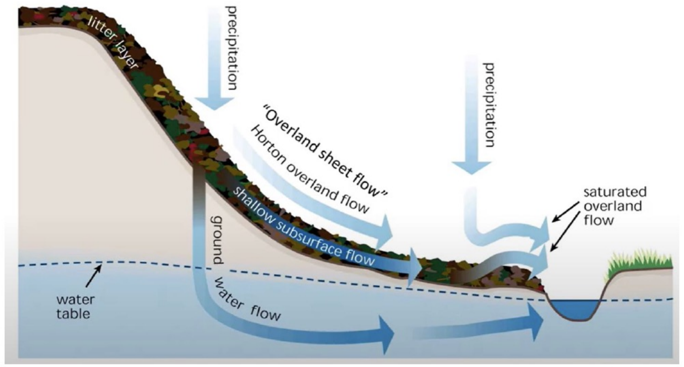
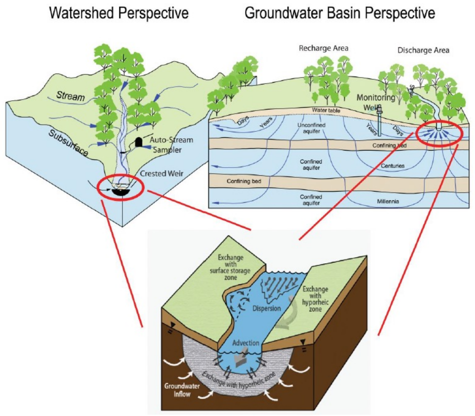
Hydrological and hydraulic perspectives of fluvial ecosystems

- Spatial heterogeneity
- Hyporheic exchange
- Atmospheric exchange

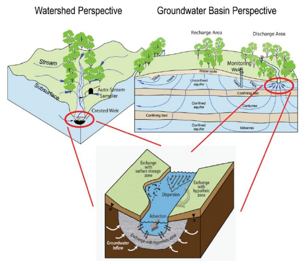
How do various flow paths of water through the landscape affect streamwater chemistry?

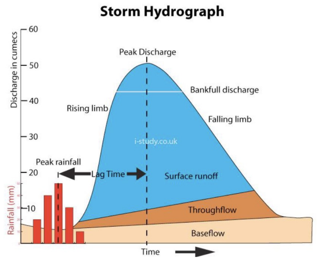


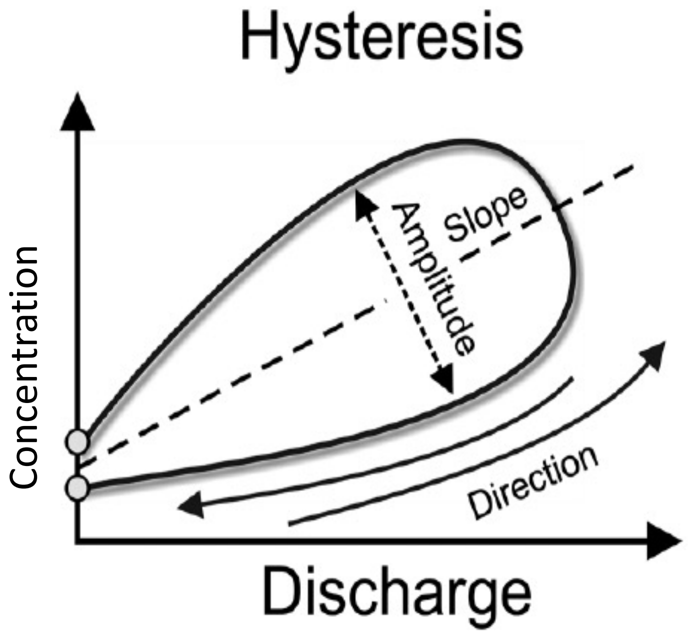


Hydrological flow paths and the chemical birth of water

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 potentially high terrestrial inputs
- A clockwise direction of change over the course of the storm event indicates that solute sources are proximal to the stream and spatially connected to each other
- 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 — high hydrological connectivity

Journal of Hydrology 559 (2018) 282–293

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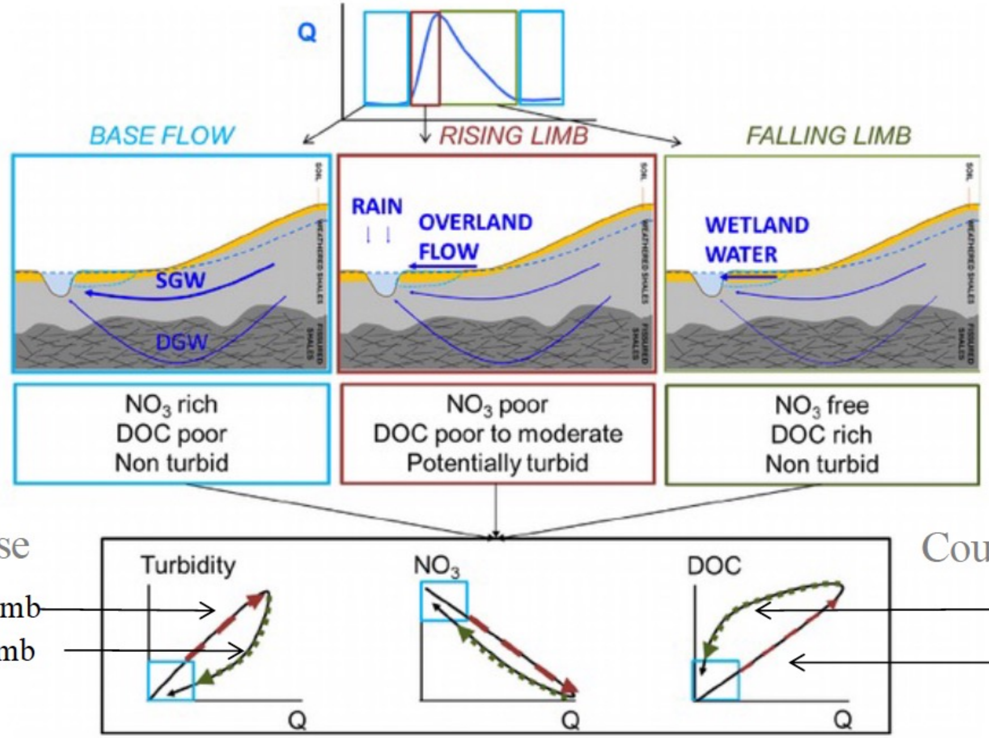
Research papers

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

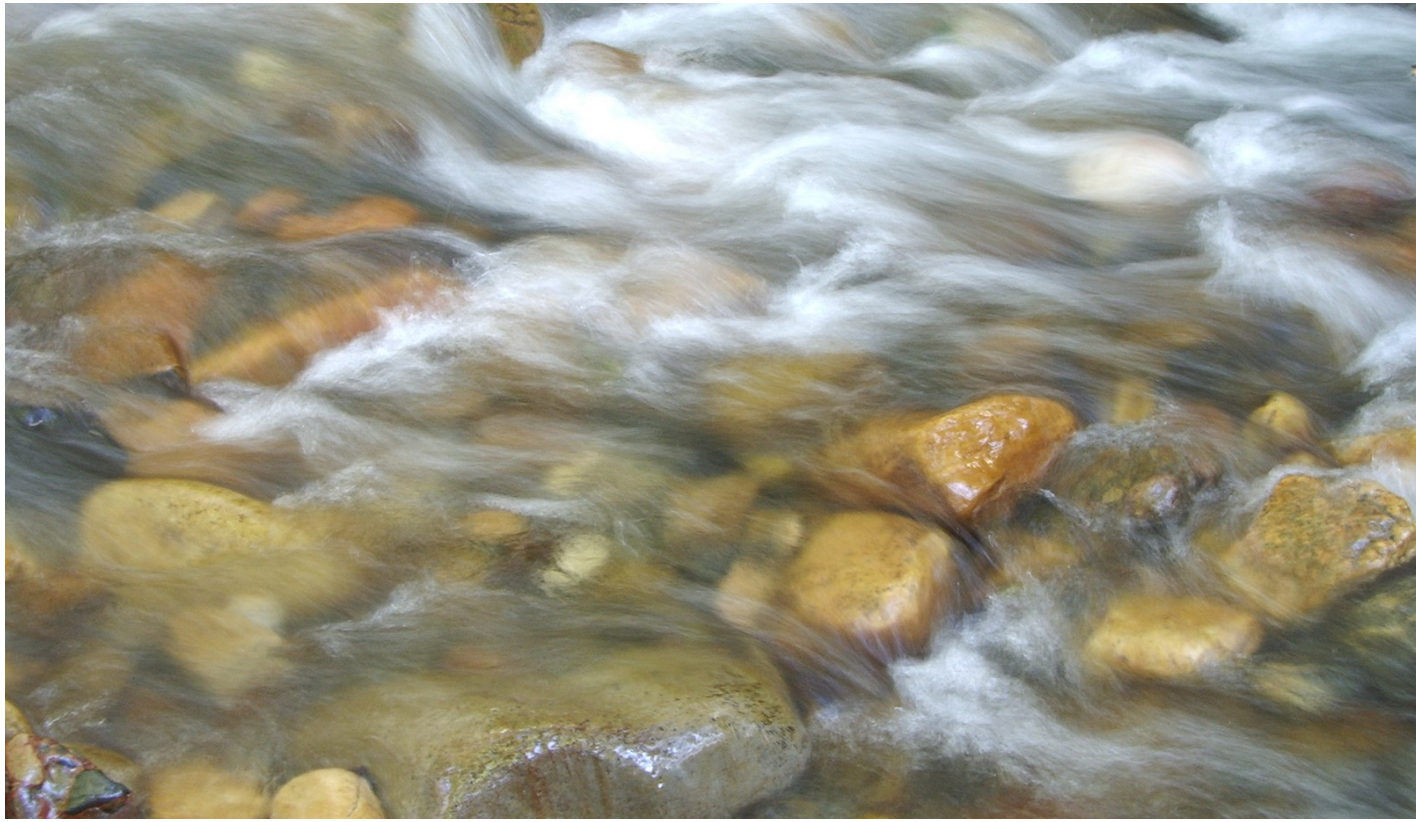
Fig. 4. Sketch of the successive dominant flow paths and related properties regarding their chemical composition. SGW: shallow groundwater; DGW: deep groundwater. Such a succession leads to the typical observed hysteretic patterns: Clockwise Tu-Q with accretion, Clockwise NO3-Q with dilution and Anticlockwise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

Mobilisation of sediments

Diluting effect on NO_3-rich groundwater

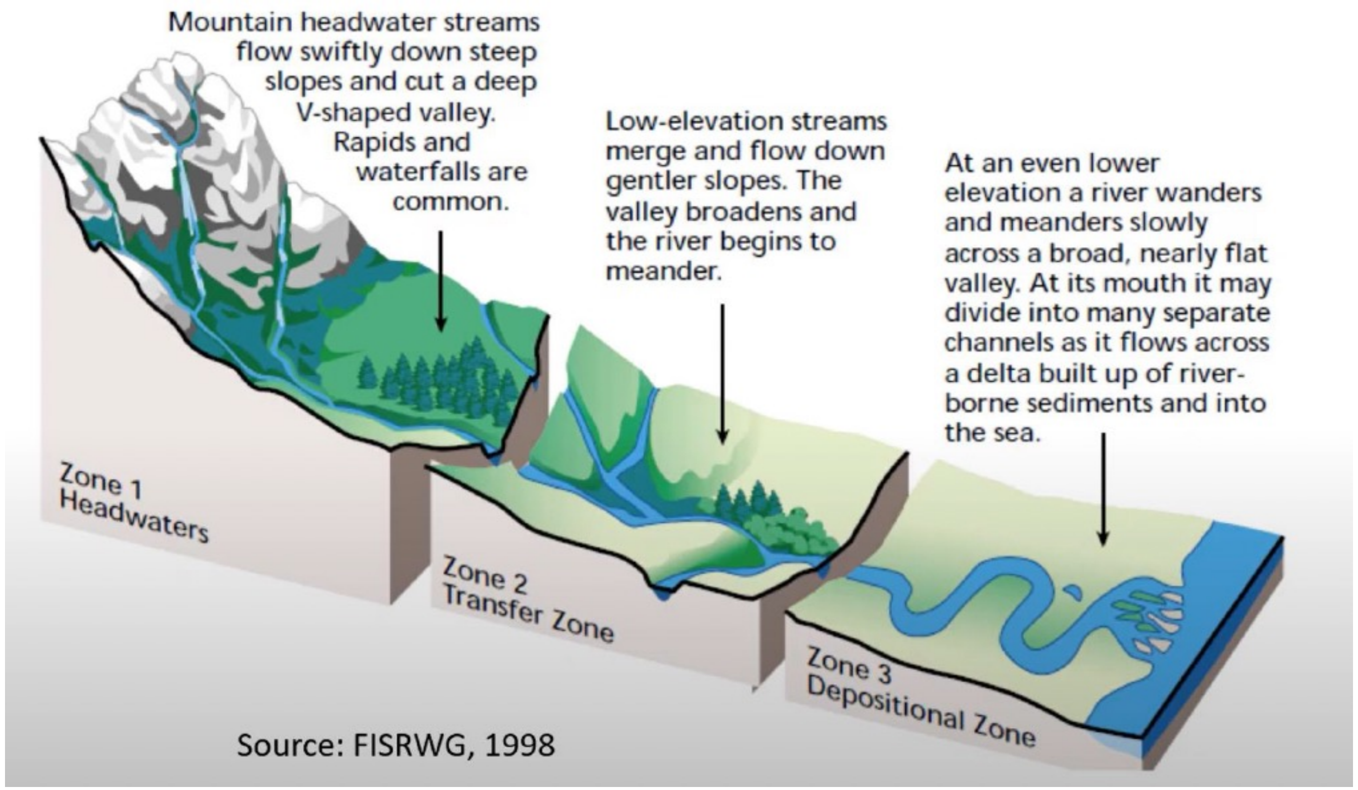
Mobilisation of DOC from sources other than sediments and NO_3

Spatial heterogeneity of streams and rivers



Spatial heterogeneity of streams and rivers

[spanning catchments and biomes — hence elevational gradients]

