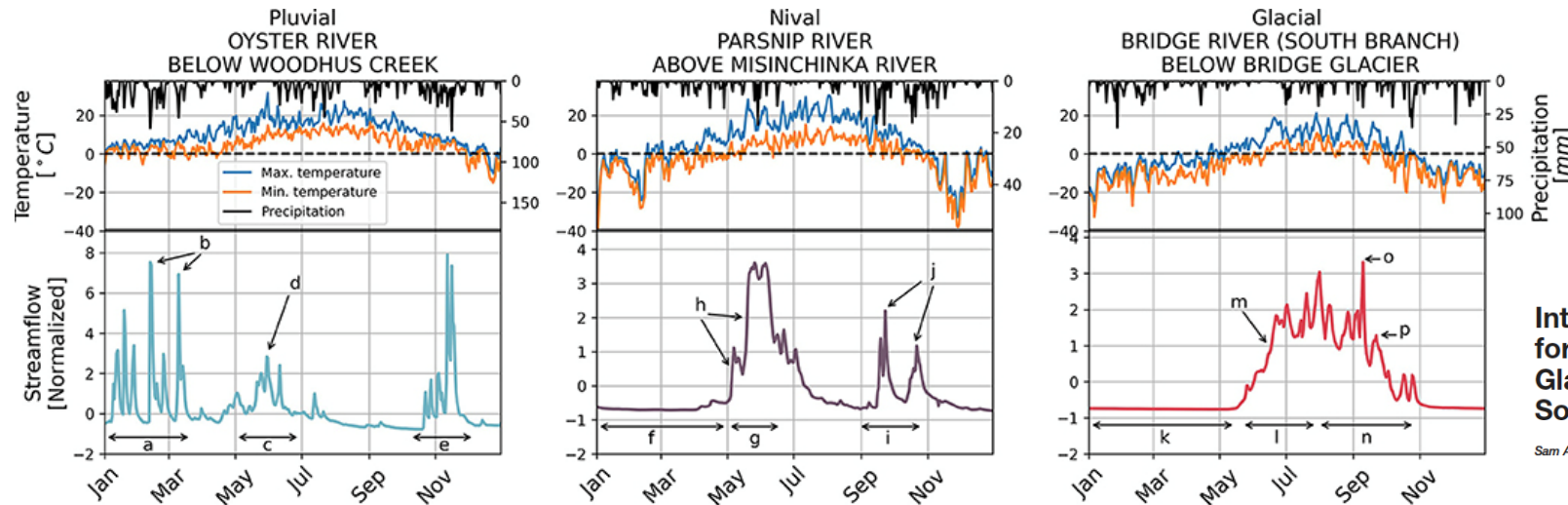
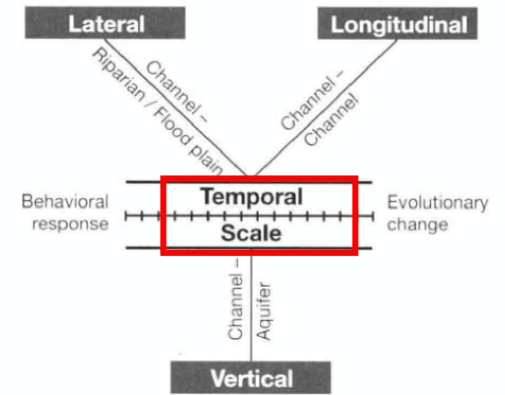
4) Temporal — Residence times

- 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

4) Temporal — Flow regimes



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

Sam Anderson and Valentina Radic*

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

4) Temporal — Flow regimes

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

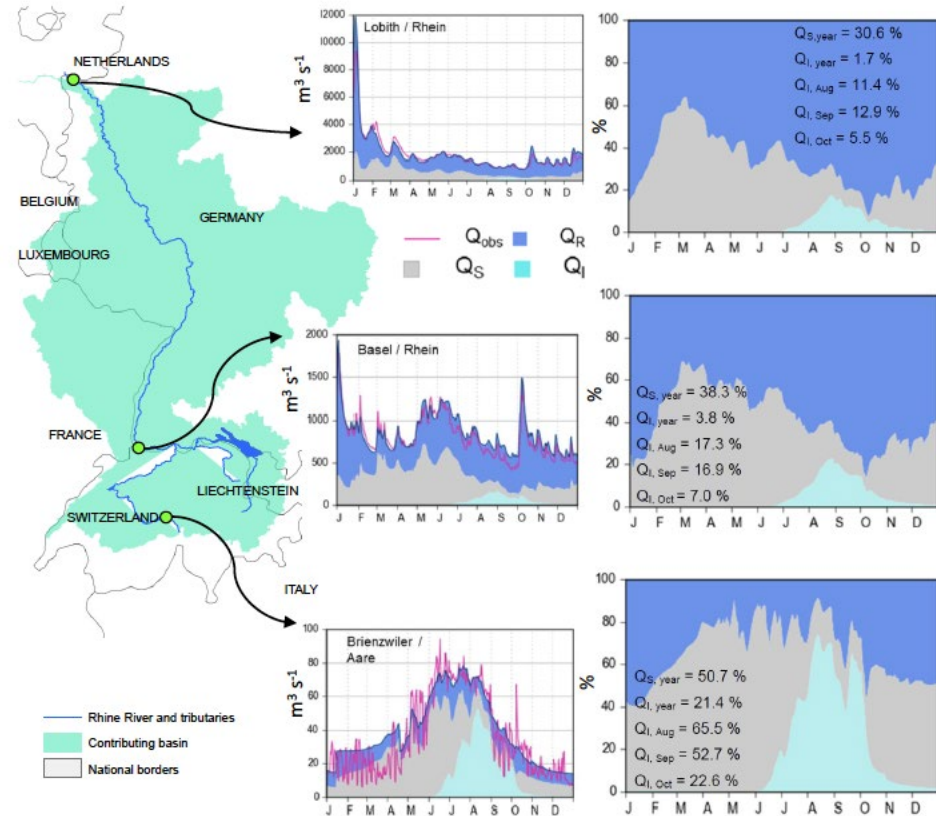
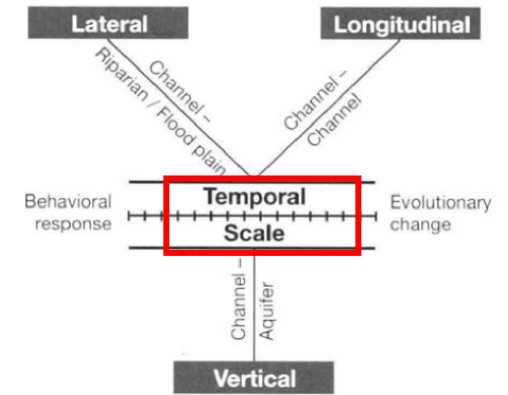


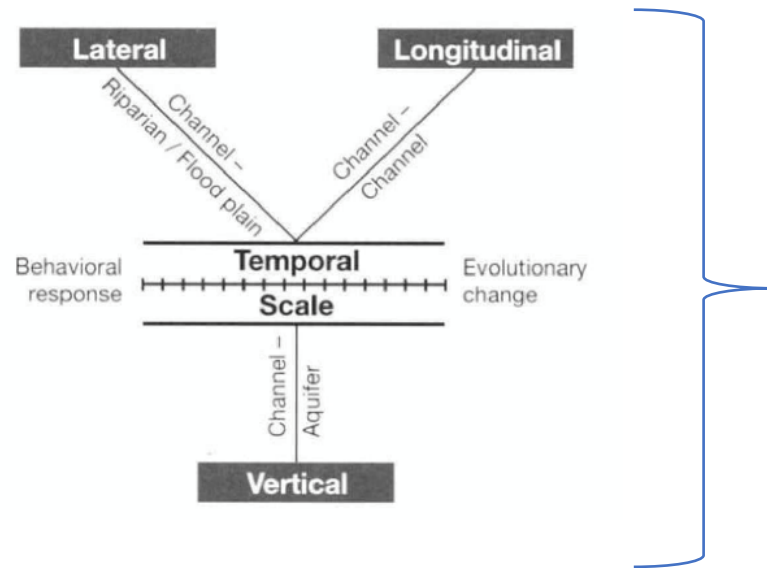
Figure 2.2: The role of ice melt along the Rhine River during drought conditions according to the CHR project. Absolute and relative estimated contributions of rain, snowmelt and ice melt to runoff are presented at the locations of Brienzwiler, Basel and Lobith in year 2003. Q_{obs} : Observed discharge,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



