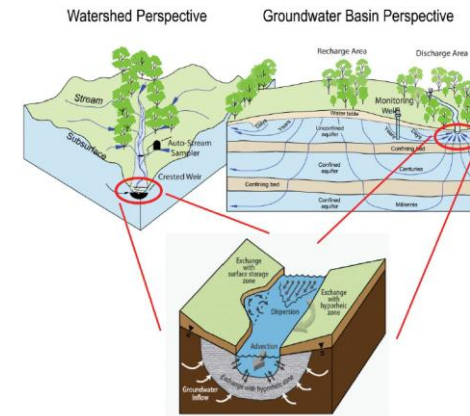
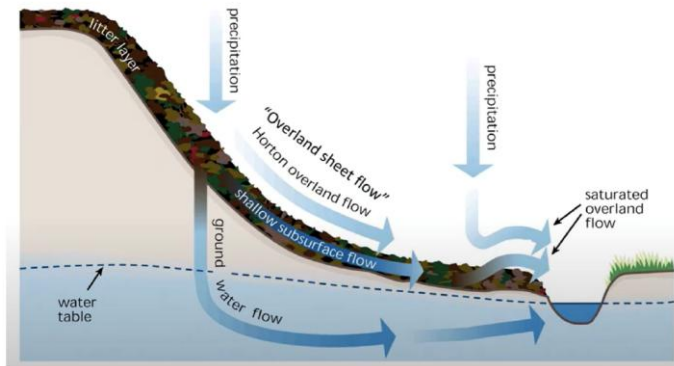
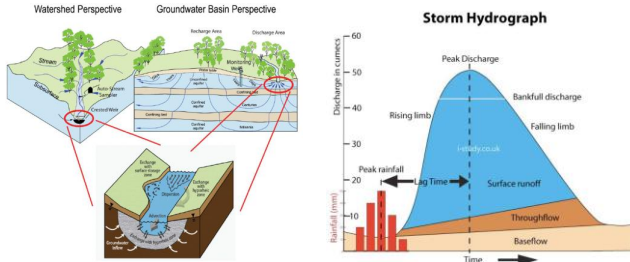