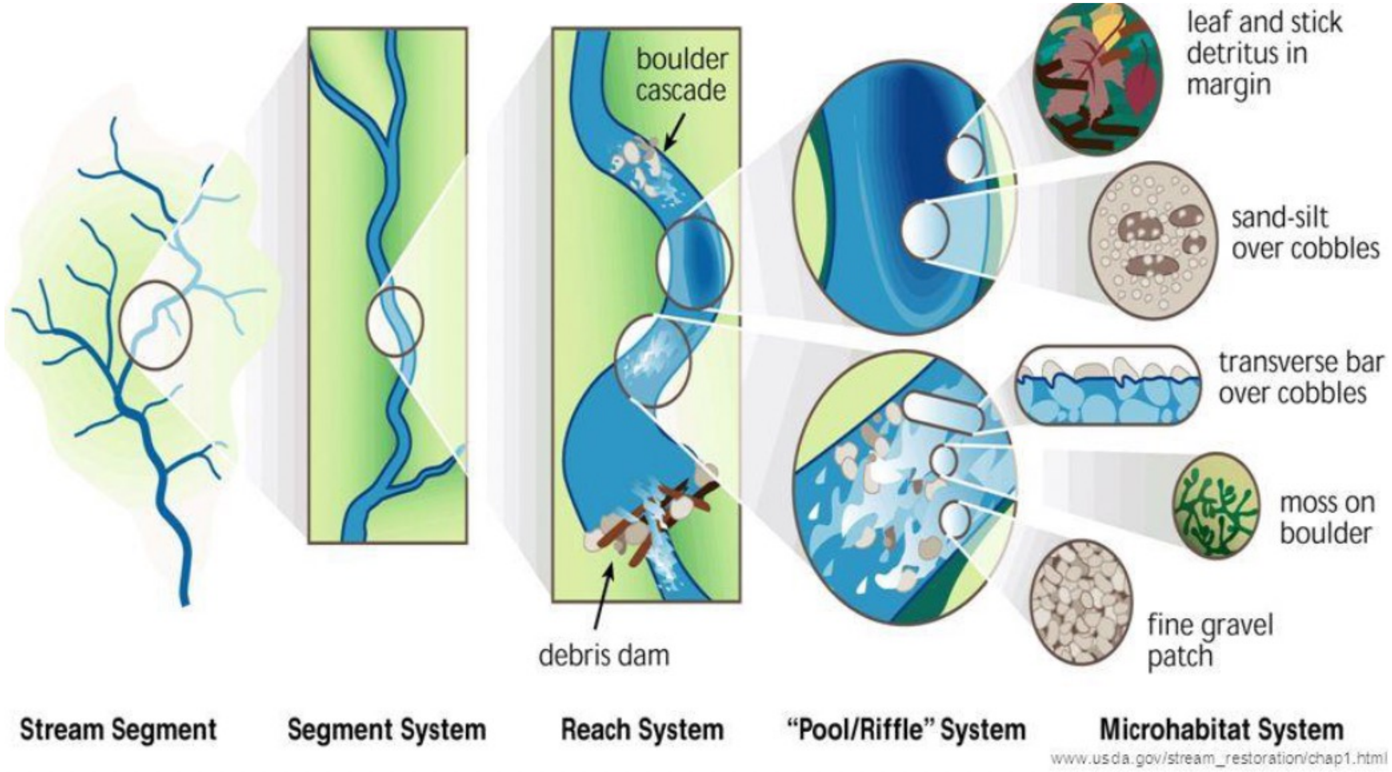


Landscape-scale spatial heterogeneity

- 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

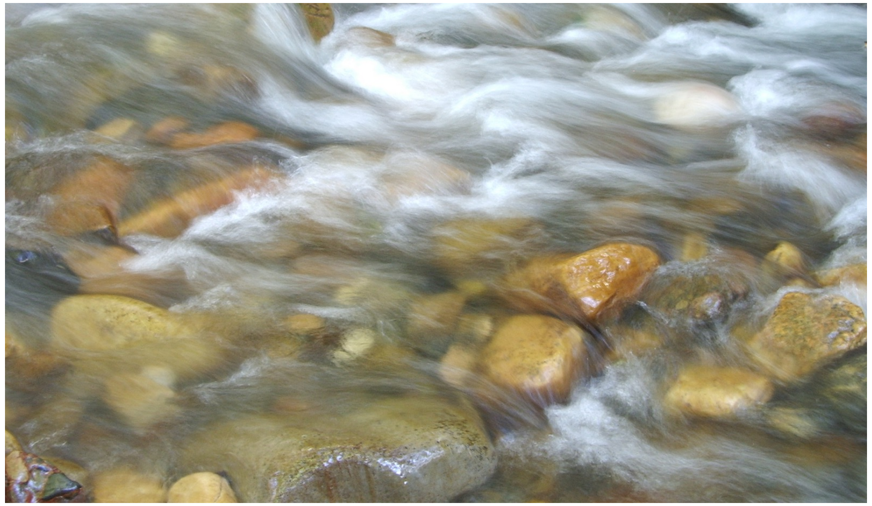


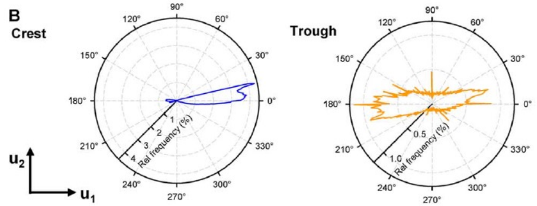
- Cross-scale spatial heterogeneity — at the interface beween geomorphology and hydraulics — from the reach to microhabitats
- Critical for biodiversity and ecosystem functioning

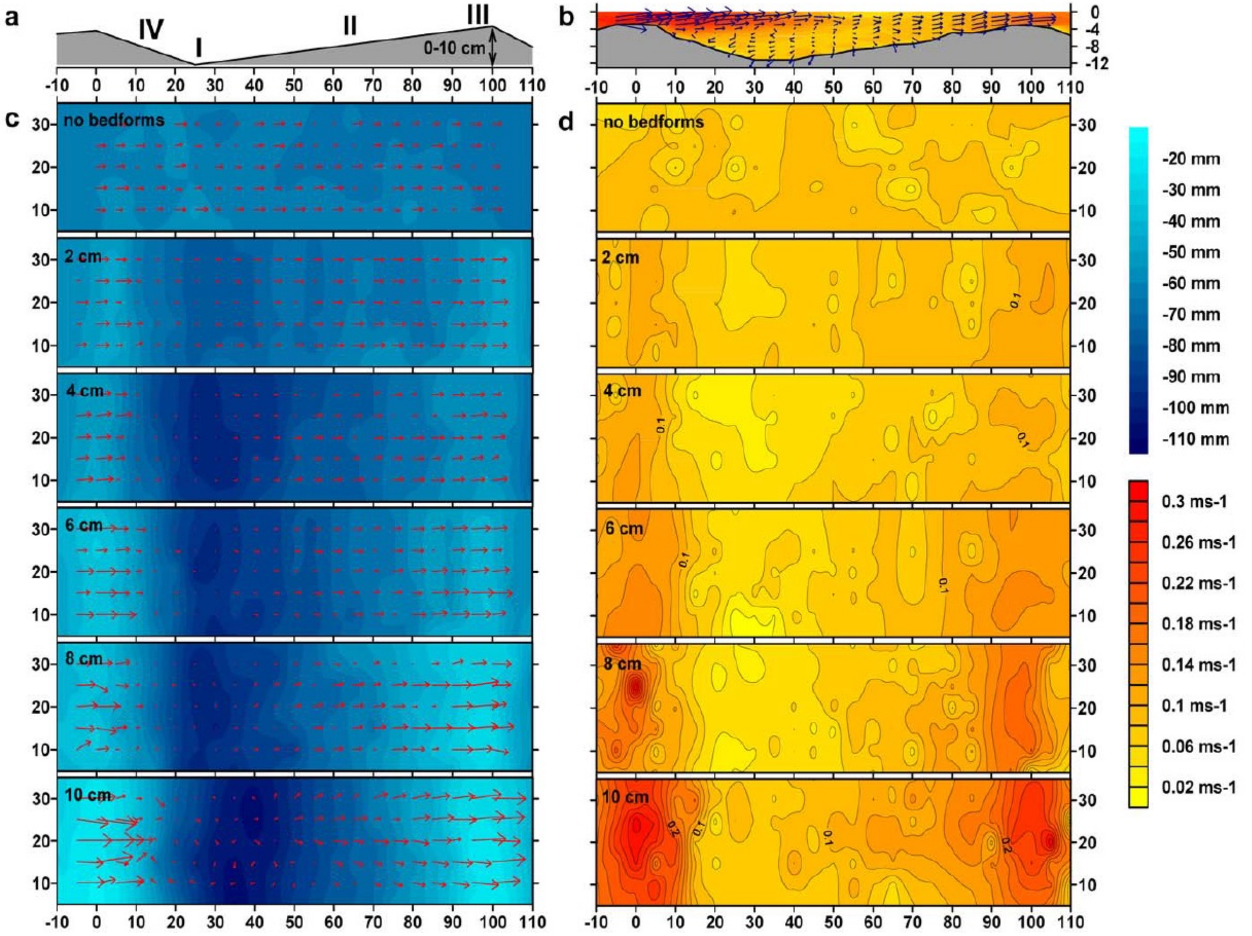
Small-scale hydraulic heterogeneity
Microhabitats

Bedforms

- 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



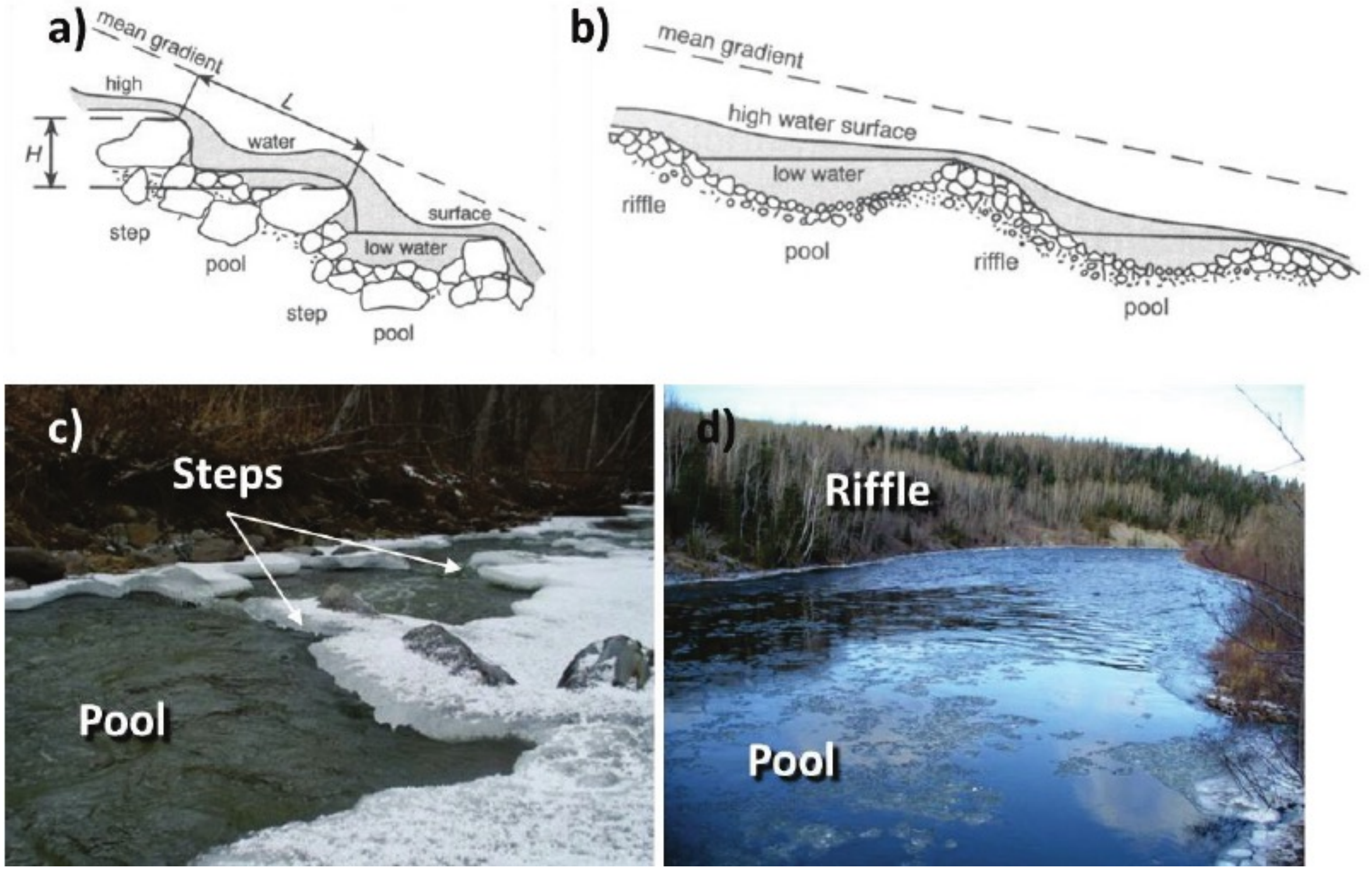




Water depth distributions

Three-dimensional flow velocity distributions

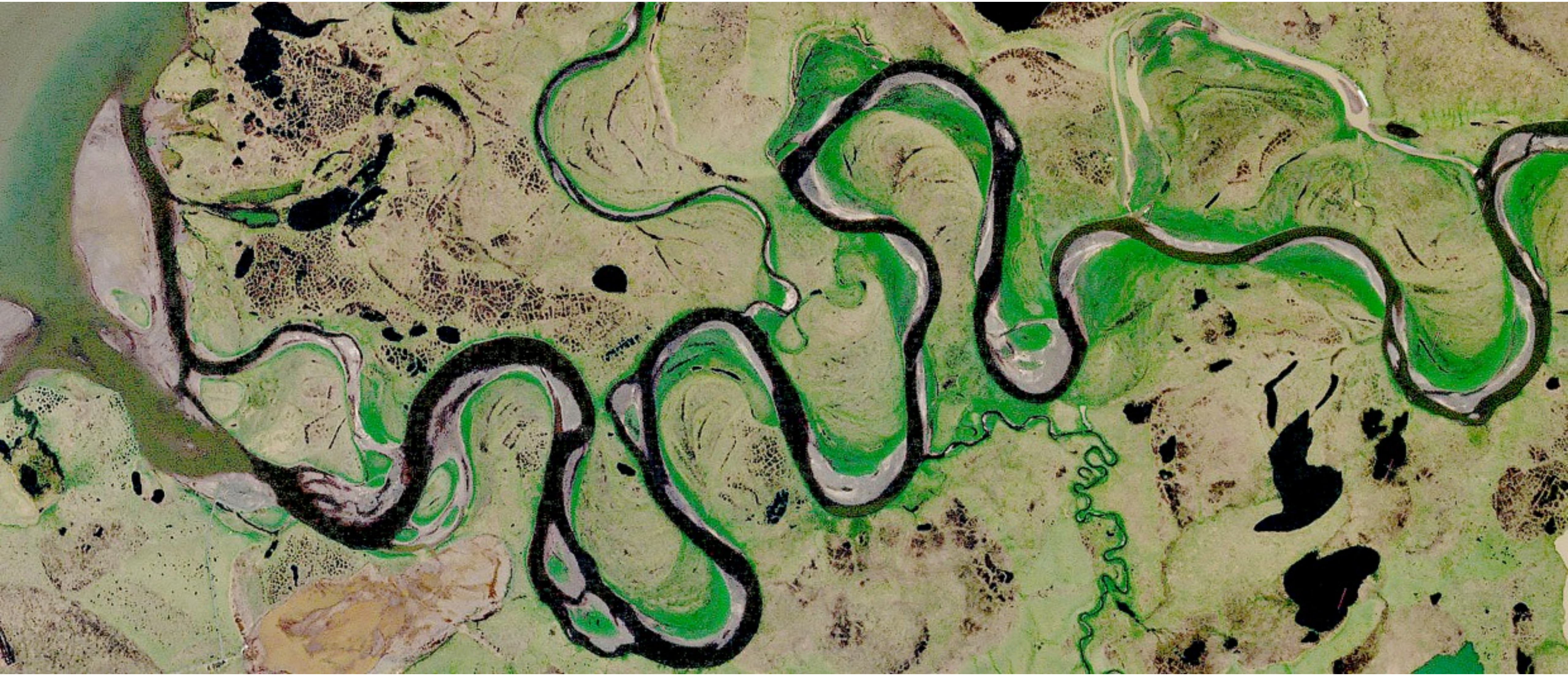
Reach-scale satial heterogeneity
Step-pool and riffle-pool sequences