Glaciers

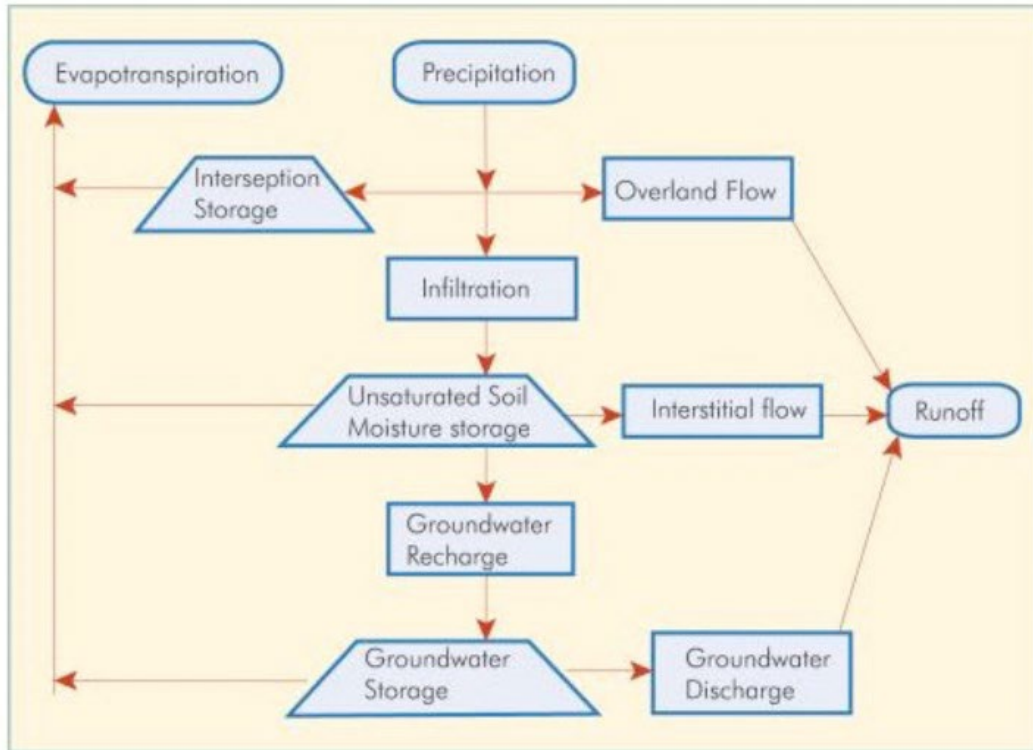
HYDRO-CH2018 SYNTHESIS REPORT CHAPTERS: "FUTURE CHANGES IN HYDROLOGY"

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



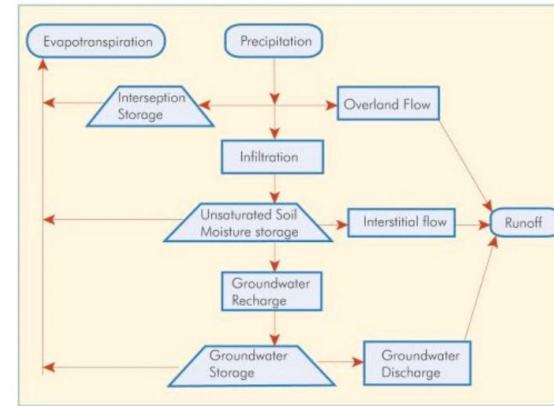
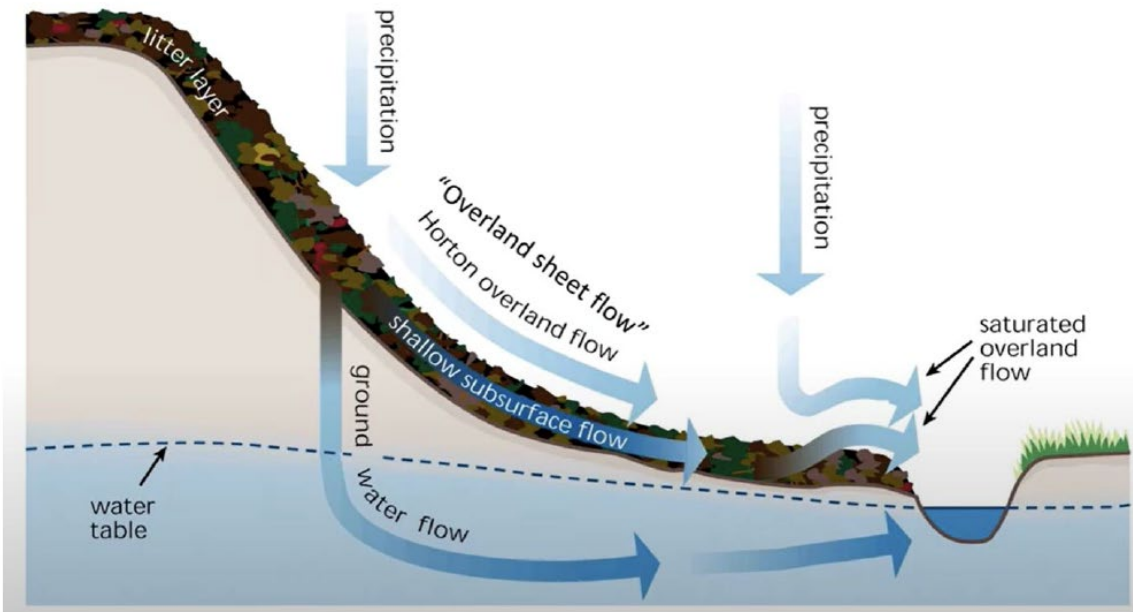
- Runoff generation
- Flow regimes
- Consequences for ecosystem functioning

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

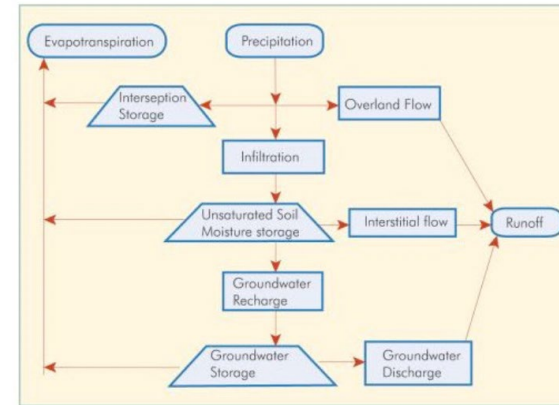
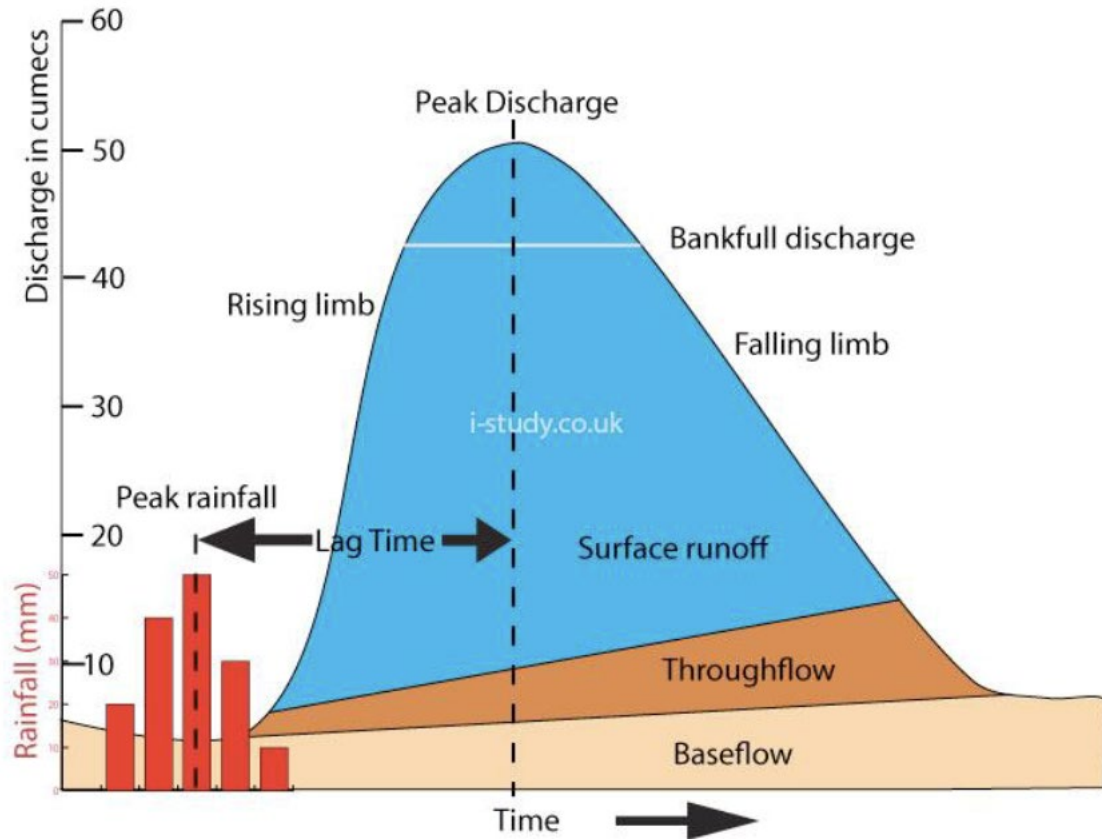
How does runoff generate and what are (some of) its consequences?



- 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?