# How do various flow paths of water through the landscape affect streamwater chemistry?

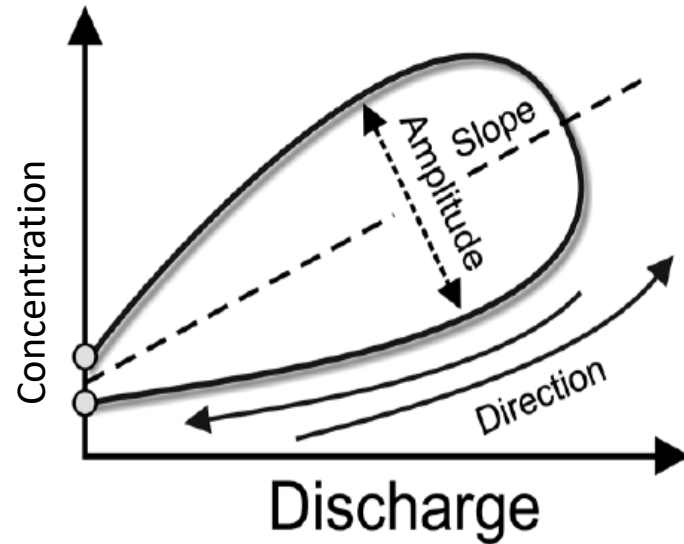


# Hydrological flow paths and the chemical birth of water

## Hysteresis loops



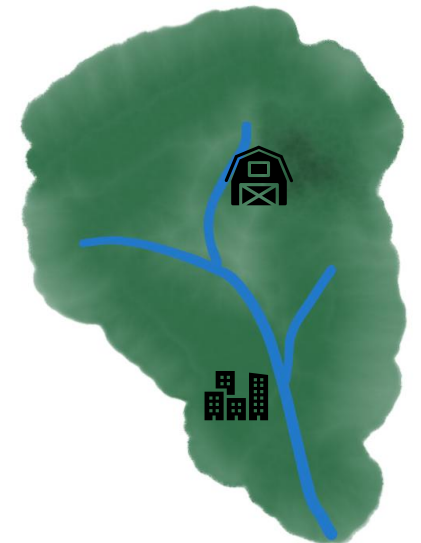
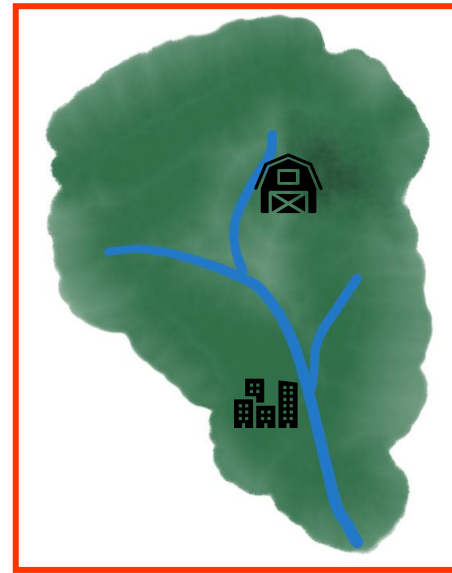
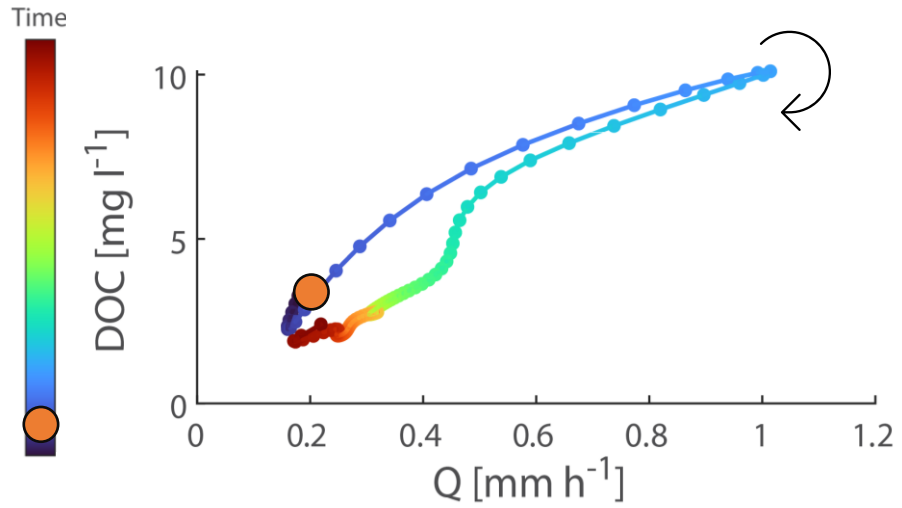
## Hysteresis



- 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 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

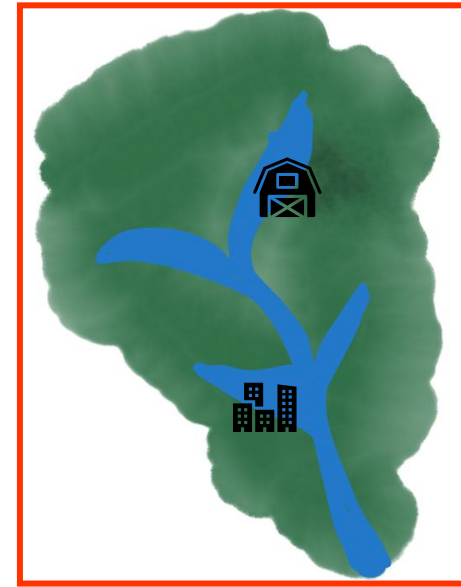
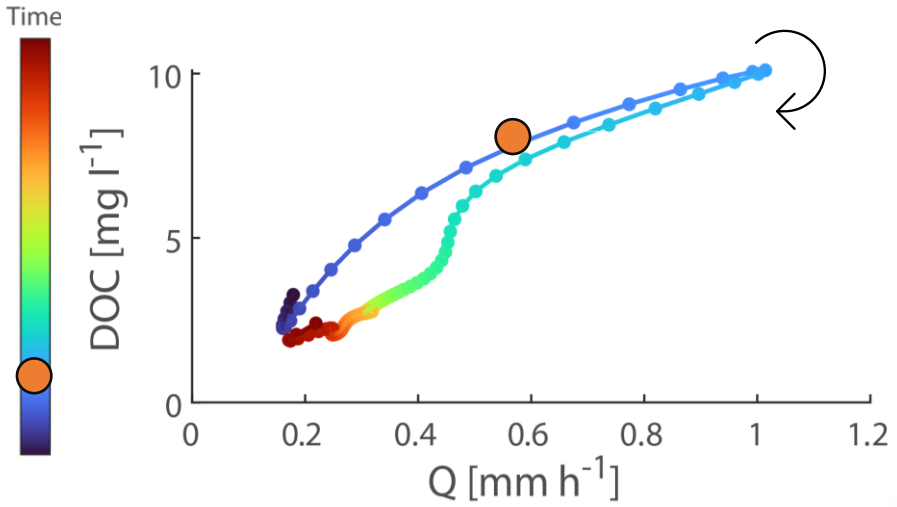
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Clockwise