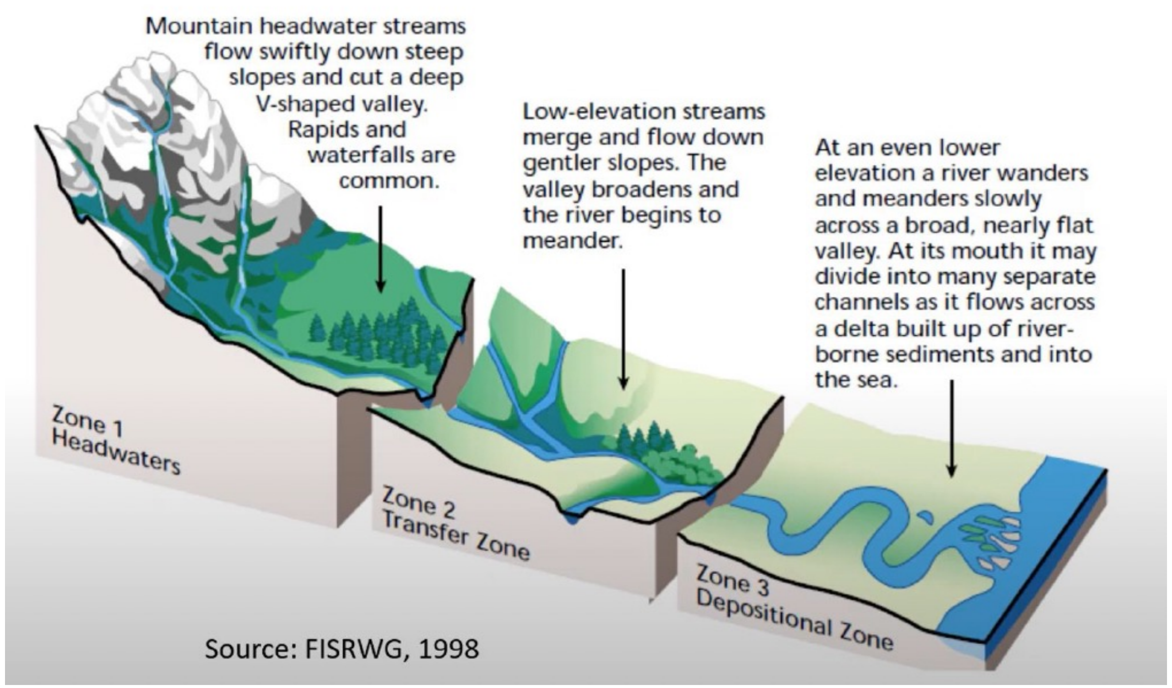
Elevated slope: step-pool
Reduced slope: riffle-pool

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

Larger-scale channel features: meandering and braided rivers



From braided to meandering streams and rivers

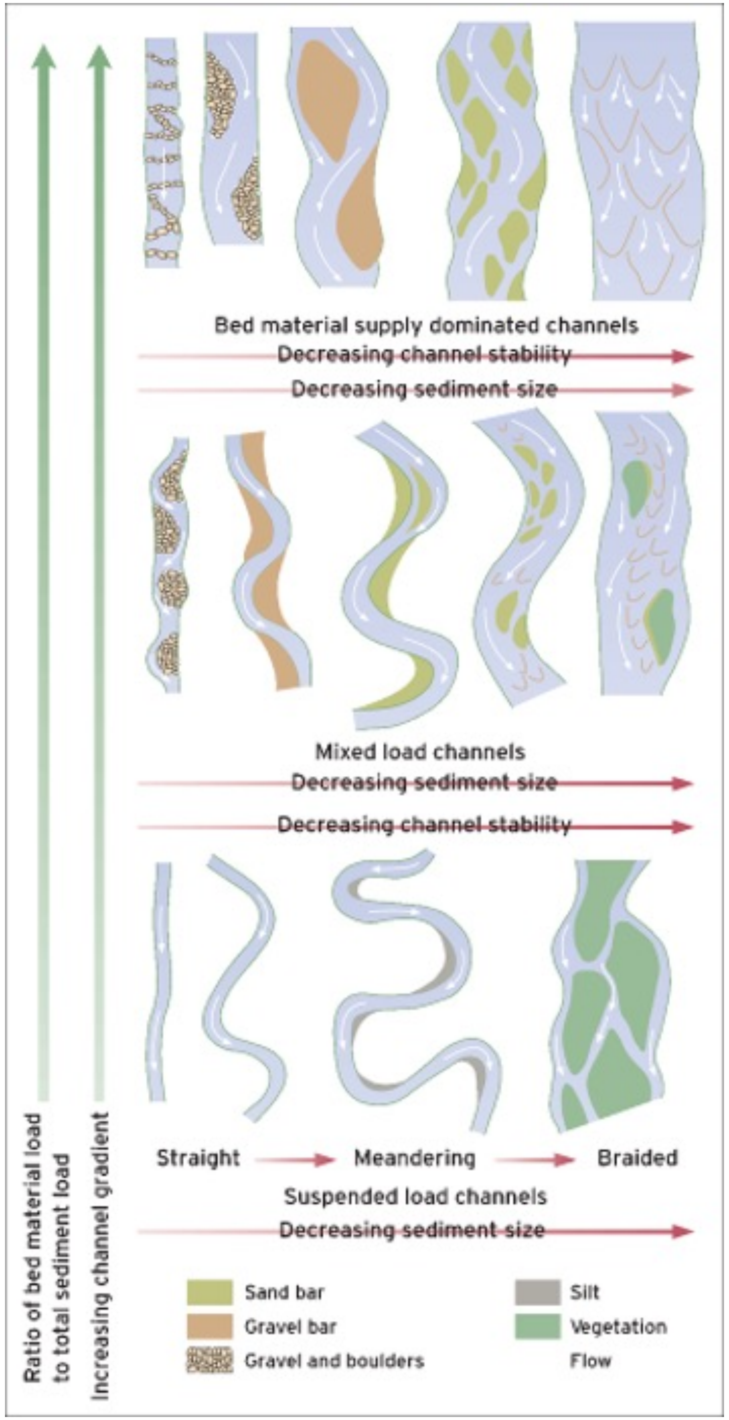


- High gradient channels
- Elevated bed load
- Incised and relatively confined channels
- Sediment dynamics with river corridor (alternating bars)

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

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

- Low-gradient channels
- Reduced bed load – more suspended load
- Less incised and confined, more dynamic channels
- Reduced sediment size



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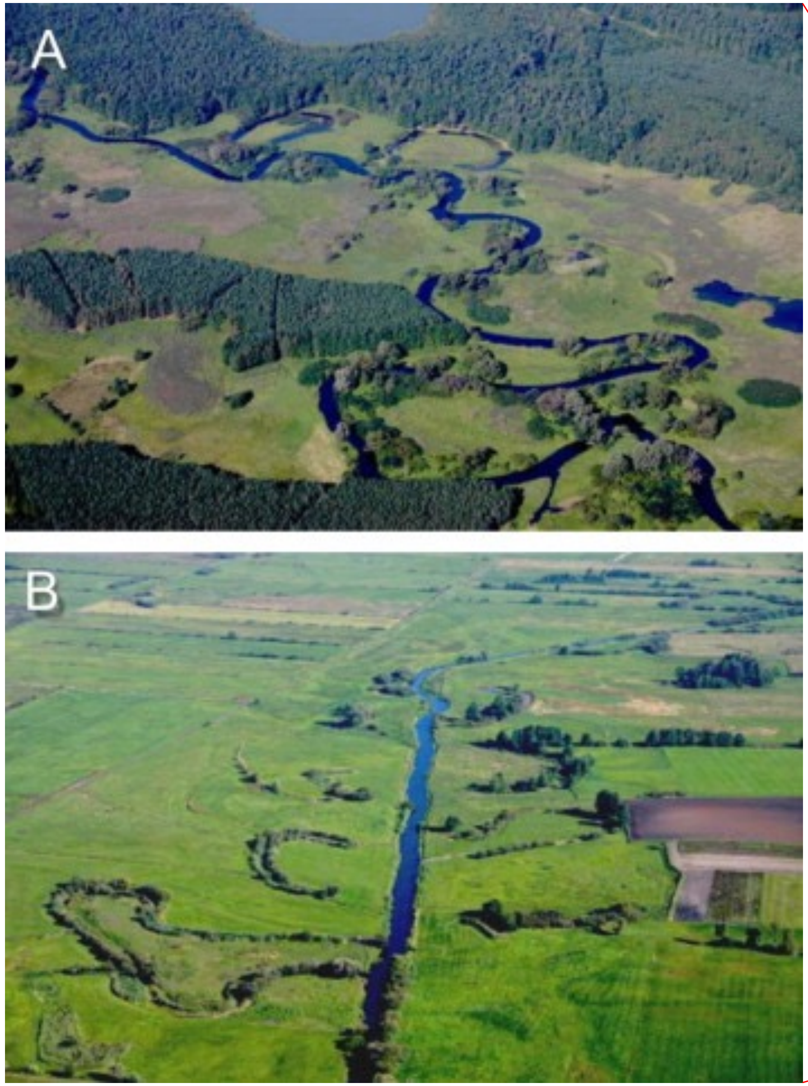
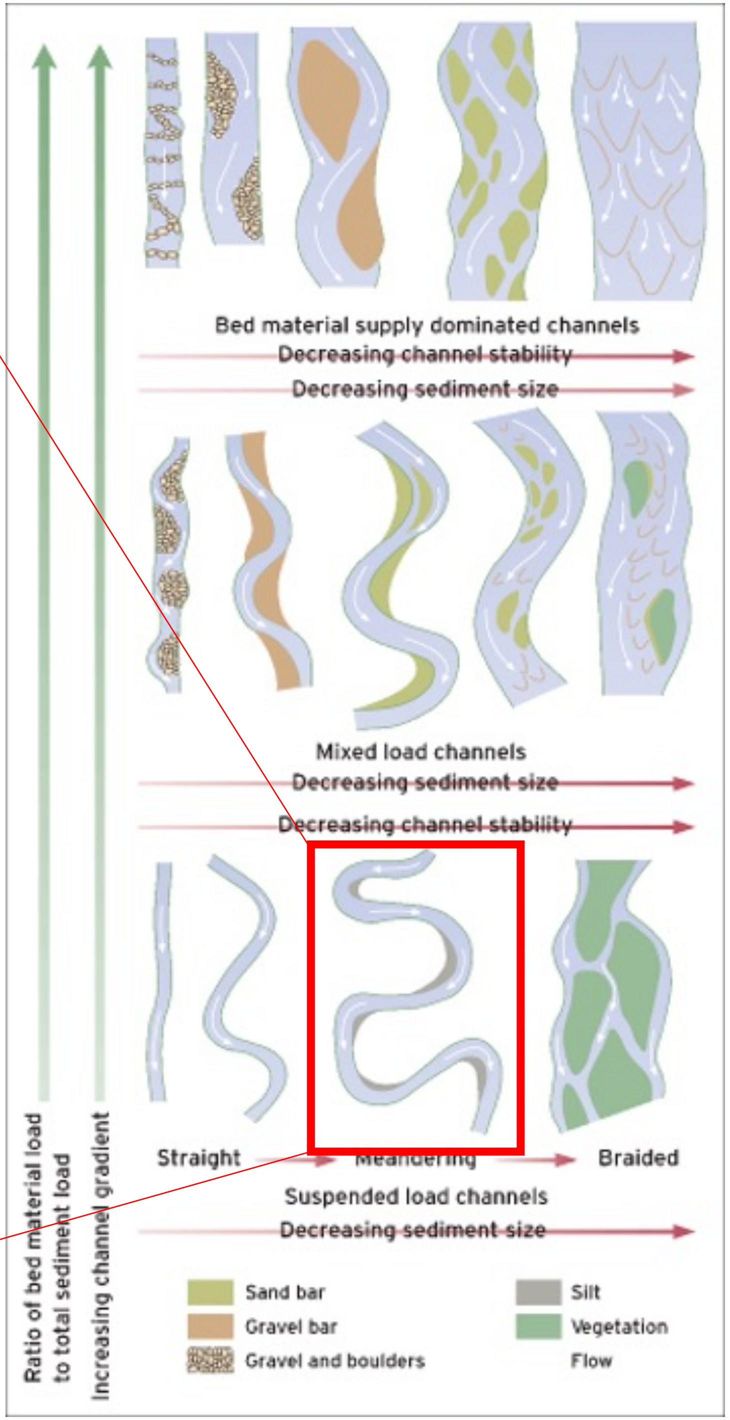
From braided to meandering streams and rivers





- Meandering rivers occupy large surface ares in the lowlands
- Conflict with land use (urbanisation, agriculture)
- Channelisation

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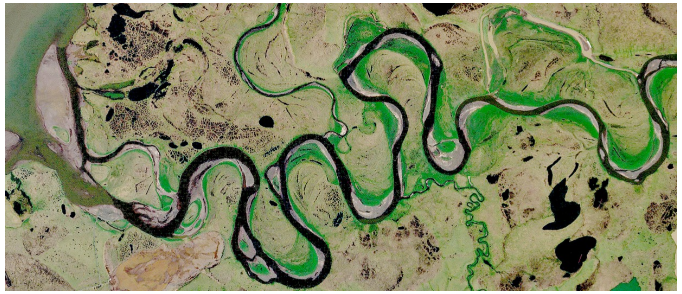
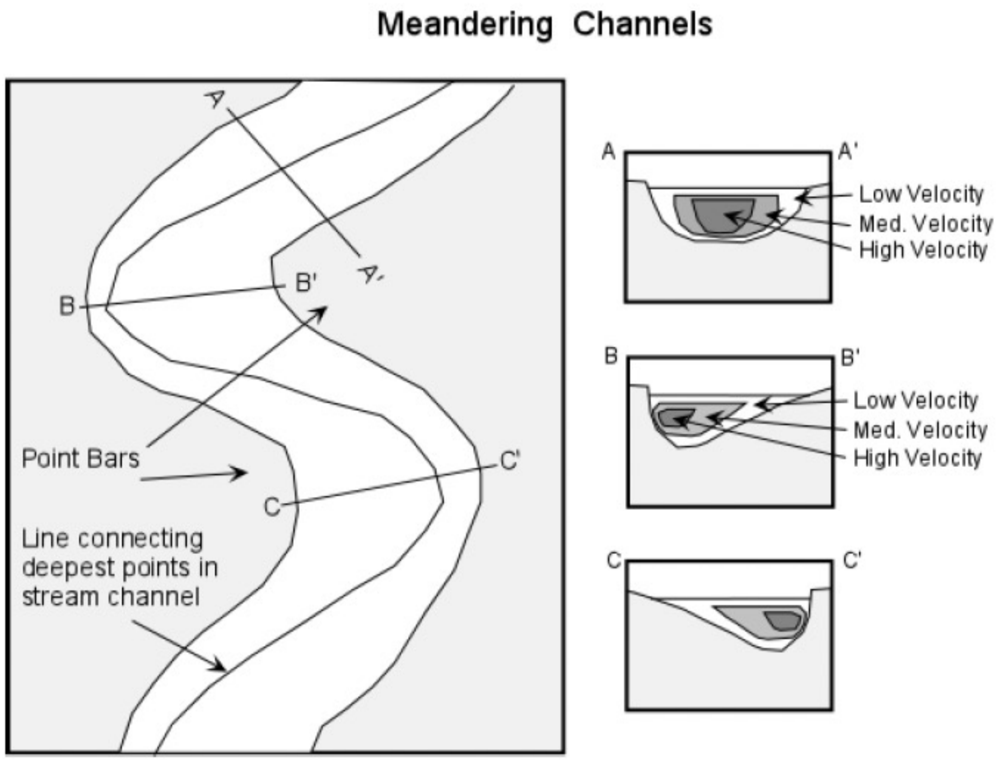
https://www.youtube.com/watch?v=dHERpWgA84Y