Storm Hydrograph

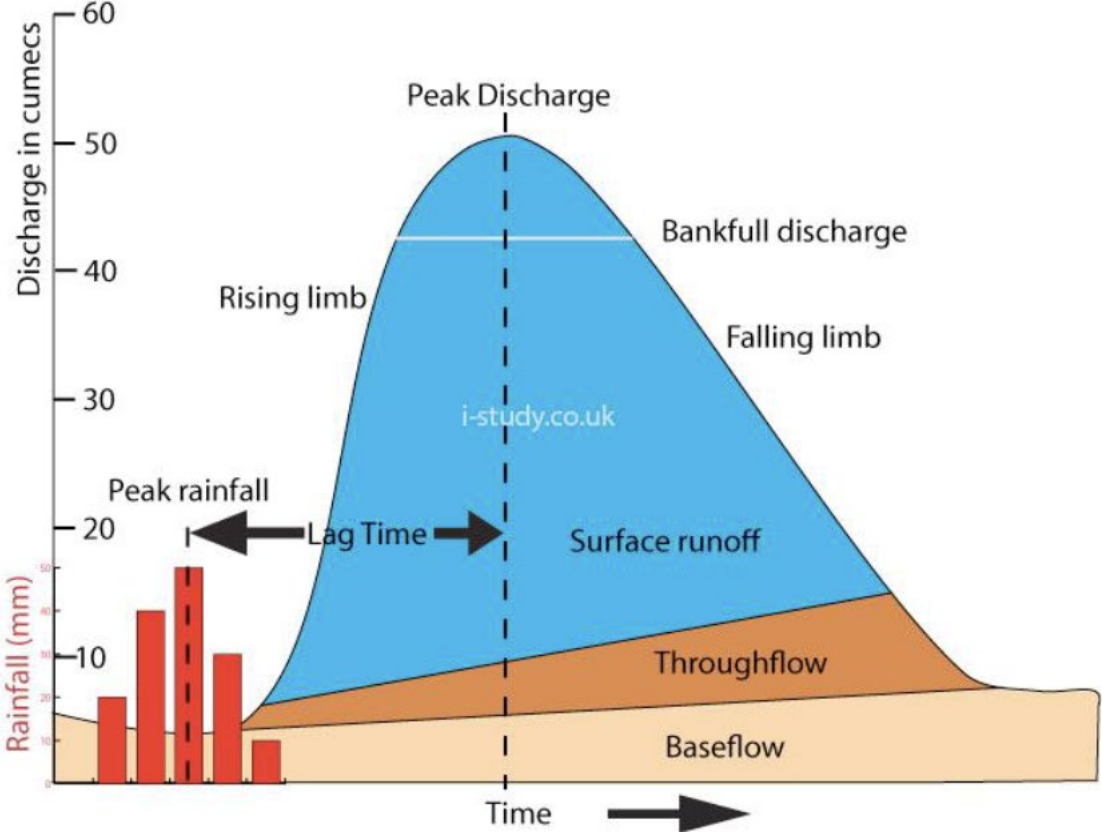


Hydrograph separation

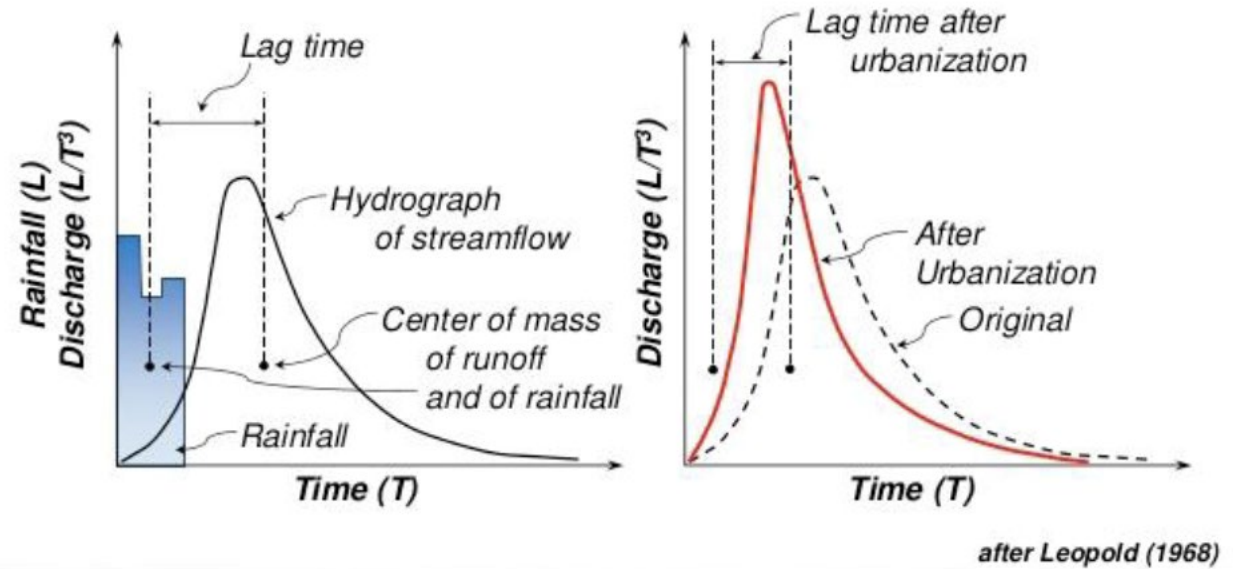
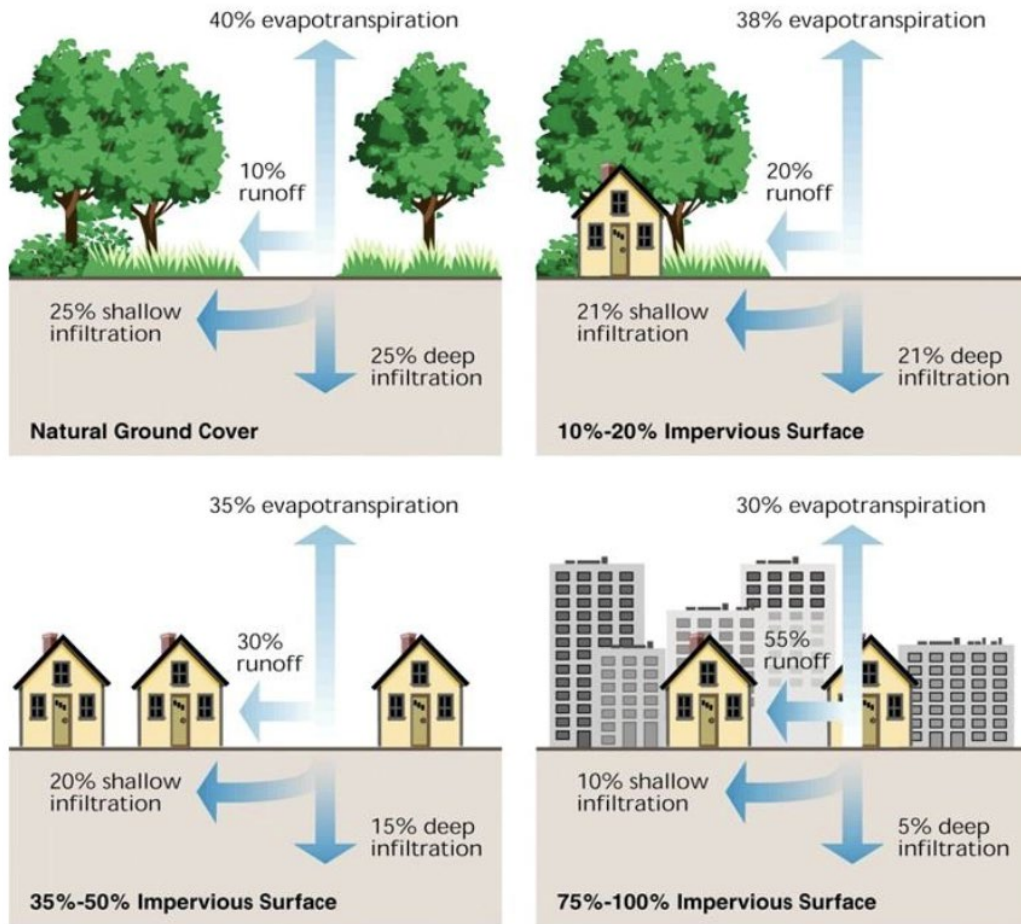
- Baseflow (from groundwater)
- Throughflow (interstitial flow)
- Surface runoff (overland flow)