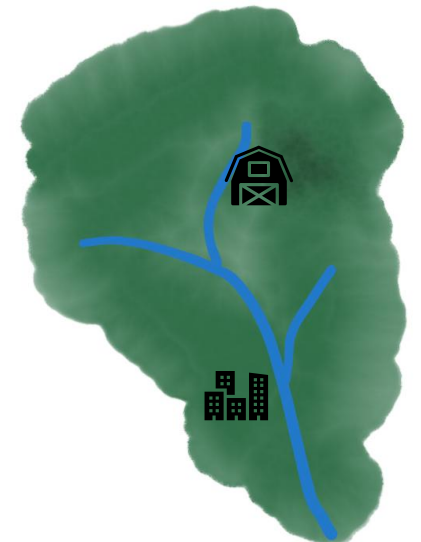
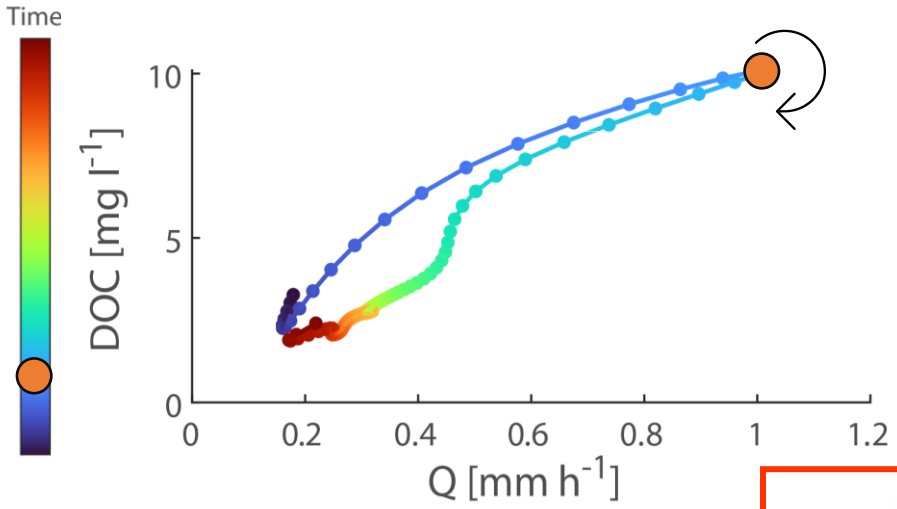
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Clockwise