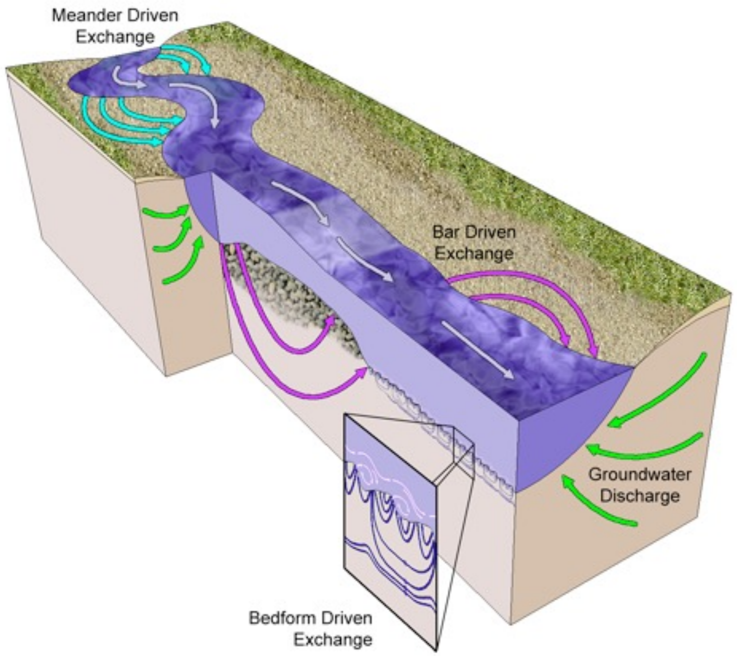
Meander formation





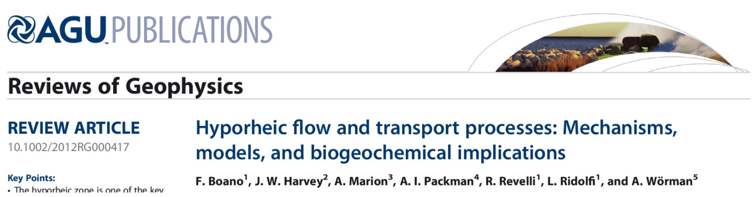
- Interplay between downstream directed sequences of erosion and deposition
- Sediment erosion of an outer bend and deposition of this material on inner bends downstream
- Depending on in-channel velocity distributions and stability of parent material

Hyporheic exchange



Hyporheic exchange across spatial and temporal scales

- Residence times
- Biogeochemical reaction rates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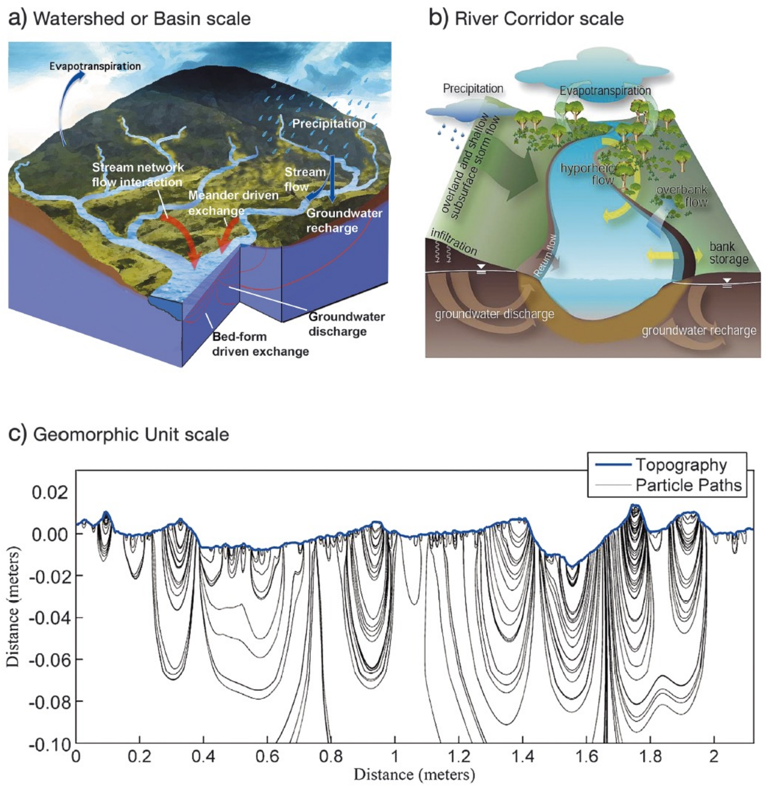
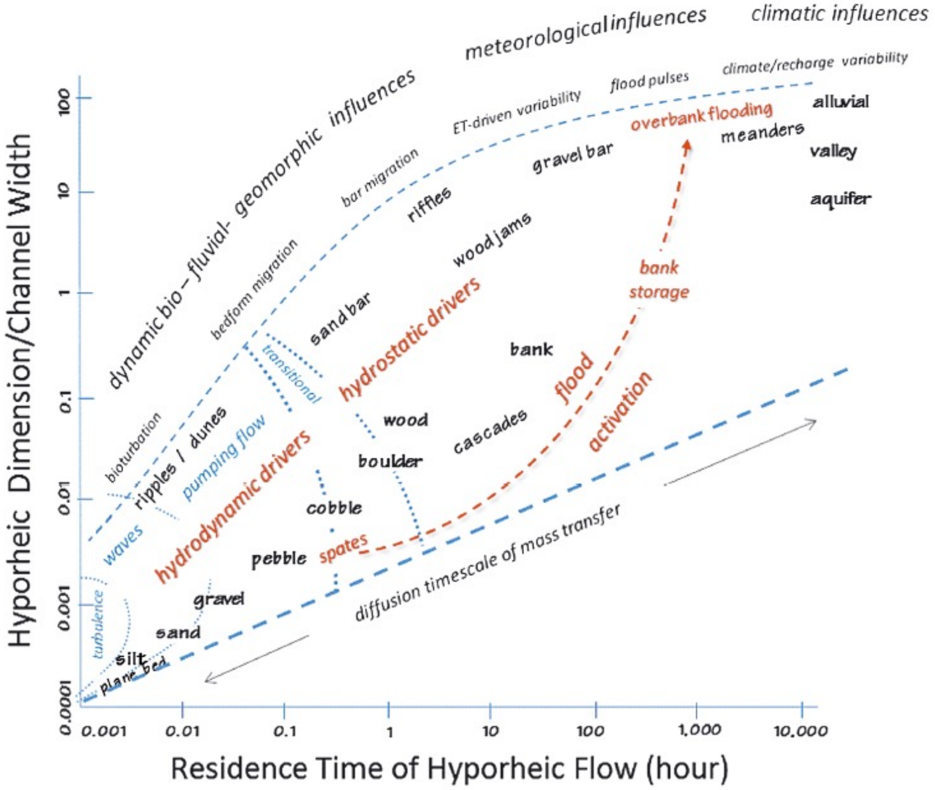
Reviews of Geophysics
REVIEW ARTICLE
10.1002/2012RG000417
Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications
F. Boano[1], J. W. Harvey[2], A. Marion[3], A. I. Packman[4], R. Revelli[1], L. Ridolfi[1], and A. Wörman[5]





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F. Boano[1], J. W. Harvey[2], A. Marion[3], A. I. Packman[4], R. Revelli[1], L. Ridolfi[1], and A. Wörman[5]

Key Points:
• The hyporheic zone is one of the key

There are both static and dynamic contributors to hyporheic flow

- At a point on the streambed the "<u>hydrostatic</u>" component represents the contribution to <u>total hydraulic head</u> given by water height regardless of flow.

- The "<u>hydrodynamic</u>" component represents the forces arising from <u>surface water flow</u> around roughness features on the streambed and the resulting momentum transfer to the streambed.

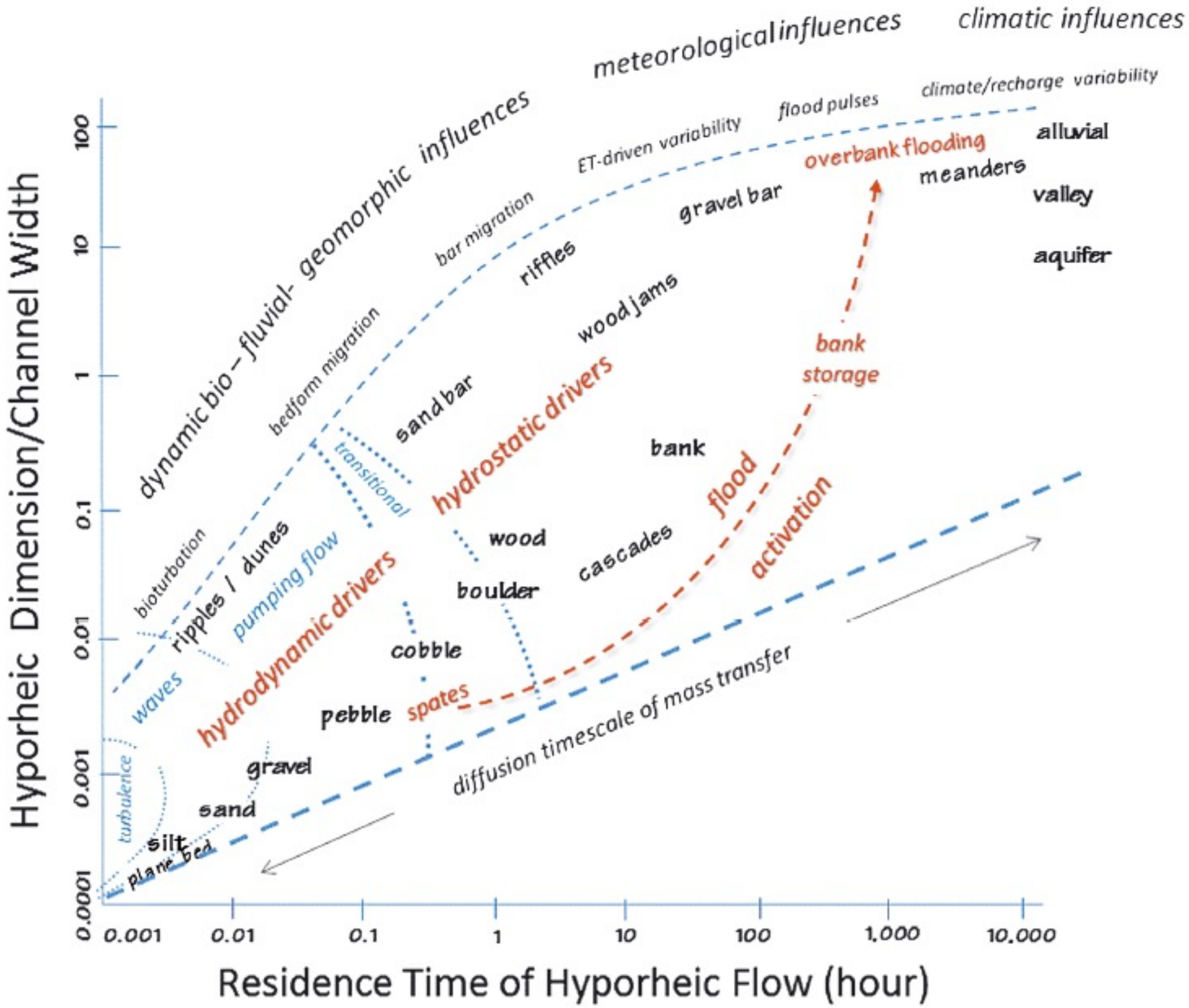

Figure 2. Spatial and temporal scaling of hyporheic flow. Important regimes of hyporheic flow are denoted in red with minor regimes in blue and typical channel features that influence hyporheic exchange are shown in black. The approximate spatial and temporal limits of hyporheic flow are illustrated with dashed lines, with external biological, fluvial, and geomorphological influences shown in grey. Hyporheic flow dimension (depth or length) is divided by channel width to account for scaling of size of channel features with river size.

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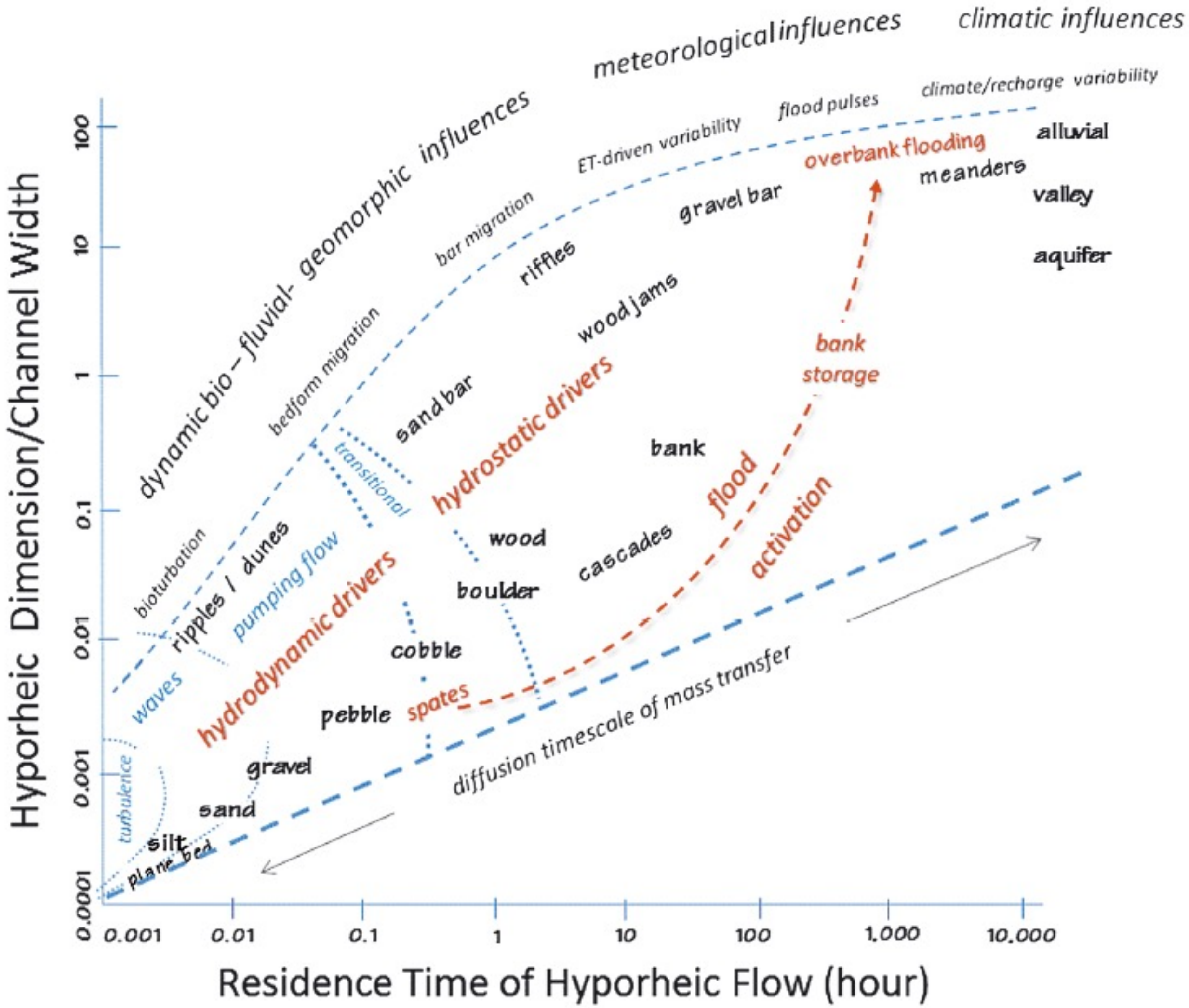
Key Points:
• The hyporheic zone is one of the key

- Hydrostatic conditions in streams imply that the hydraulic head at the streambed interface is equal to the height of overlying surface water.
- Hydrostatically influenced hyporheic flow will therefore be affected by the variability in the height and slope of the streamwater surface and its effect on head gradients in the subsurface.
- Hydrostatically driven hyporheic flow tends to have its greatest influence at spatial scales governed by the streambed's larger topographic undulations that emerge above stream and guide streamflow around bars and over steps, cascades, and riffles, and between meandering banks.