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

Storm Hydrograph



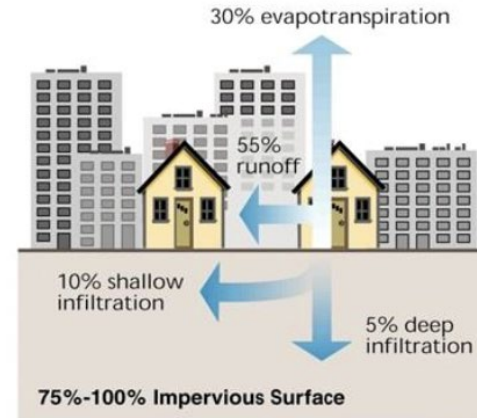
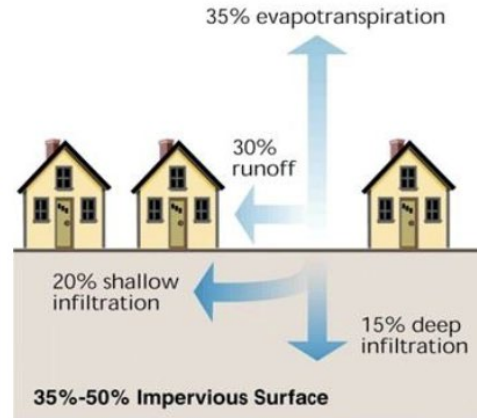
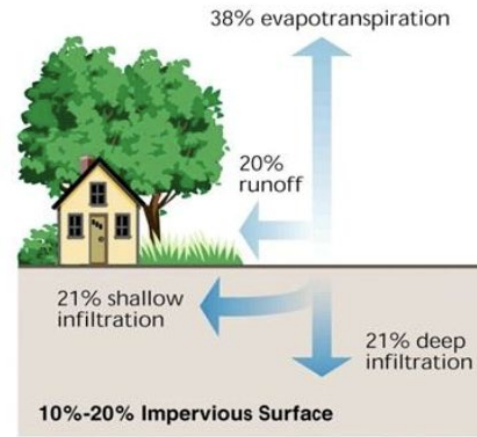
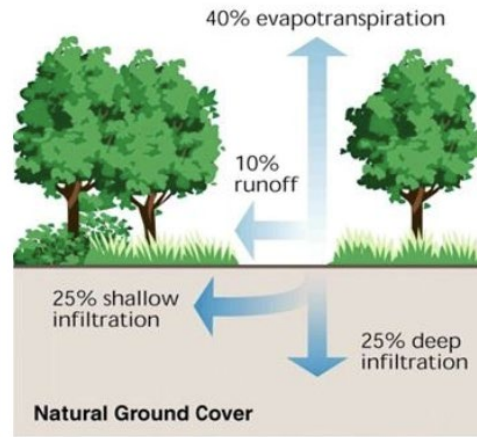
How does runoff generate and what are (some of) its consequences?



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



Inundation in central and eastern Europe

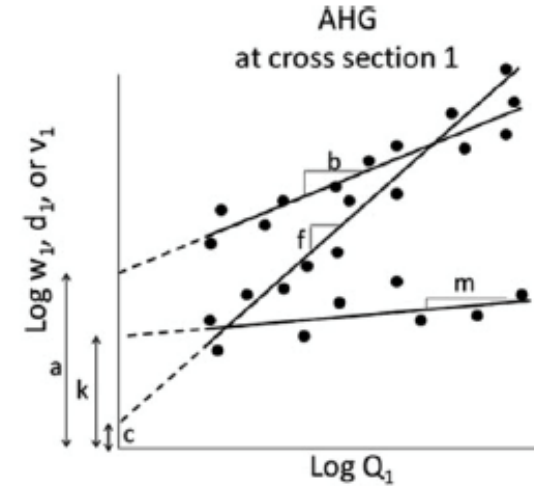
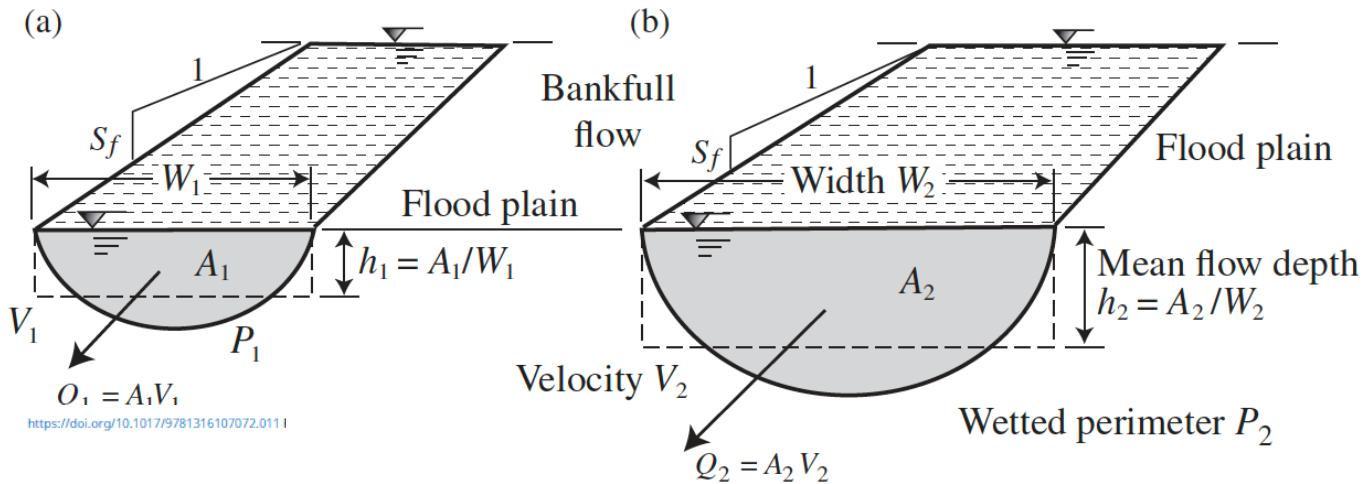


Catchment impermeabilisation,
hydrological response curves and
reduced residence times



What about river channelization (straightening and deepening channels)?

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

Continuity equation, $Q = wdv$,

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

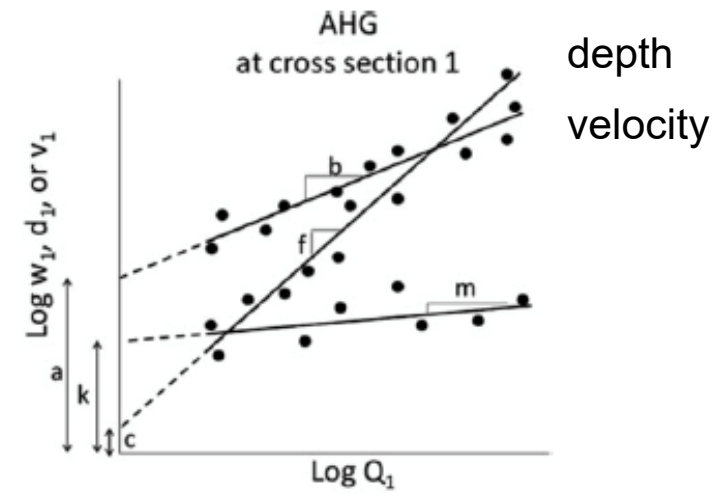
$$Q = ack Q^{b+f+m}$$

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

The consequences of which are.....

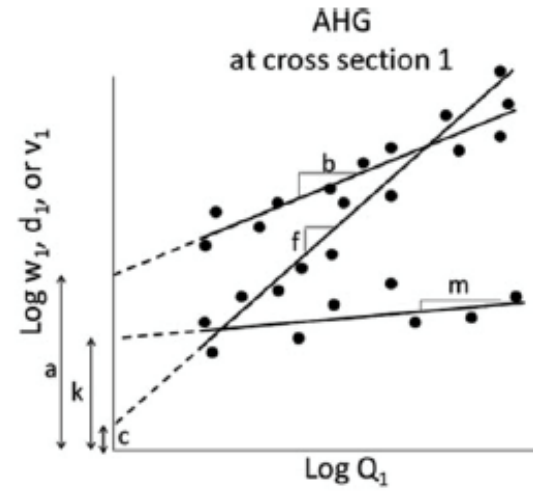


Hydraulic geometry

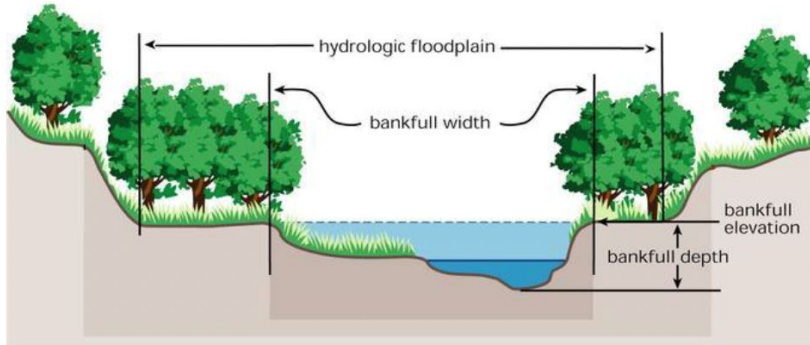


Elevated response in depth and velocity for channels that are constrained in width

Hydraulic geometry

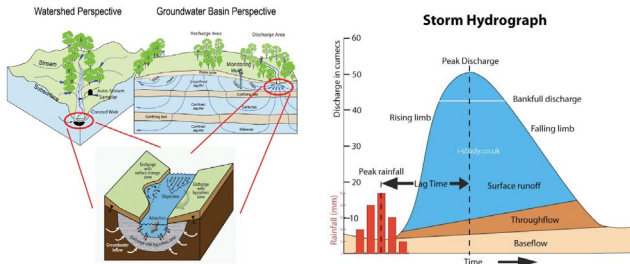


Elevated response in width — can lead to over-topping of the river banks — creating innundations