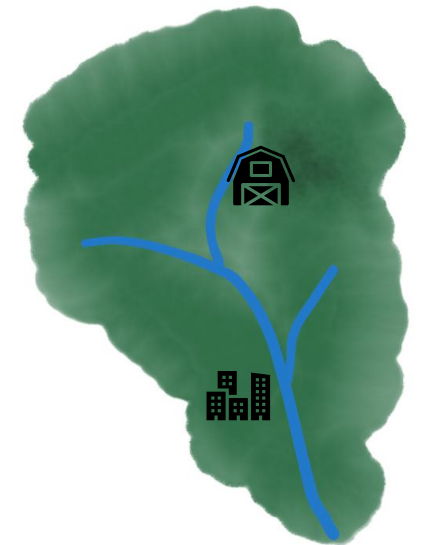
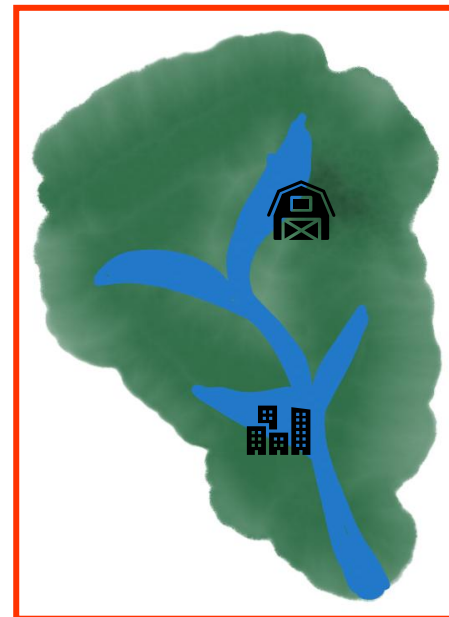
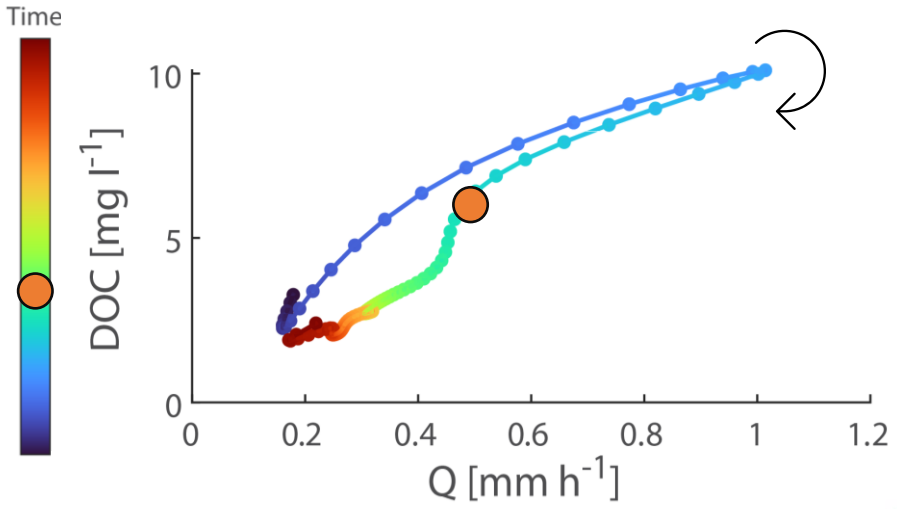
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Clockwise



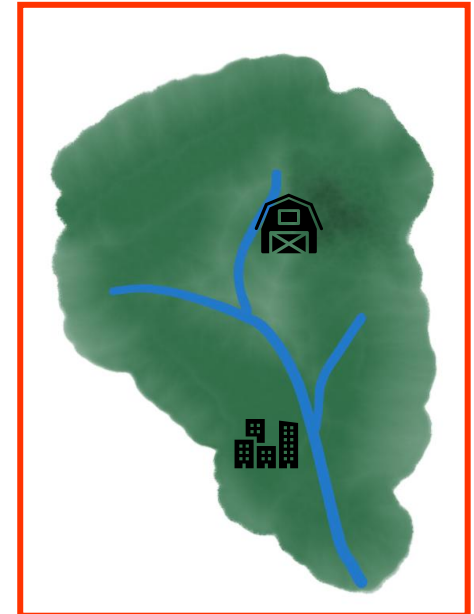
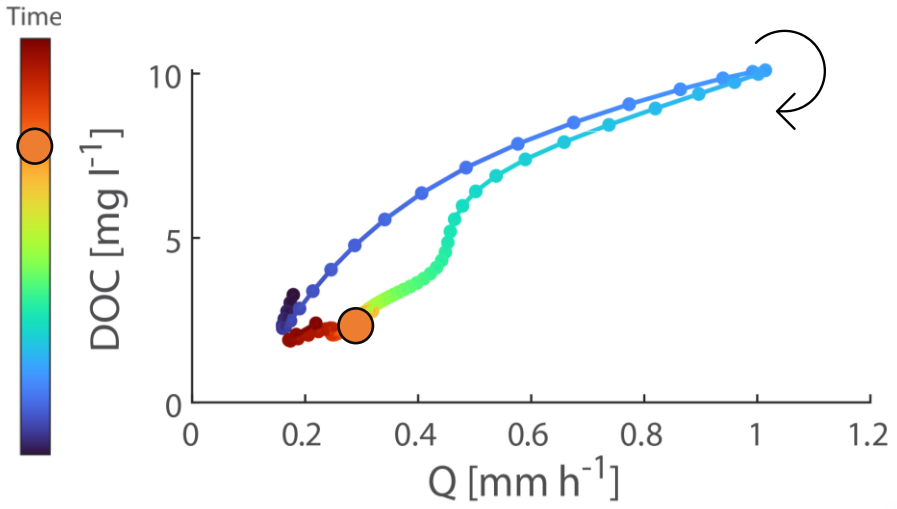
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Clockwise