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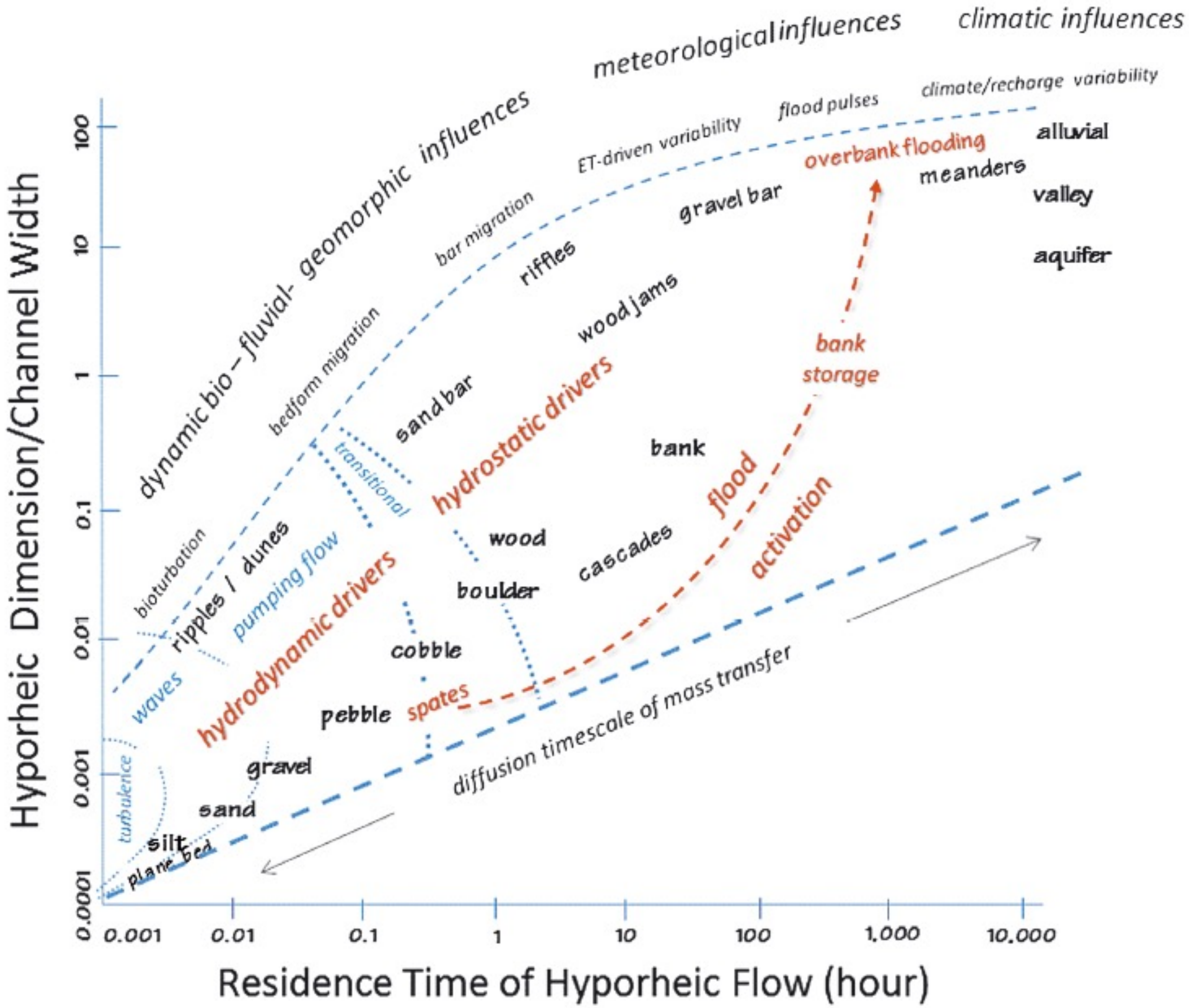
Key Points:

- The hyporheic zone is one of the key

- Hydrodynamically driven hyporheic flow has its greatest influence at finer scales of variability in streamwater velocity flowing over submerged bedforms, which affects momentum transfer to the streambed.
- Hydrodynamic forces tend to be most influential in driving shallow hyporheic flows through pathways that are typically smaller than streamwater depth



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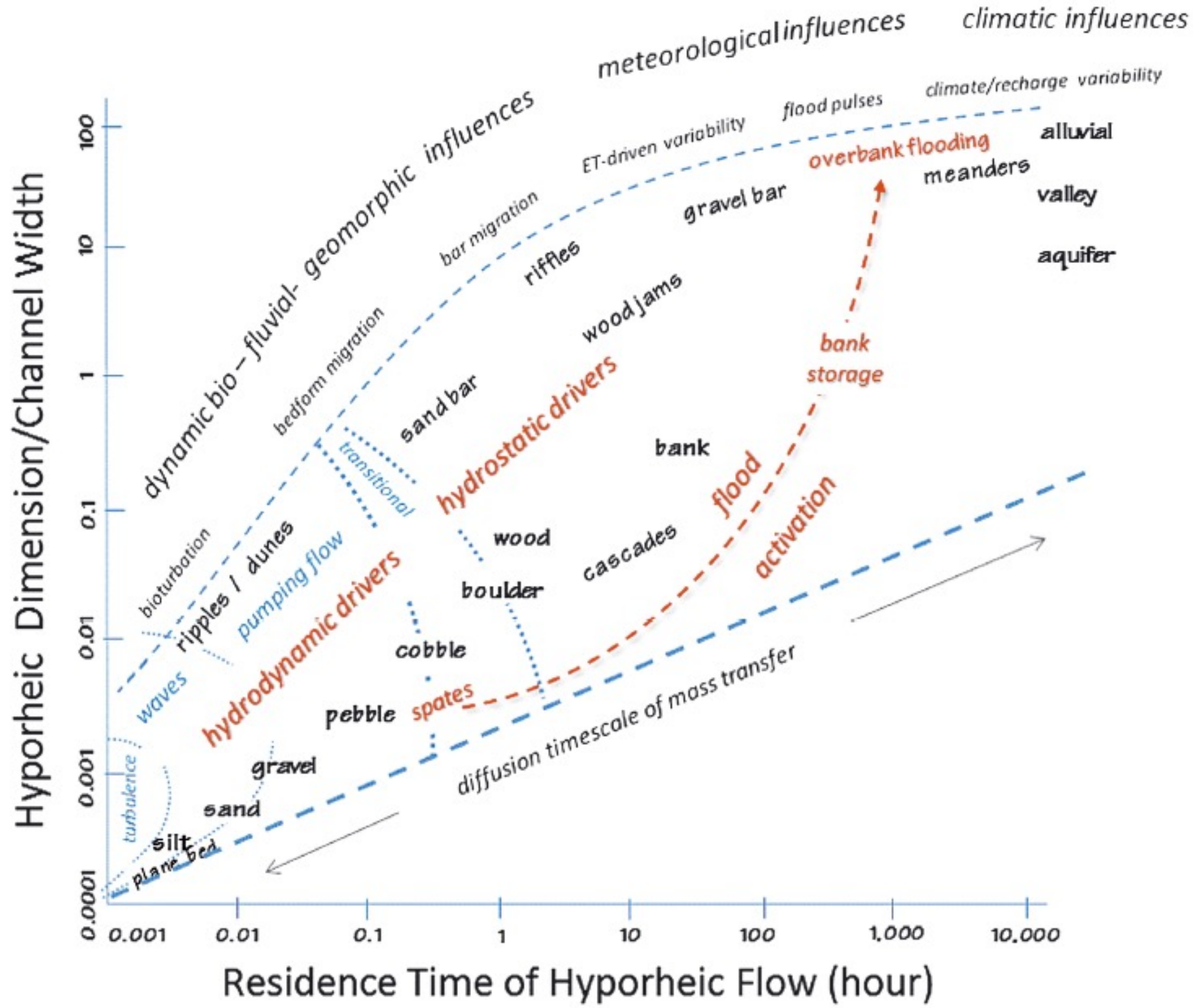
Key Points:

- The spatial extent of exchange and the associated time that river water spends in storage are positively related and scale approximately with the size of bedforms, barforms, and other roughness features such as downed wood in channels, as well as frequency, size, and duration of spates and floods.



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Water Resources Research

REVIEW ARTICLE

10.1002/2015WR017617

Special Section:

River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins

Jud Harvey[1] and Michael Gooseff[2]

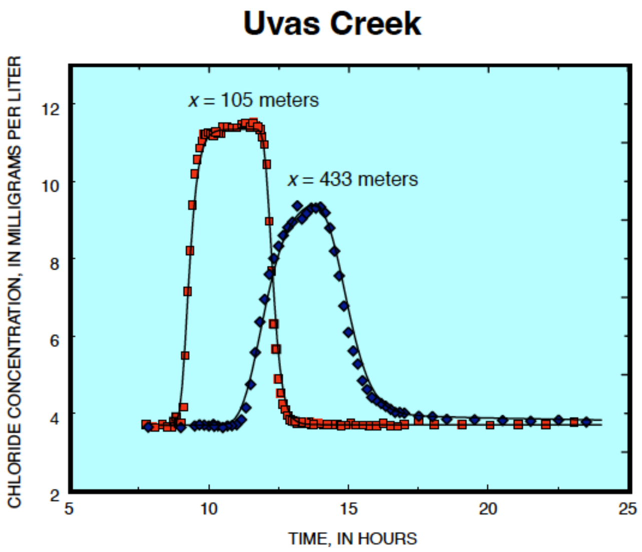
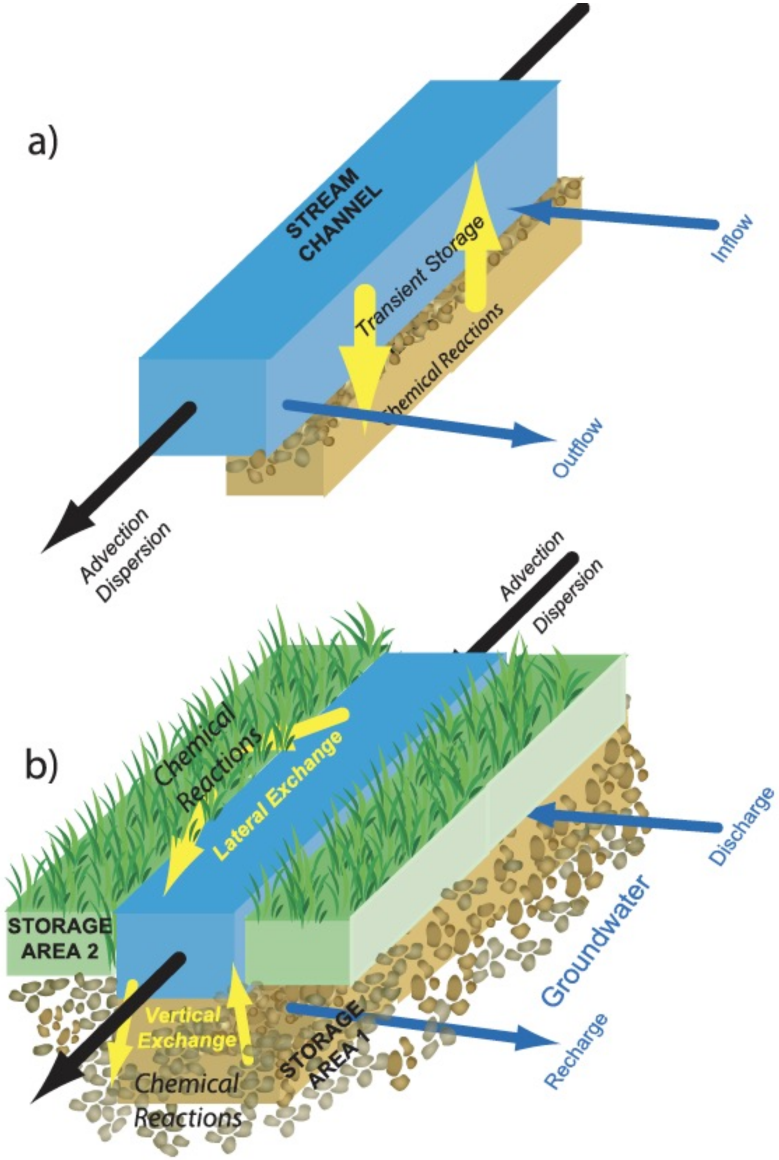


Figure 3. Simulated (solid lines) and observed (symbols) chloride concentrations in Uvas Creek, California.



The transient storage model simulates

- in-channel advection and longitudinal dispersion in a stream
- hydrologic connections with groundwater and with "transient storage zones," (i.e., slowly moving surface water at channel sides and hyporheic waters)
- reactive processes which may occur at different rates within various hydrologic compartments

Consequences of hyporheic flow and storage

Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange

John M. Buffington[1]* and Daniele Tonina[2]

- Residence time controls the development of biochemical gradients and available habitats

- Biochemical gradients will be limited in channel types characterized by short, rapid hyporheic flow paths (cascade, step-pool channels), resulting in more uniform biochemical conditions and more uniform habitats compared to channels characterized by a broad range of hyporheic path lengths and travel times

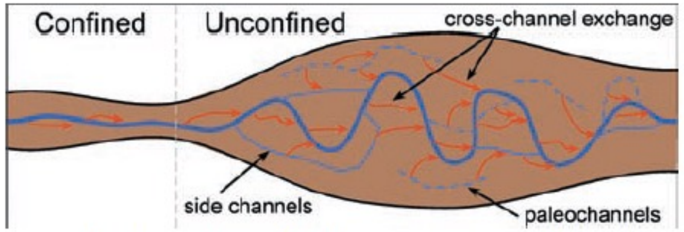


Fig. 5. Differences in lateral complexity of head gradients and hyporheic exchange in confined versus unconfined alluvial valleys.