Hydrological flow paths, reconnecting our streams and rivers

Towards restoration and risk management

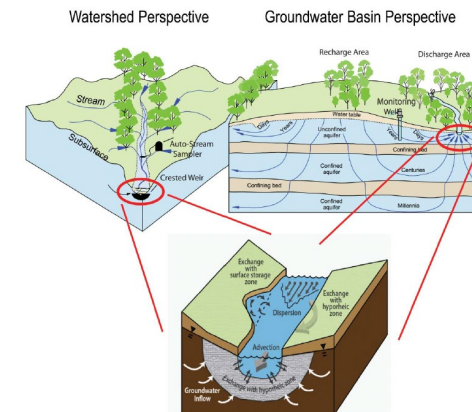
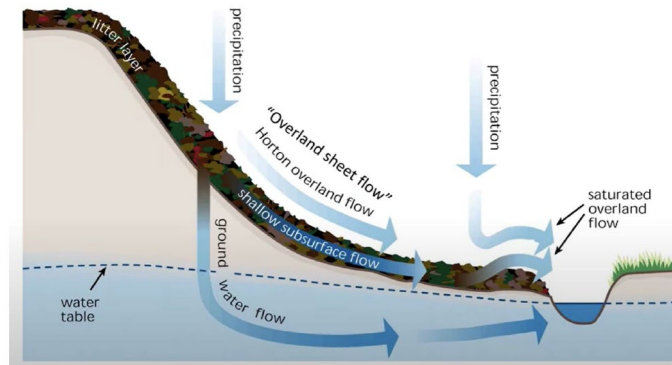


The screenshot shows the top of a webpage from the European Environment Agency (EEA). The header includes the EEA logo, the text 'European Environment Agency', and navigation links for 'Topics', 'Analysis and data', 'Countries', 'Newsroom', and 'About us'. A search icon is visible in the top right. The main content area features a large green background image of a floodplain with a river. A 'NEWS' tag is present. The article title is 'Restoring floodplains would improve state of water, ecosystems and climate protection in Europe'. The text below the title states: '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.' At the bottom of the article preview, it says 'Published 19 Nov 2018 — Last modified 19 Nov 2018 — 1 min read — Photo: © Suleyman Uzumcu, WaterPIX / EEA' and a PDF icon.

Home > News > Restoring floodplains would ...

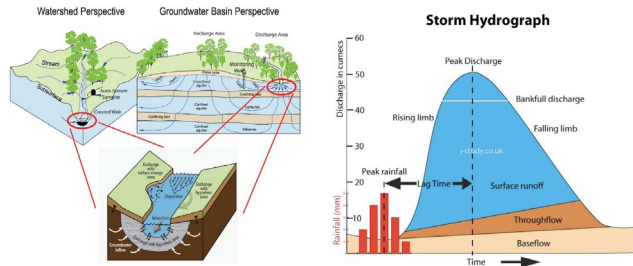
The EEA briefing [‘Why should we care about floodplains?’](#) analyses the potential benefits of restoring natural areas next to rivers that are covered by water during floods. According to the analysis, these areas can deliver valuable cultural and ecosystem services, including a cost-effective alternative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

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

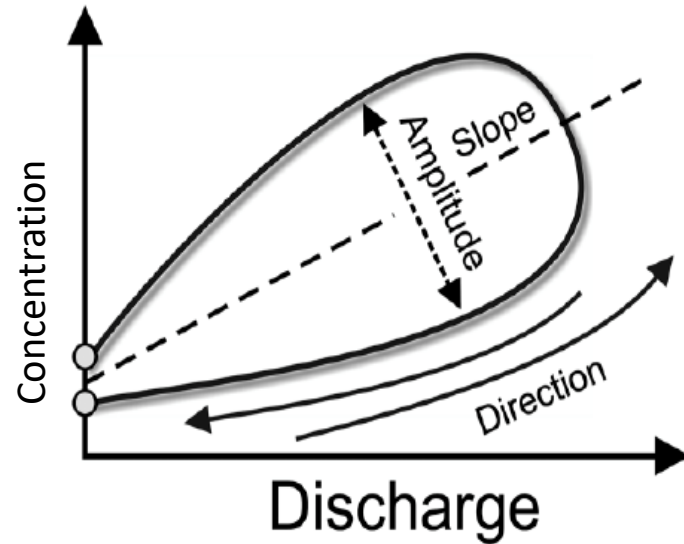


Hydrological flow paths and the chemical birth of water

Hysteresis loops



Hysteresis



- 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

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-Oudoux ^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

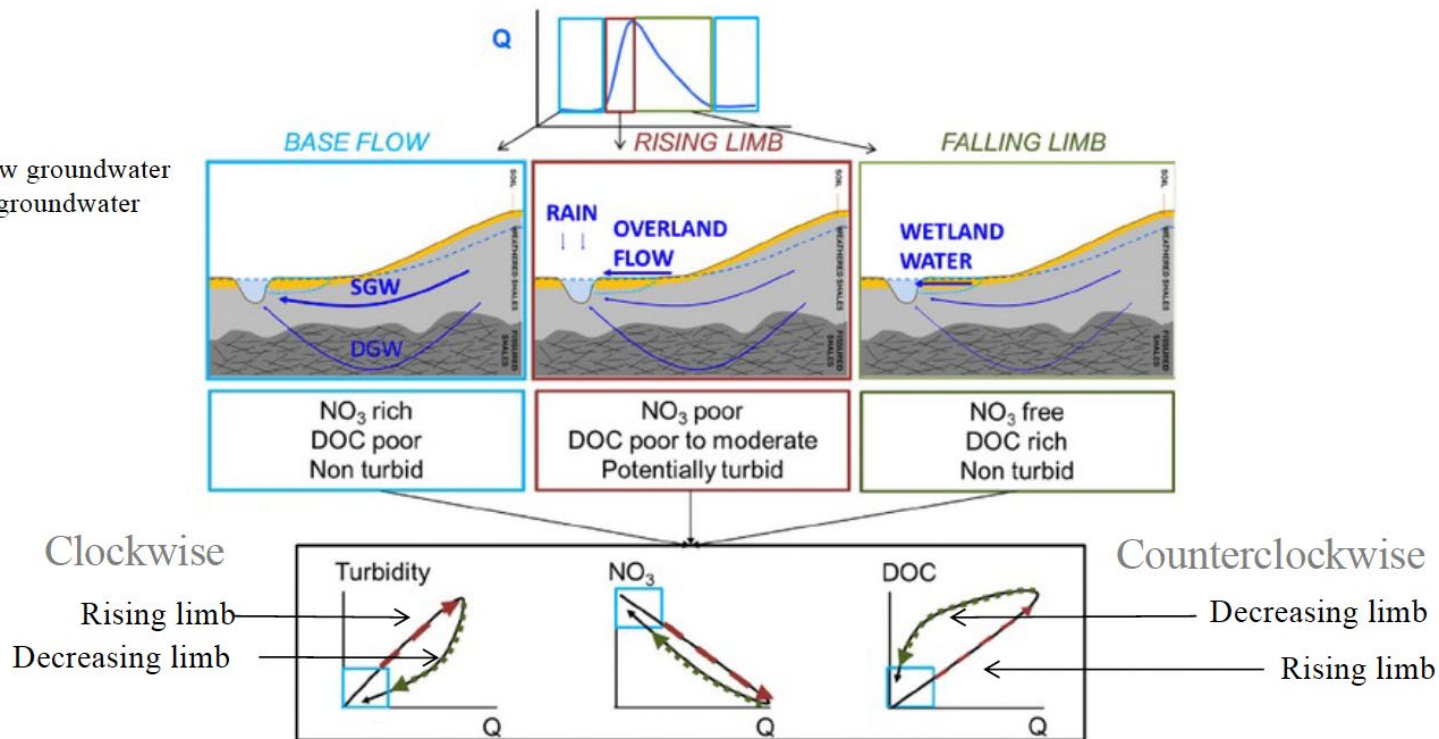


Fig. 4. Sketch of the successive dominant flow paths and related properties regarding their chemical composition. SGW: shallow groundwater; DGW: deep groundwater. Such a succession leads to the typical observed hysteretic patterns: Clockwise Tu-Q with accretion, Clockwise NO₃-Q with dilution and Anticlockwise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