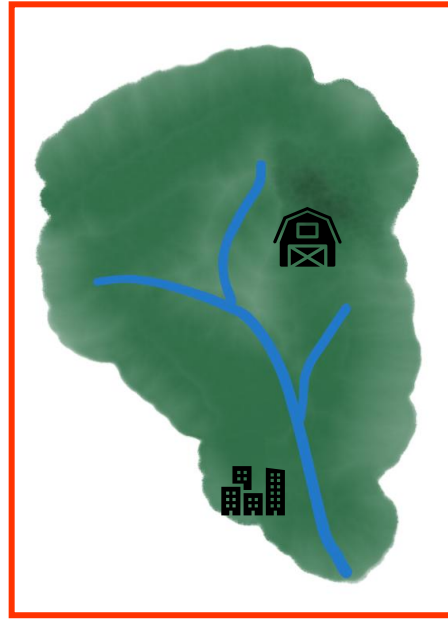
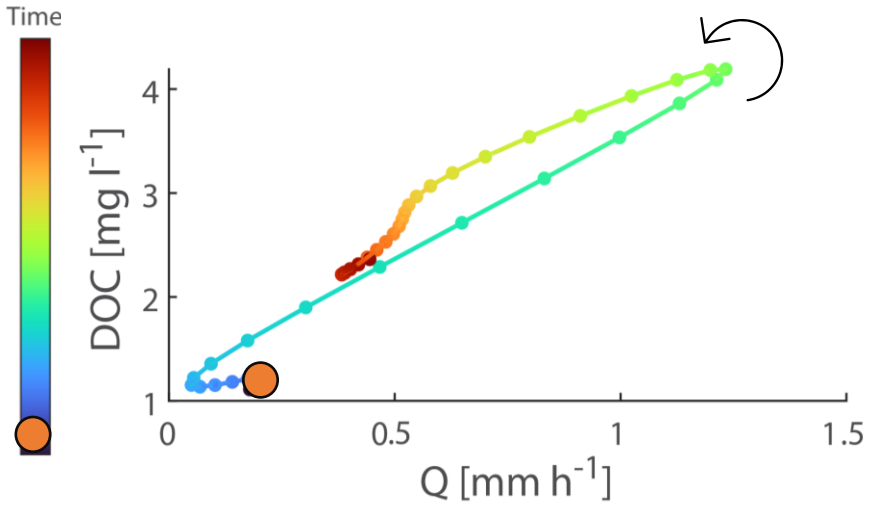
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Clockwise



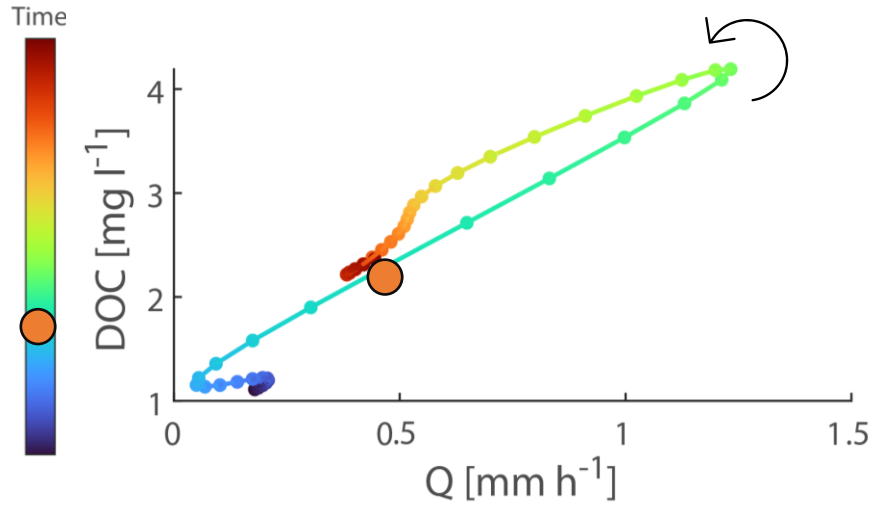
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Counterclockwise