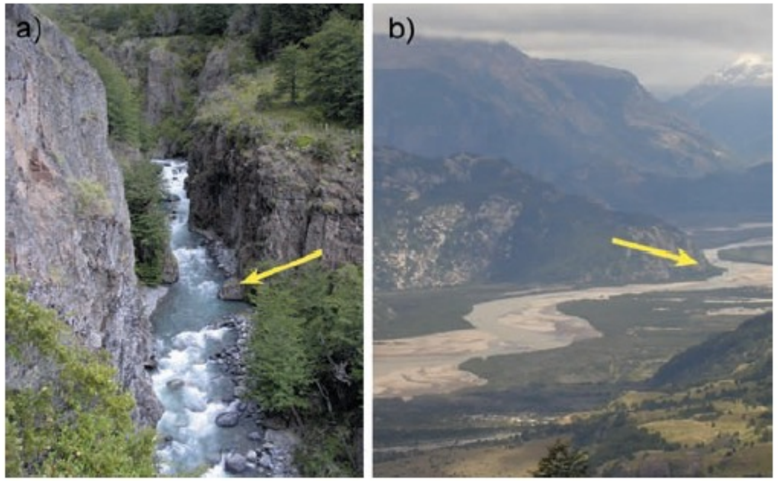


Fig. 6. Photographs of (a) confined and (b) unconfined channels. Arrows indicate bedrock projections that locally constrict alluvial area.

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Geography Compass 3/3 (2009): 1038–1062, 10.1111/j.1749-8198.2009.00225.x

Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange

John M. Buffington[1]* and Daniele Tonina[2]

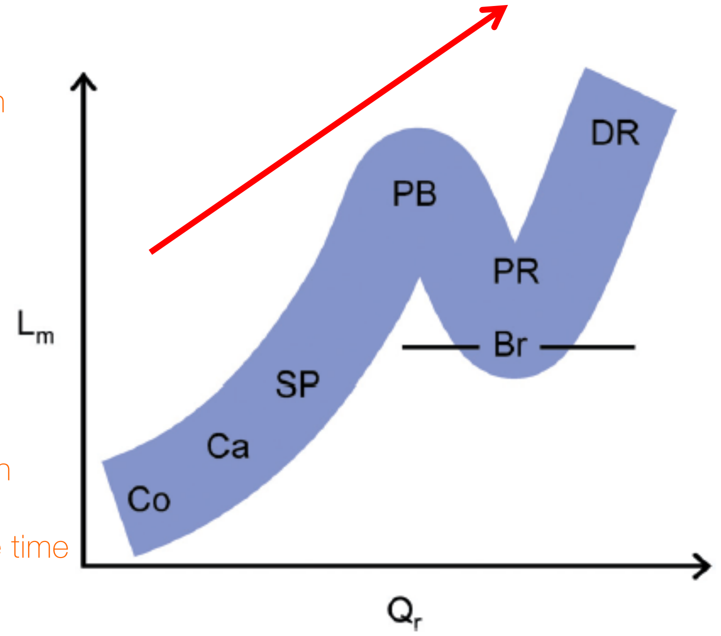
Downstream gradient
(Hydraulic geometry)

Length scale for complete mixing between surface and hyporheic waters, or the hydrological turnover length

$$L_m = \frac{Q_r}{q_h P}$$

Q_r stream flow (discharge)
q_h downwelling flux (per unit streambed area)
P wetted channel perimeter

High turnover length
Low mixing
Low residence time



Low turnover length
High mixing
Elevated residence time

Fig. 8. Conceptual plot of length scales for complete mixing of river and hyporheic waters (L_m) as a function of river discharge (Q_r) and channel type (Co = colluvial, Ca = cascade, SP = step-pool, PB = plane-bed, PR = pool-riffle, BR = braided, DR = dune-ripple).

- Discharge (Q) changing predictably from up- to downstream (see hydraulic geometry)
- Downwelling (q_h) typically decreases downstream (slope, roughness, sediment)
- Develop a predictable framework for hyporheic importance

Hyporheic Exchange in Mountain Rivers II: Effects of Channel Morphology on Mechanics, Scales, and Rates of Exchange

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Length scale for complete mixing between surface and hyporheic waters, or the hydrological turnover length

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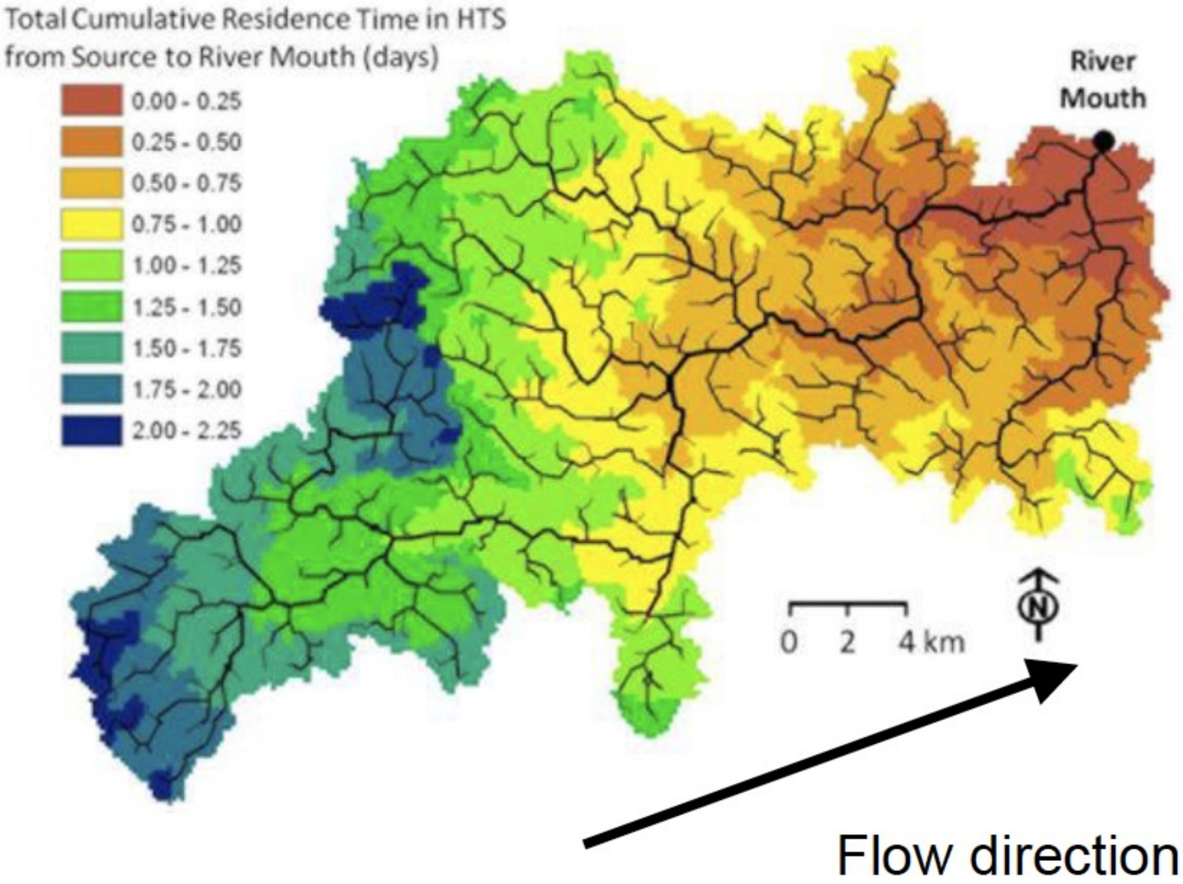


- Discharge (Q) changing predictably from up- to downstream
- Downwelling (q_h) typically decreases downstream (slope, roughness, sediment)
- Develop a predictable framework for hyporheic importance

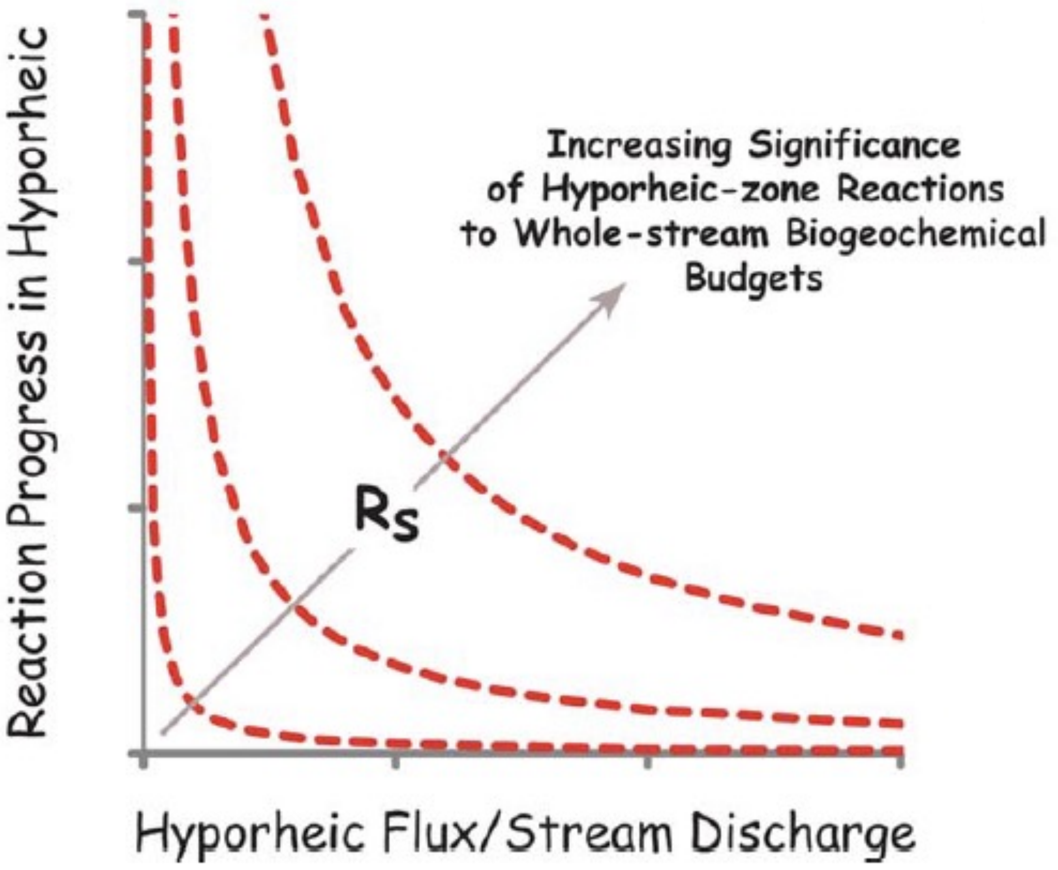
Consequences of hyporheic flow and storage
Reaction Significance Factor

- Hydrologic and biogeochemical factors combine to determine reach scale significance of a stream for ecosystem processes

- On the one hand greater reaction progress in individual hyporheic flow paths (i.e. higher rate and/or longer subsurface residence time) increases significance.

- Alternatively, significance is increased by greater hyporheic flux and by greater turnover rate of the stream through the hyporheic zone. The resulting whole-stream significance is expressed as the dimensionless product Rs, comprised of average hyporheic flow path-scale factors and reach-scale hydrologic factors.

- The dashed lines are isolines with increasing values of Rs toward the upper right denoting the fraction of the reactant removed per characteristic (dimensionless) distance travelled in the stream.



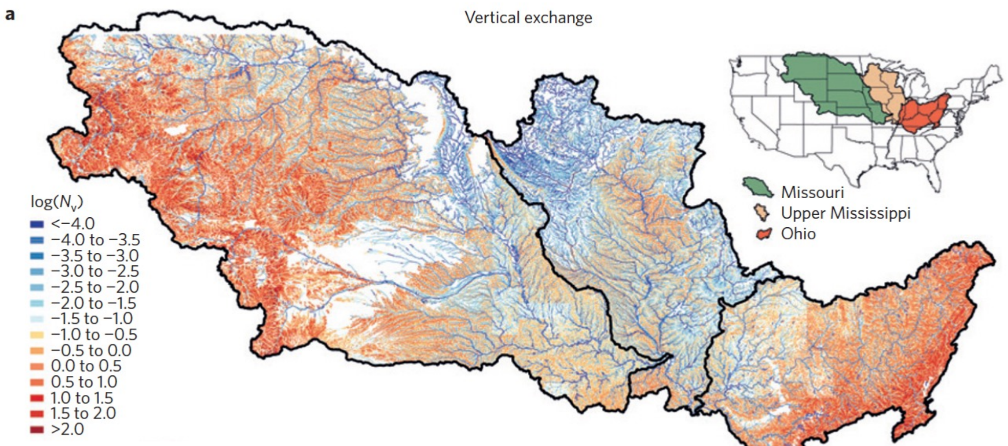
Consequences of hyporheic flow and storage

Reaction Significance Factor

nature geoscience
LETTERS
PUBLISHED ONLINE: 26 OCTOBER 2015 | DOI: 10.1038/NGEO2567

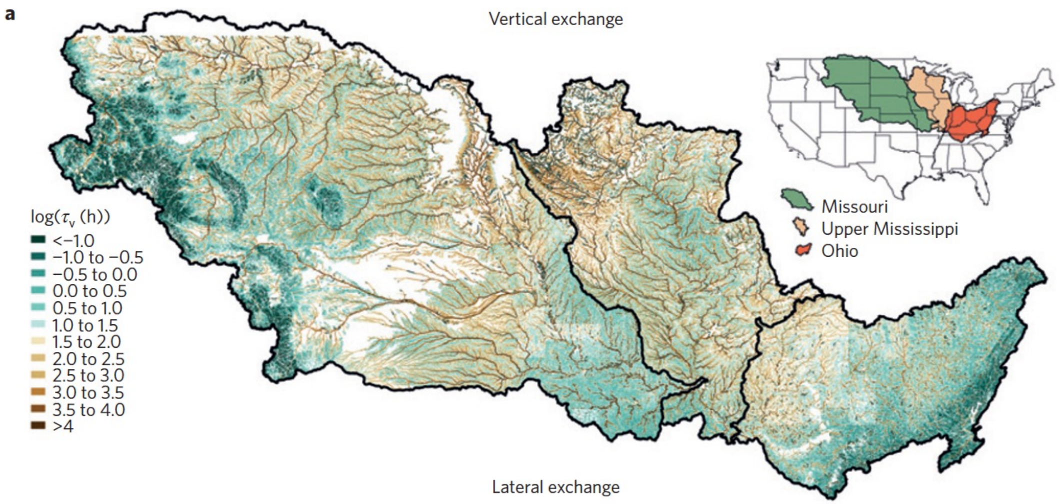
Denitrification in the Mississippi River network controlled by flow through river bedforms

Jesus D. Gomez-Velez[1,2]*, Judson W. Harvey[1], M. Bayani Cardenas[3] and Brian Kiel[3]