Mobilisation of sediments

Diluting effect on NO₃-rich groundwater

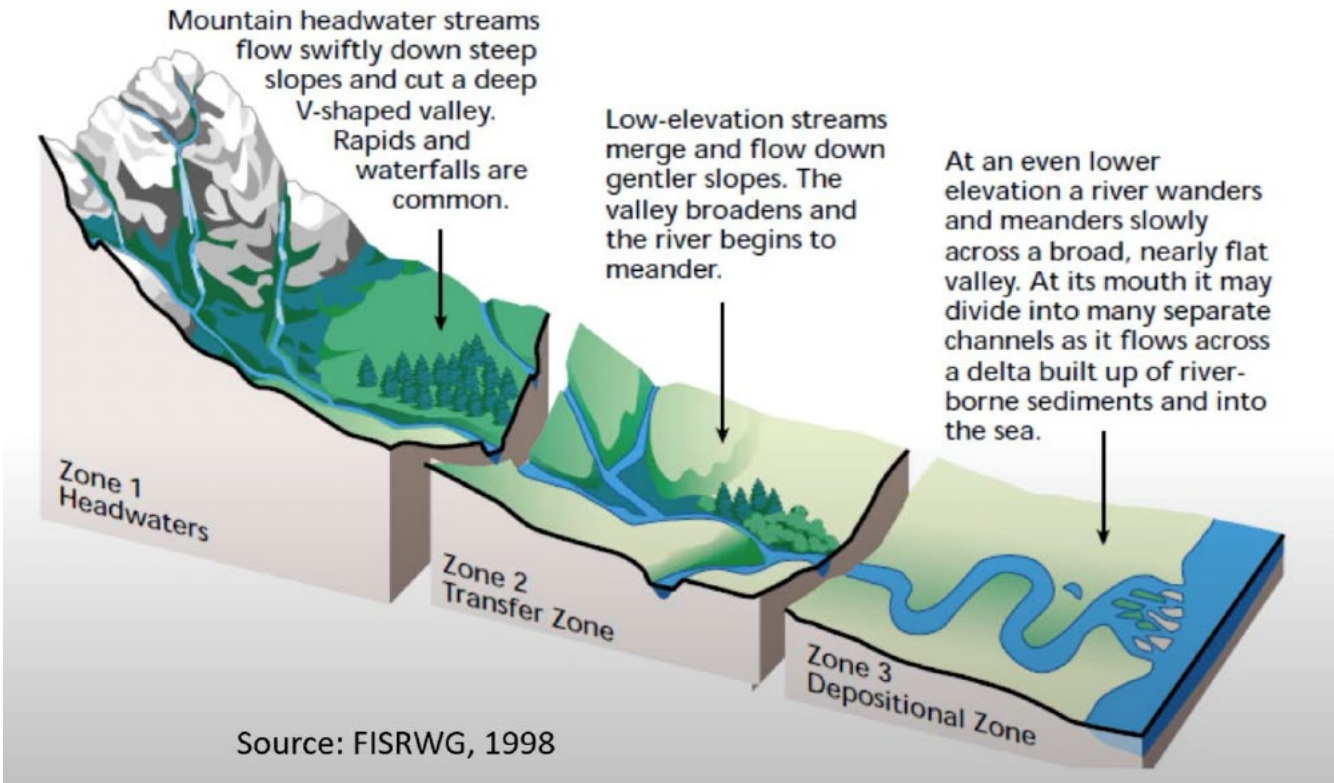
Mobilisation of DOC from sources other than sediments and NO₃

Spatial heterogeneity of streams and rivers



Spatial heterogeneity of streams and rivers

[spanning catchments and biomes — hence elevational gradients]

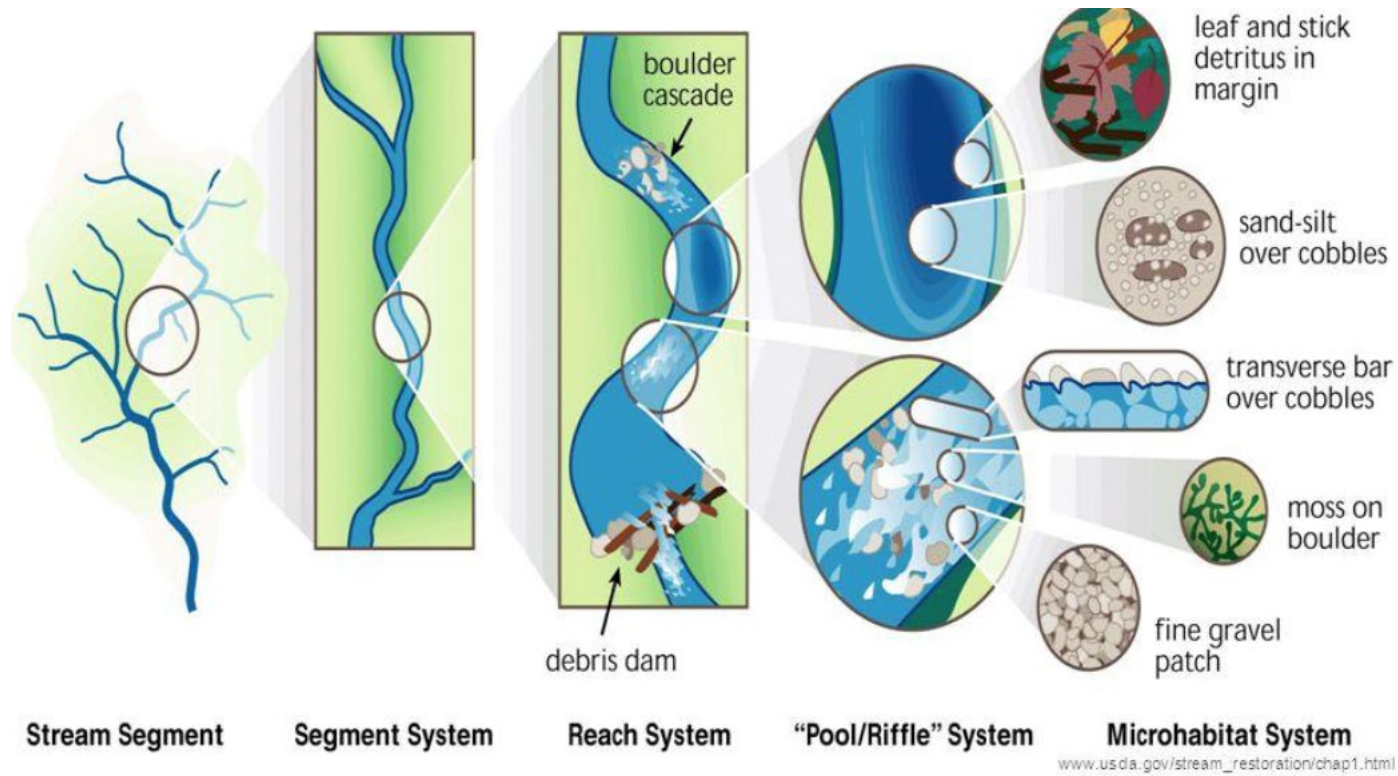


Landscape-scale spatial heterogeneity

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

Spatial heterogeneity of streams and rivers

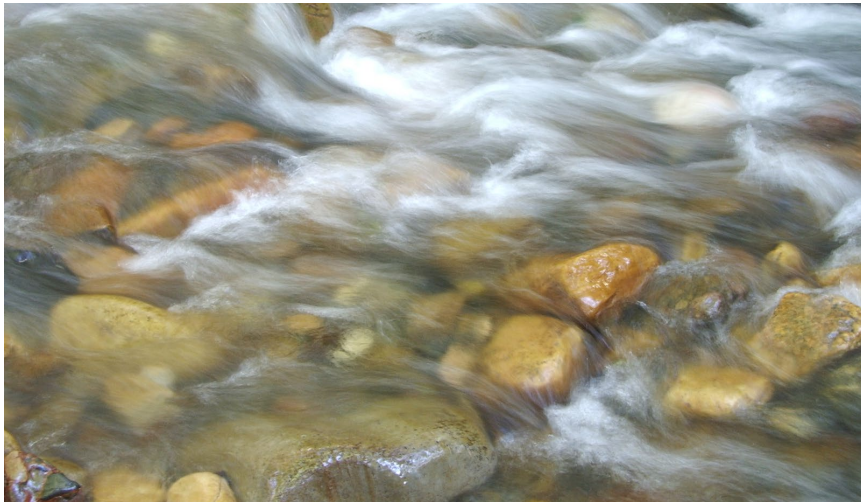
From networks to microhabitats



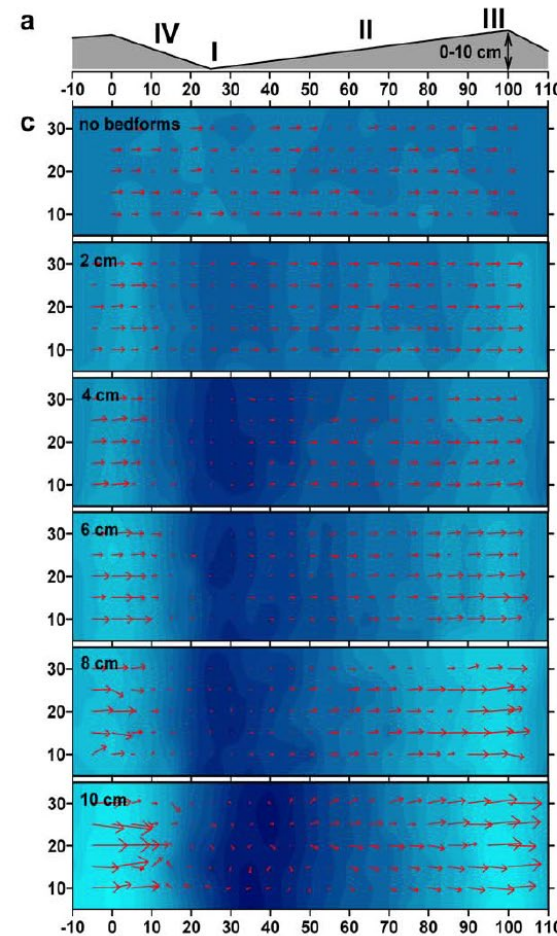
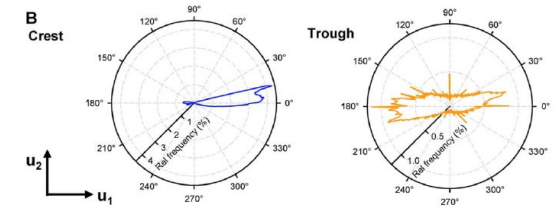
- Cross-scale spatial heterogeneity — at the interface between geomorphology and hydraulics — from the reach to microhabitats
- Critical for biodiversity and ecosystem functioning