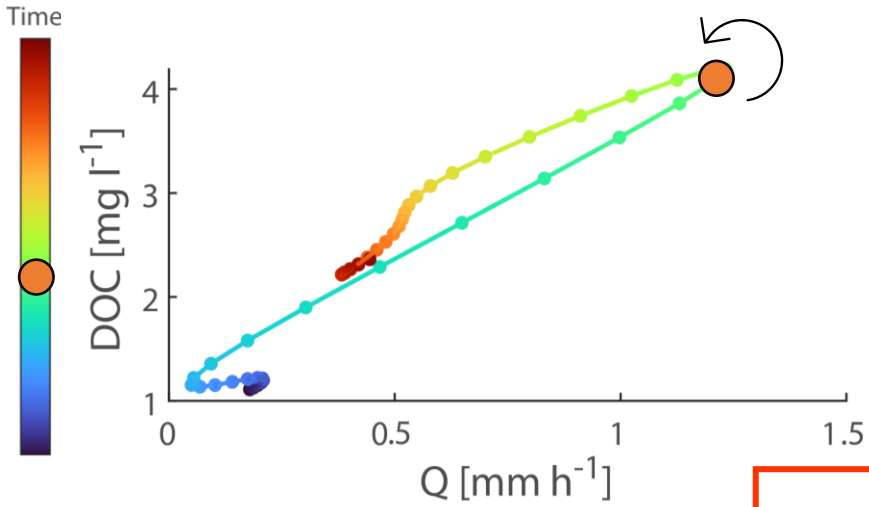
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Counterclockwise



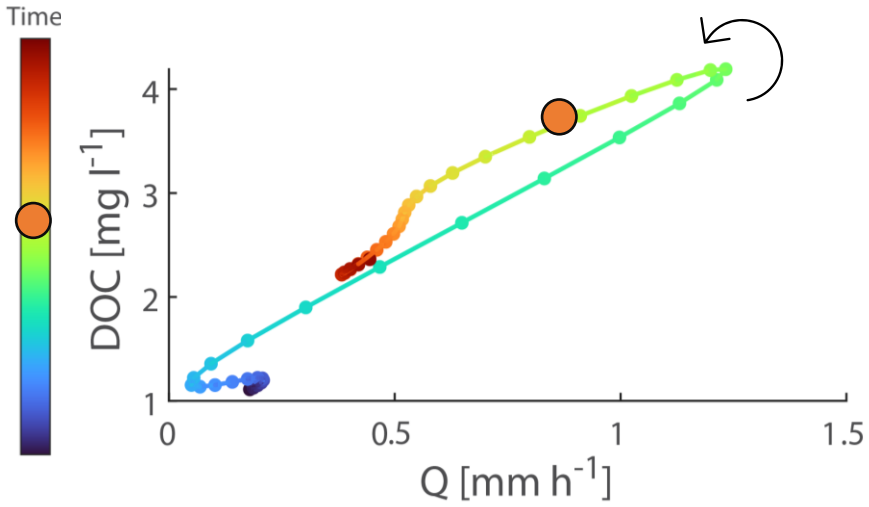
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Counterclockwise