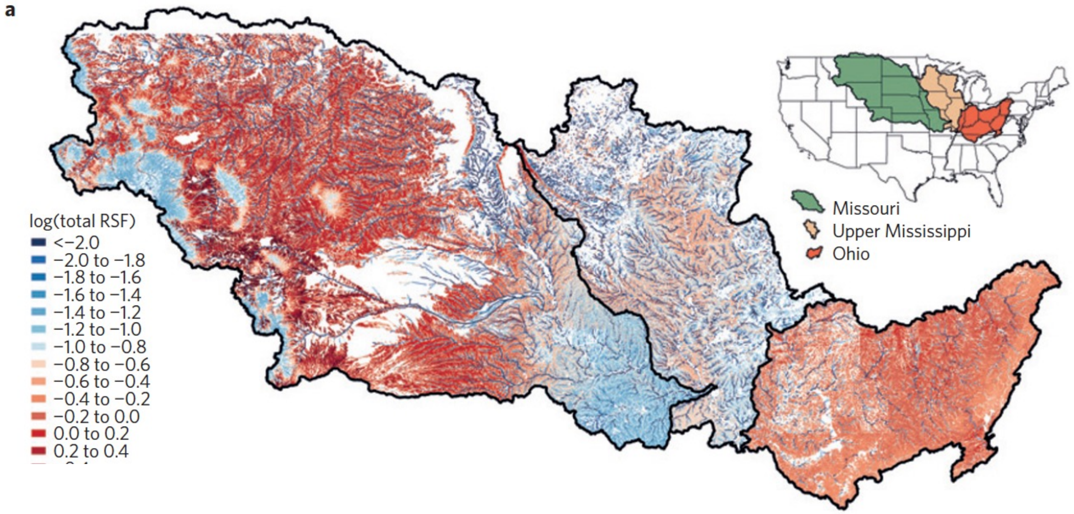


Median hydrological turnover length

Promoting the development of permeable bedforms at the streambed—and thus vertical hyporheic exchange — is effective at enhancing river denitrification in large river basins

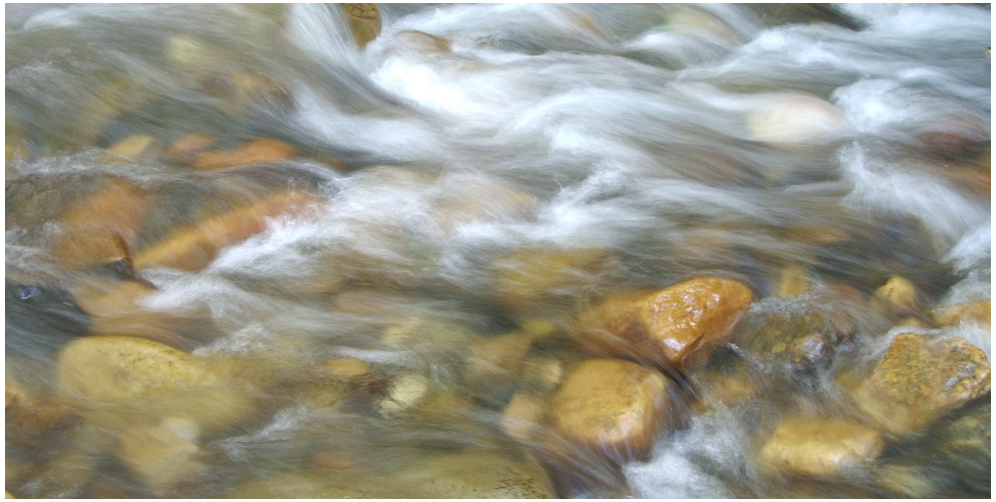


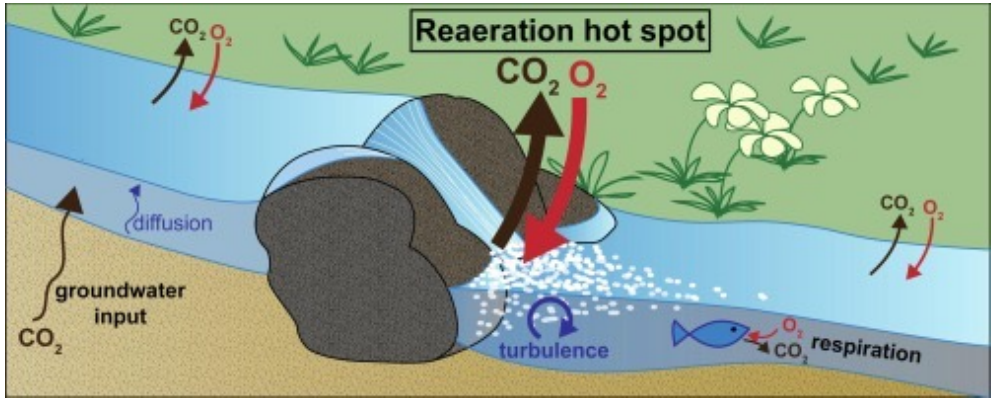
Median hyporheic residence time

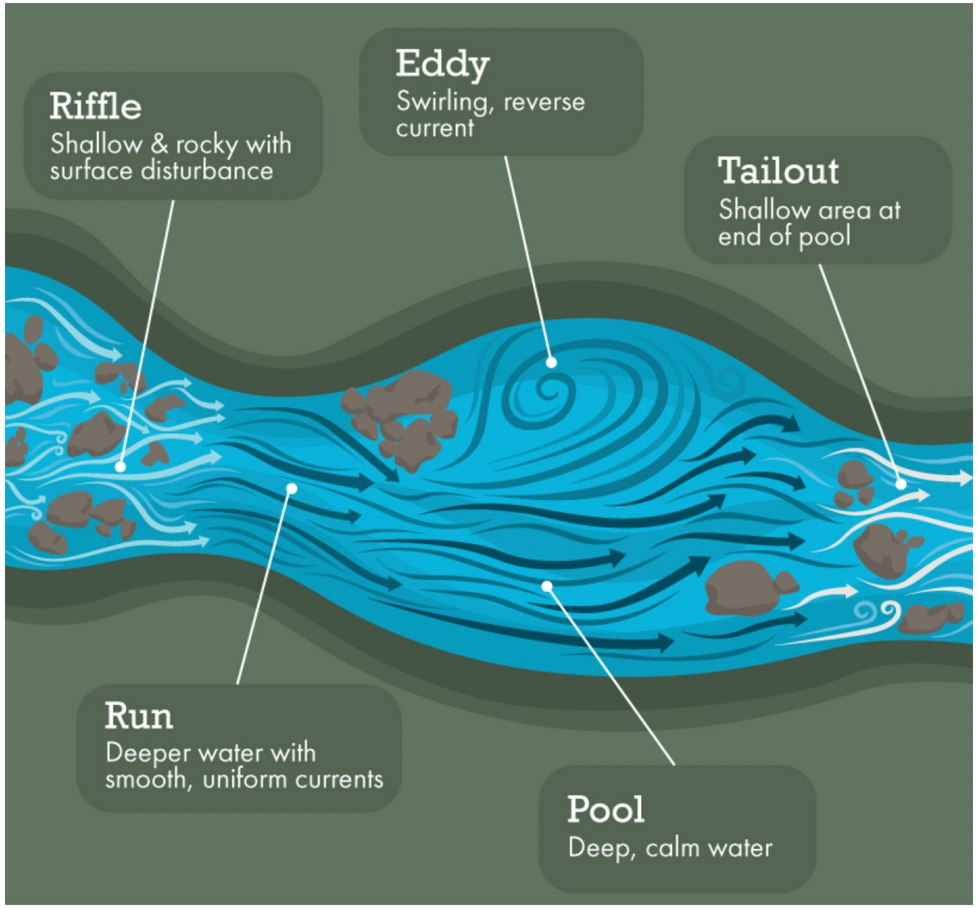


Reaction Significance Factor for denitrification

Streambed topographic heterogeneity and gas exchange





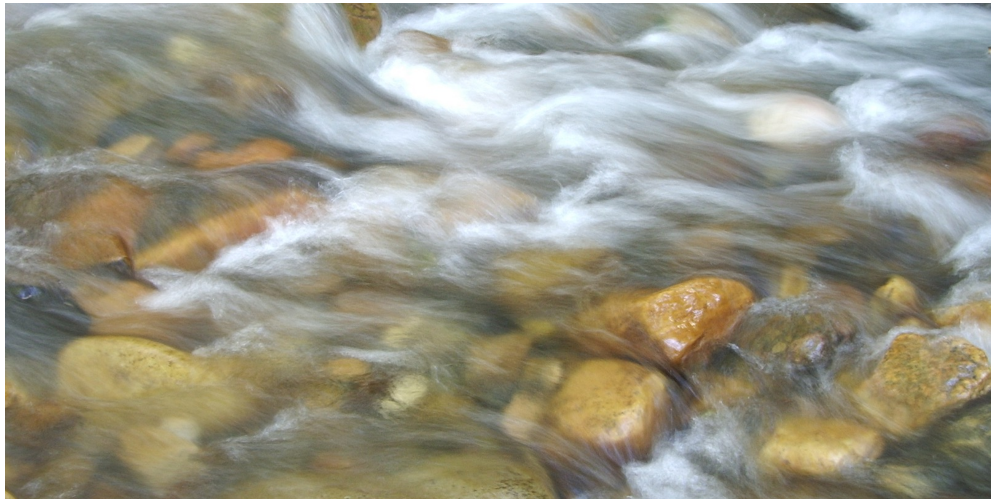


- Oxygenation — biodiversity & fish population; degradation and purification
- GHG emissions

A universal scaling for the air-water gas transfer velocity *k* as a function of the dissipation rate of turbulent kinetic energy ε

$$k=\alpha(\varepsilon \nu)^{1/4} Sc^{-n}$$

ν is the kinematic viscosity of water, *Sc* is the Schmidt number (i.e. the ratio of kinematic viscosity and the diffusion coefficient of the corresponding gas in water) and α is a scaling coefficient



Non-peer reviewed preprint submitted to EarthArXiv

Hydrodynamic control of gas-exchange velocity in small streams

Andreas Lorke[1*], Pascal Bodmer[1], Kaan Koca[1] and Christian Noss[1]

Gas exchange velocity (k_{600}) scales with surface flow type /turbulence structure

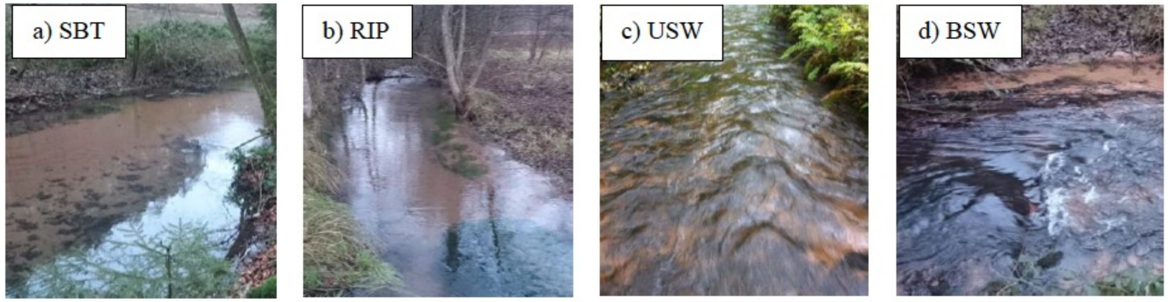


Figure 1: Study sites at the Wellbach featuring different surface flow types: a) Smooth boundary turbulence (SBT), b) rippled flow (RIP), c) unbroken standing wave (USW) and d) broken standing wave (BSW).

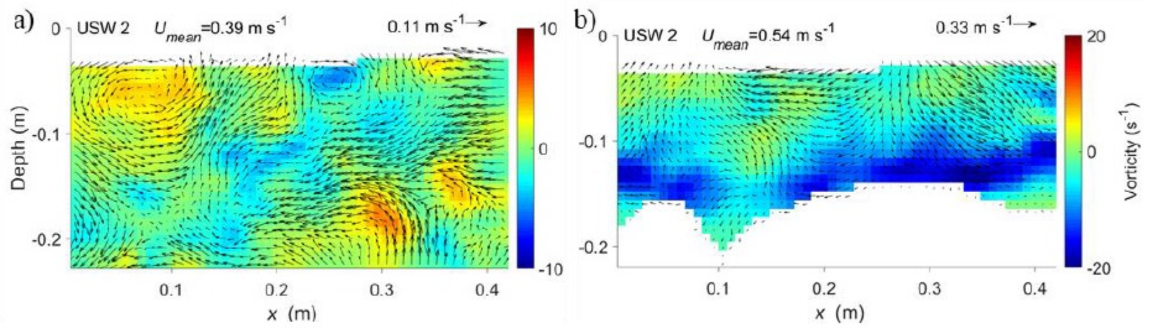
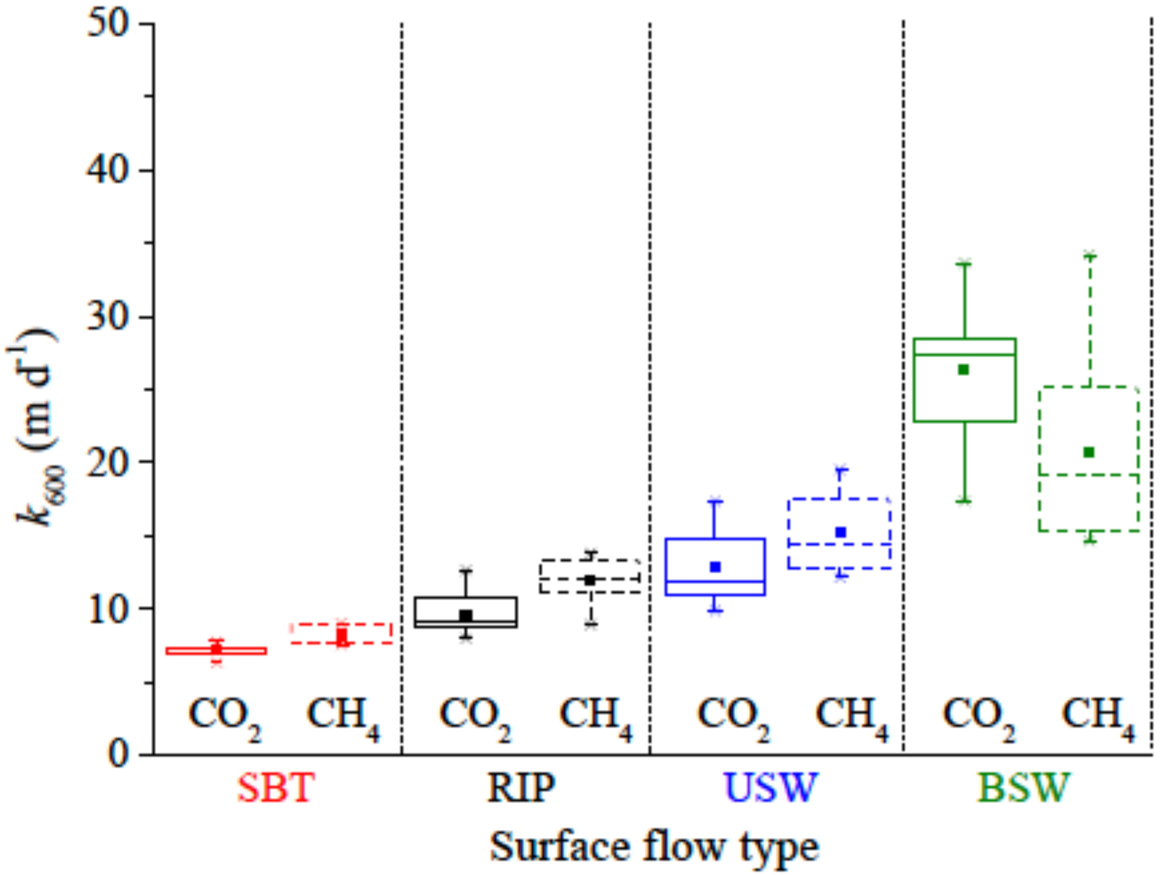


Figure 2: Snapshots of instantaneous turbulent velocity fluctuations for a) smooth boundary turbulence (SBT spot 3) and b) unbroken standing wave (USW spot 2). The vectors show magnitude and direction of turbulent velocity fluctuations (a reference arrow is provided in the top left corner of each panel). The white area at the bottom of b) masks the stream bed. The mean current speed (U_{mean}) that has been subtracted from the measured flow velocities is shown in the panel headings. The velocities are overlaid a color image showing the y-component of instantaneous vorticity. The vorticity (ω, Eq. 8) scales with the angular velocity of clockwise (blue color) and counterclockwise (red color) rotating eddies in the planar field of view.