Small-scale hydraulic heterogeneity Microhabitats

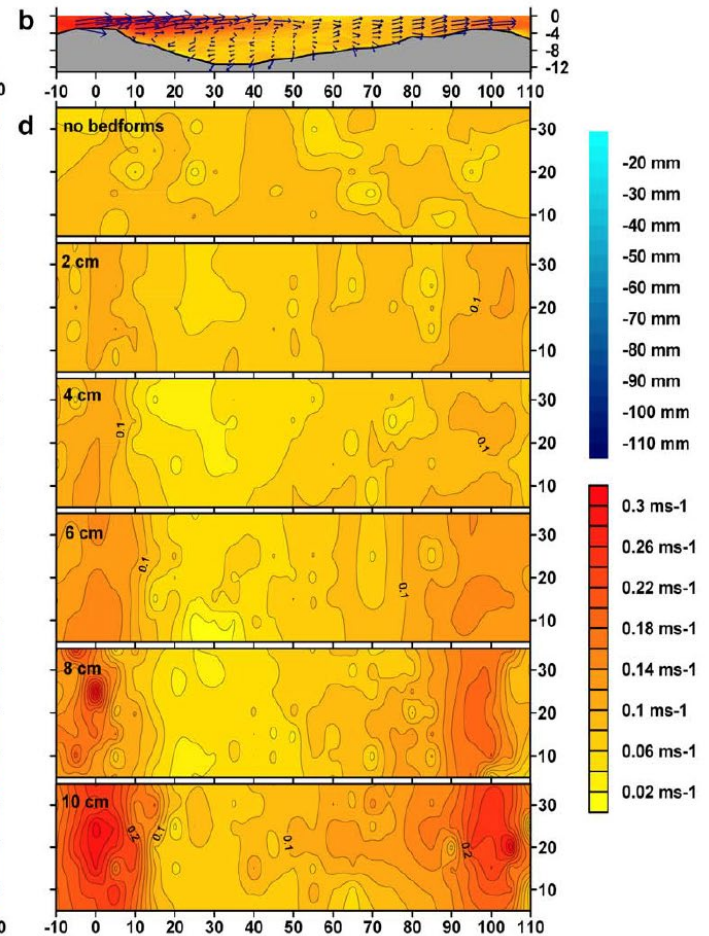
- Roughness structures and non-compressibility of water induce flow structures
- Turbulence-related phenomena (e.g., transport, shear forces, uplift, gas transfer) affect life and biogeochemistry in streams and rivers



Bedforms



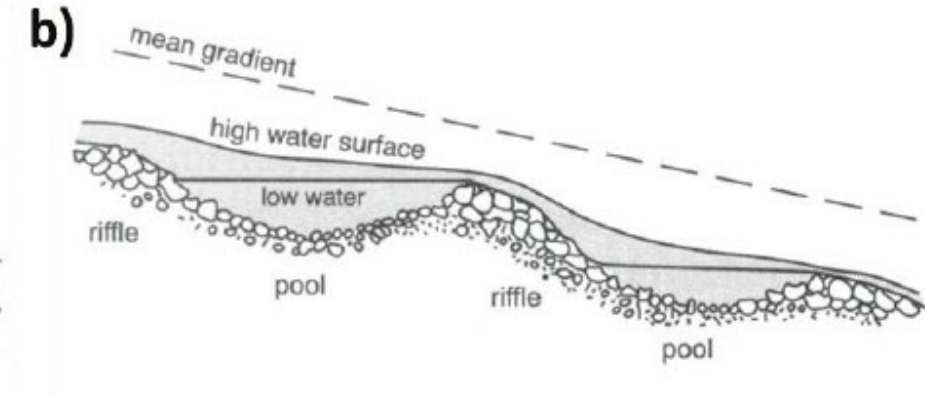
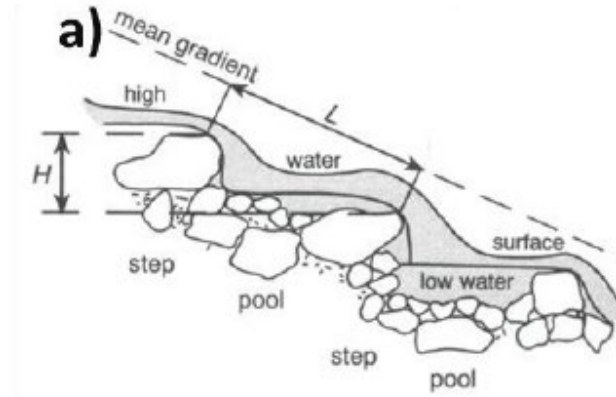
Water depth
distributions