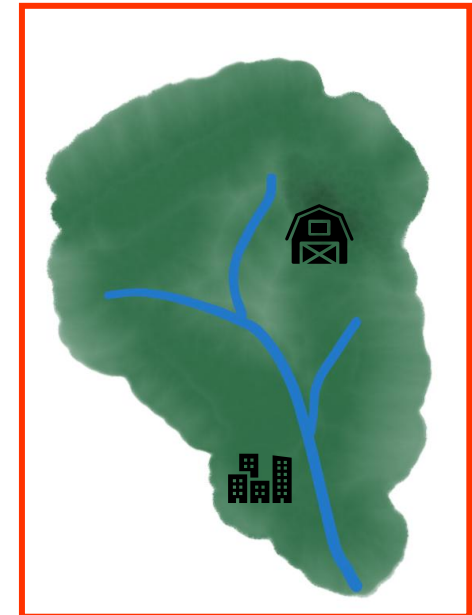
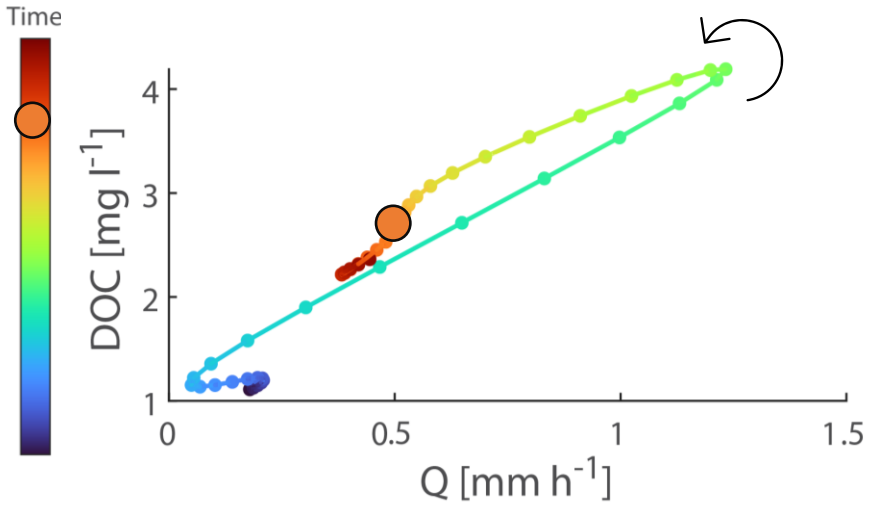
# Hydrological flow paths and the chemical birth of water