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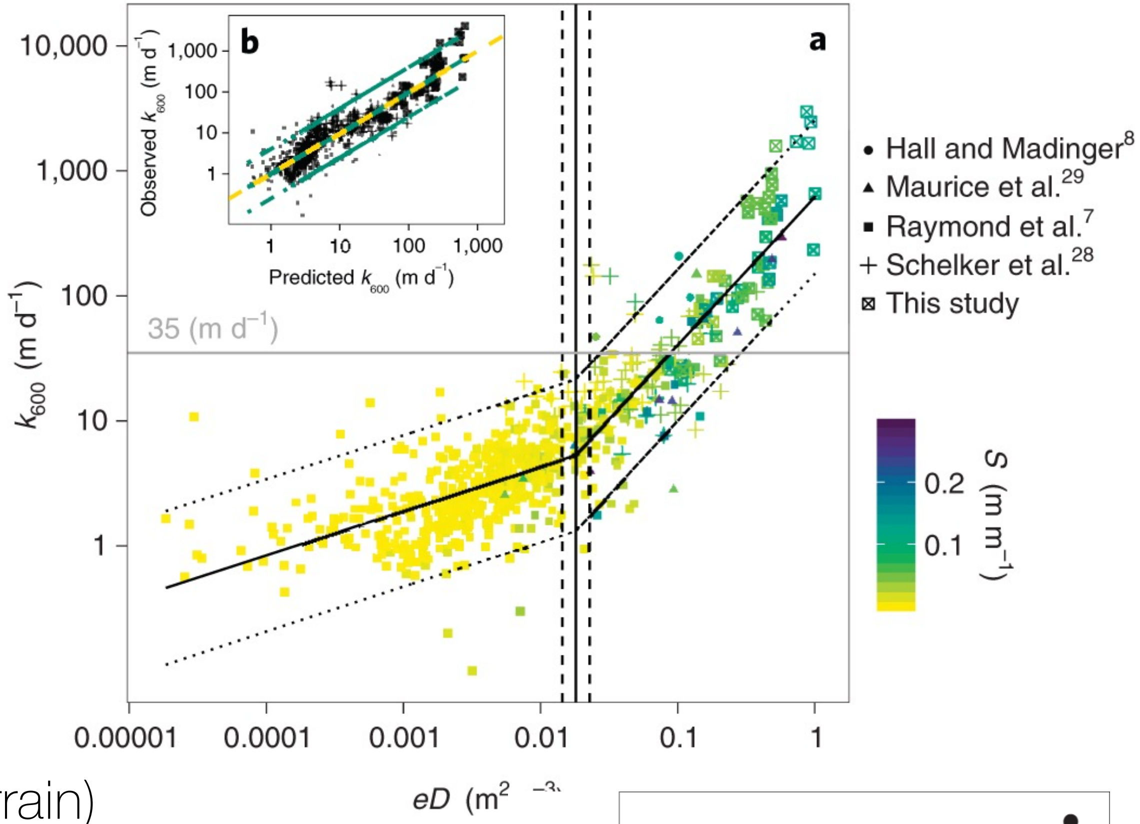
Distinct air–water gas exchange regimes in low- and high-energy streams

Amber J. Ulseth[1,4*], Robert O. Hall Jr[2], Marta Boix Canadell[1], Hilary L. Madinger[3,5], Amin Niayifar[1] and Tom J. Battin[1]

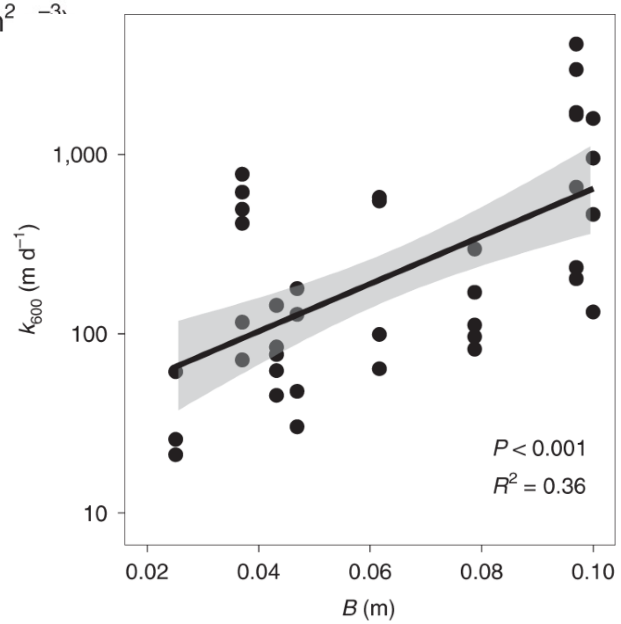


Two distinct regimes of gas exchange velocity k_{600} (depending on energy dissipation)

- Low-energy streams (low slopes, lowlands)
- High-energy streams (high slopes, mountainous terrain)

Relationship between gas exchange velocity and streambed roughness

- Shear stress and bottom energy dissipation
- Turbulent energy disspiated to water surface (low submergence)



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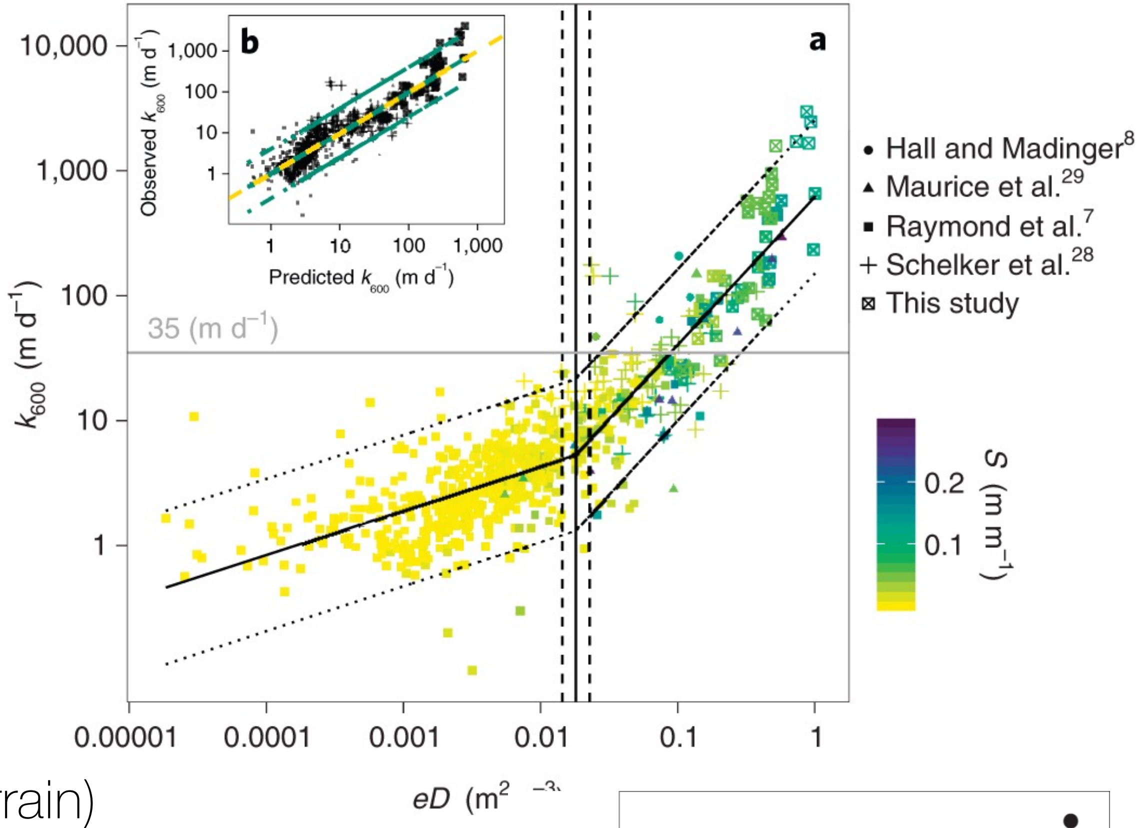
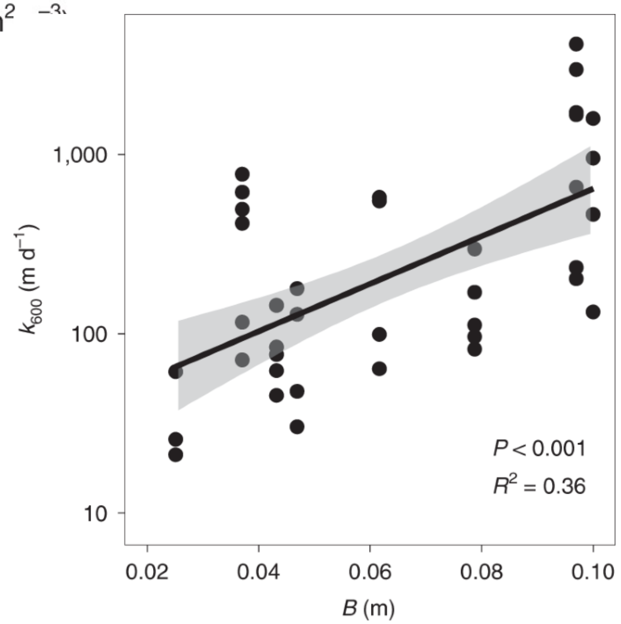


Two distinct regimes of gas exchange velocity k_{600} (depending on energy dissipation)

- Low-energy streams (low slopes, lowlands)
- High-energy streams (high slopes, mountainous terrain)

Breakpoint:

- Air entrainment into the water
- Bubbles increase surface area, hence gas exchange



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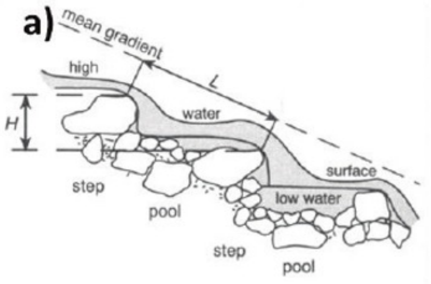
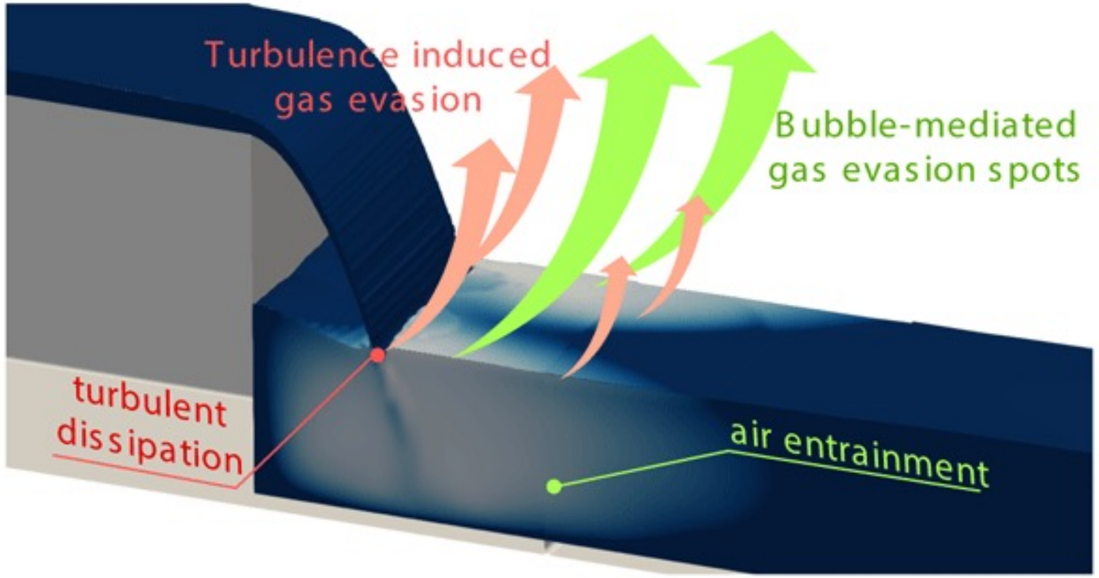
Steps dominate gas evasion from a mountain headwater stream

Received: 14 April 2022

Gianluca Botter[1], Anna Carozzani[1], Paolo Peruzzo[1] & Nicola Durighetto[1]



- Step-pool geomorphology (as frequent in mountain catchments) increases turbulent dissipation and air entrainment (white water)
- Increases gas exhange velocity
- Potentially increasing CO_2 evasion fluxes



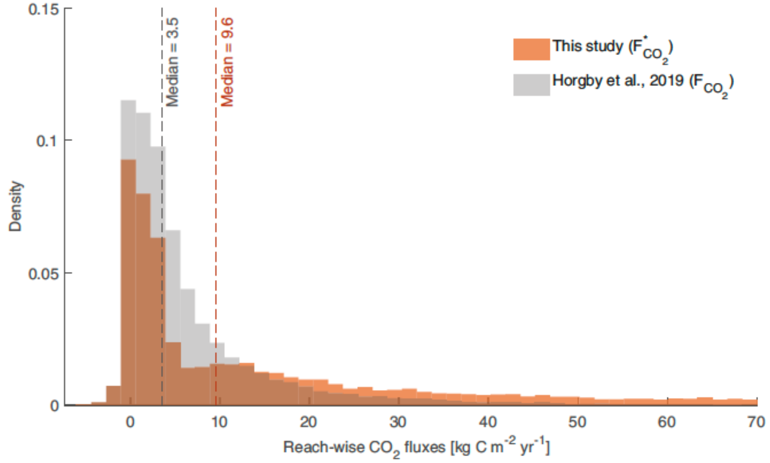


Fig. 5 | Effect of steps on CO_2 emissions from Swiss mountain streams. Frequency distribution of reach-wise CO_2 fluxes estimated by Horgby et al.[8], F_{CO_2} (gray histograms), and the corresponding frequency distribution of the fluxes estimated by taking into account the local emissions generated by steps, $F^*_{CO_2}$ (orange histograms), for 23,343 Swiss mountain streams. The black and orange dashed lines represent the median flux values estimated by Horgby et al.[8] and this study, respectively. Note that the tail of the frequency distribution including the steps reaches values up to $F^*_{CO_2} \approx 500$ kgC $m^{-2}yr^{-1}$.

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Wrapping up

- Why do surface area and both bed and channel heterogeneity matter?

- Exchange fluxes and residence times with bed sediments
- Exchange fluxes with atmosphere (oxygen, GHG)

- Streams and rivers as bioreactors with high transformation performance

- Systems underpinning for their global relevance