Three-dimensional flow
velocity distributions

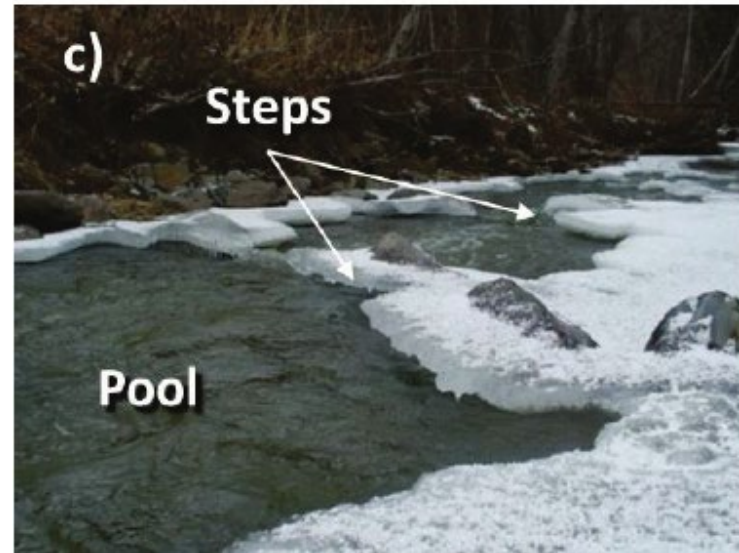
Reach-scale satial heterogeneity

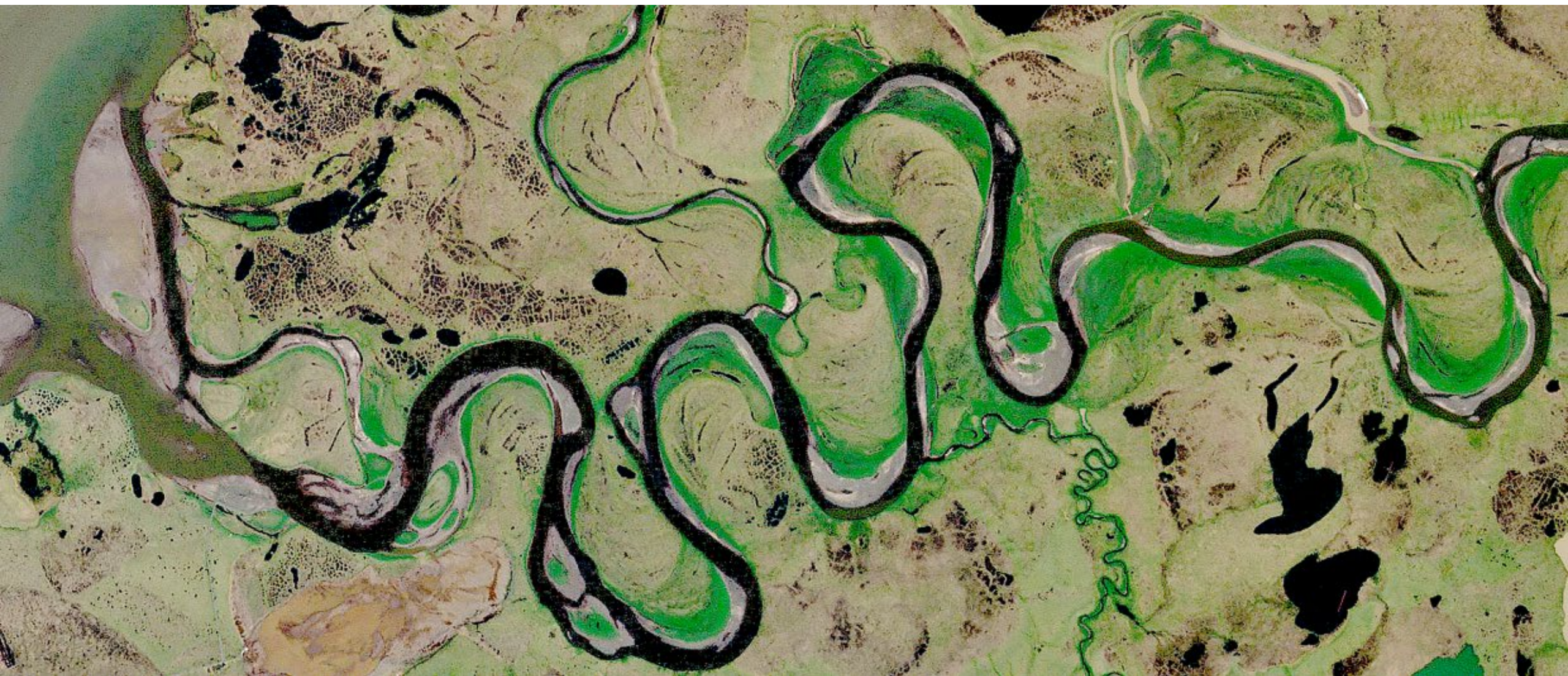
Step-pool and riffle-pool sequences



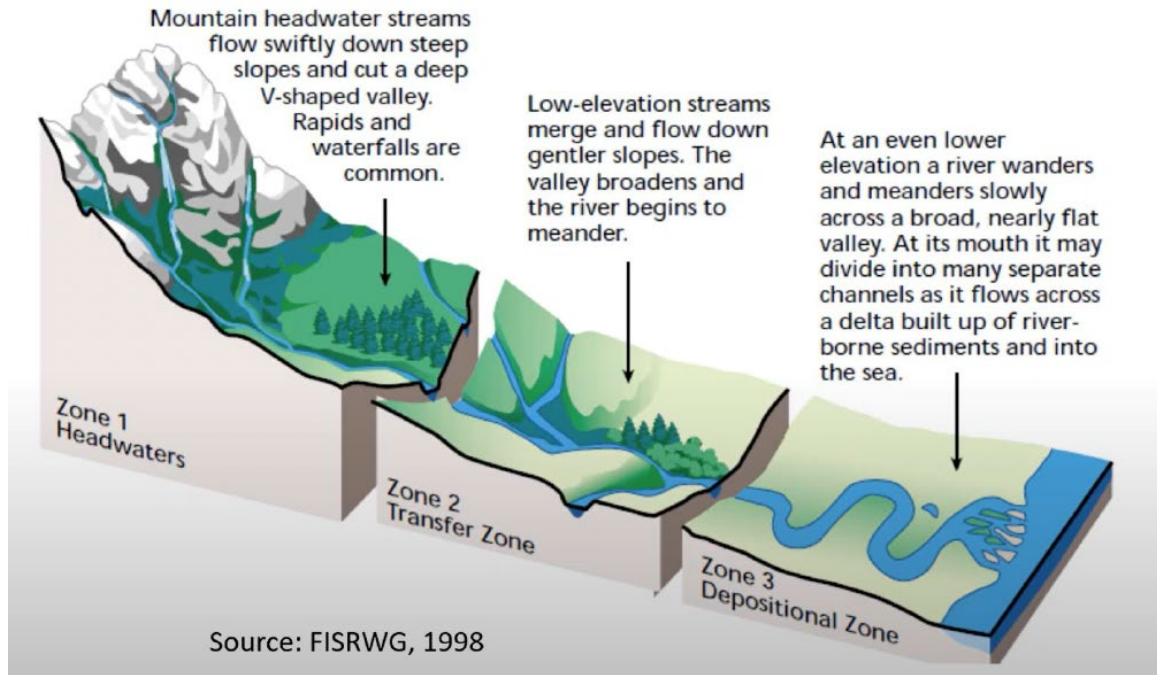
Elevated slope: step-pool
Reduced slope: riffle-pool

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



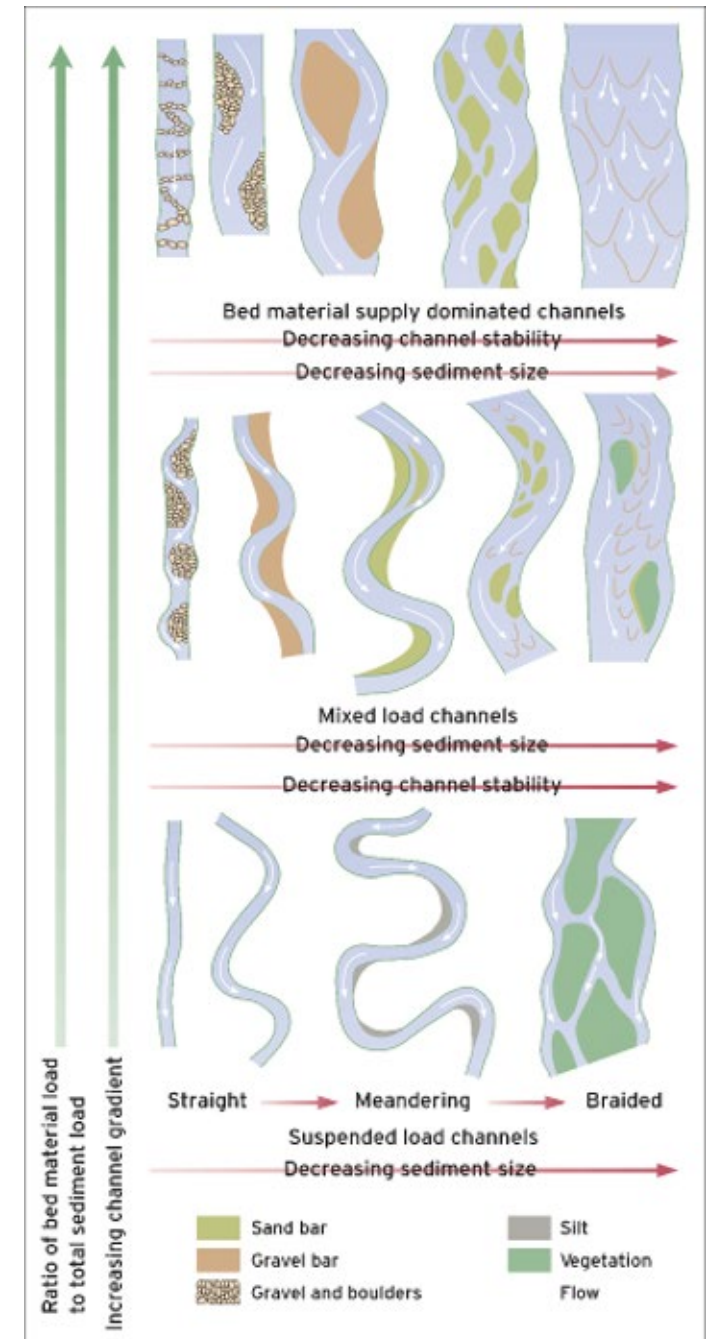


From braided to meandering streams and rivers

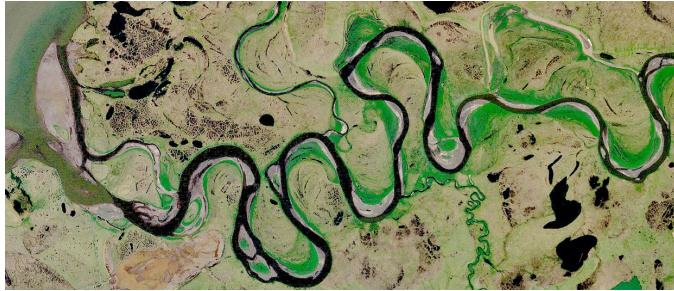


- Slope and energy
- Channel and bed stability
- Sediment load and size distribution

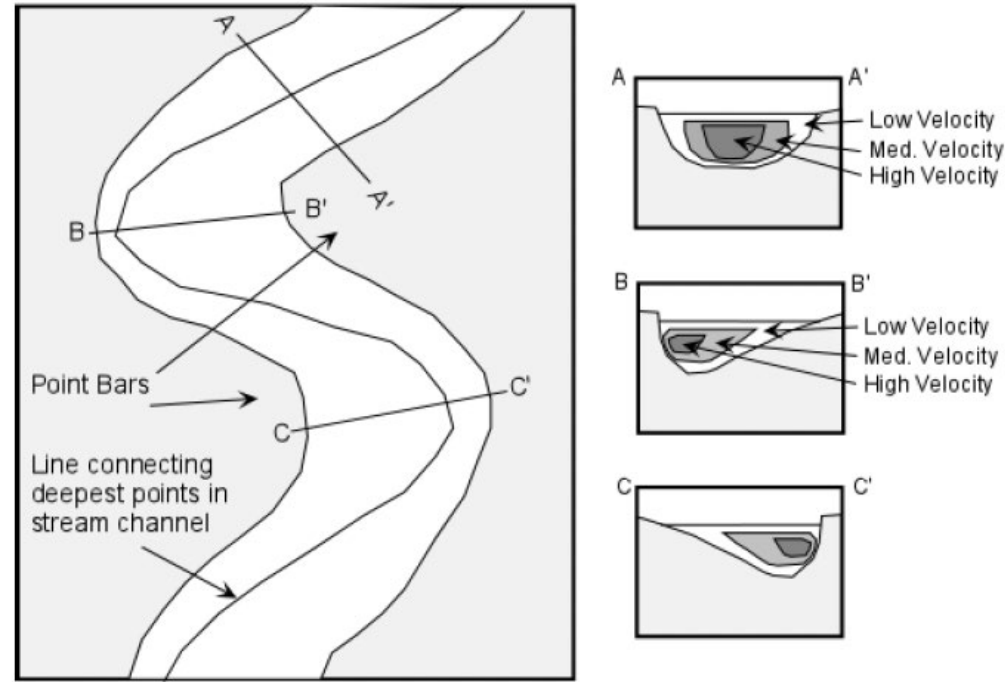
Consequences: connectivity, residence times, vegetation, biodiversity and ecosystem functioning



Meander formation



Meandering Channels



- 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