## Hysteresis loops - Counterclockwise



# Hydrological flow paths and the chemical birth of water

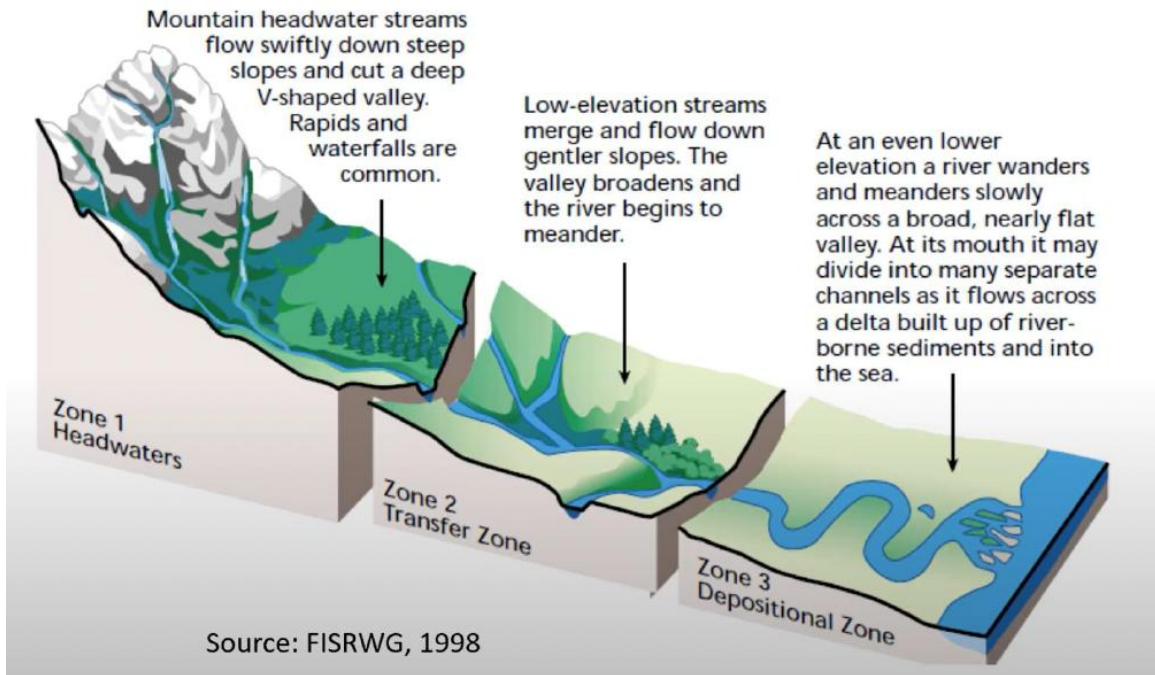
## Hysteresis loops - Counterclockwise



## Spatial heterogeneity of streams and rivers



# From braided to meandering streams and rivers

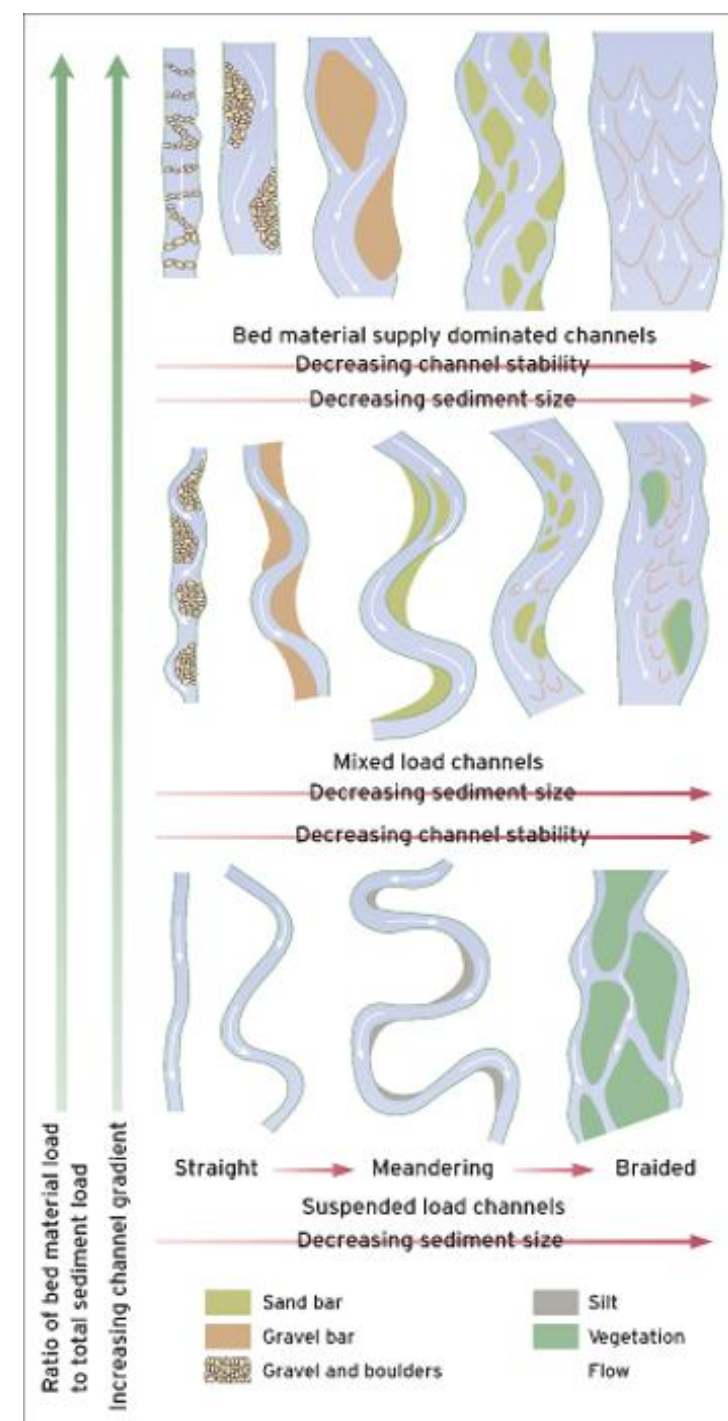


- Slope and energy
- Channel and bed stability
- Sediment load and size distribution

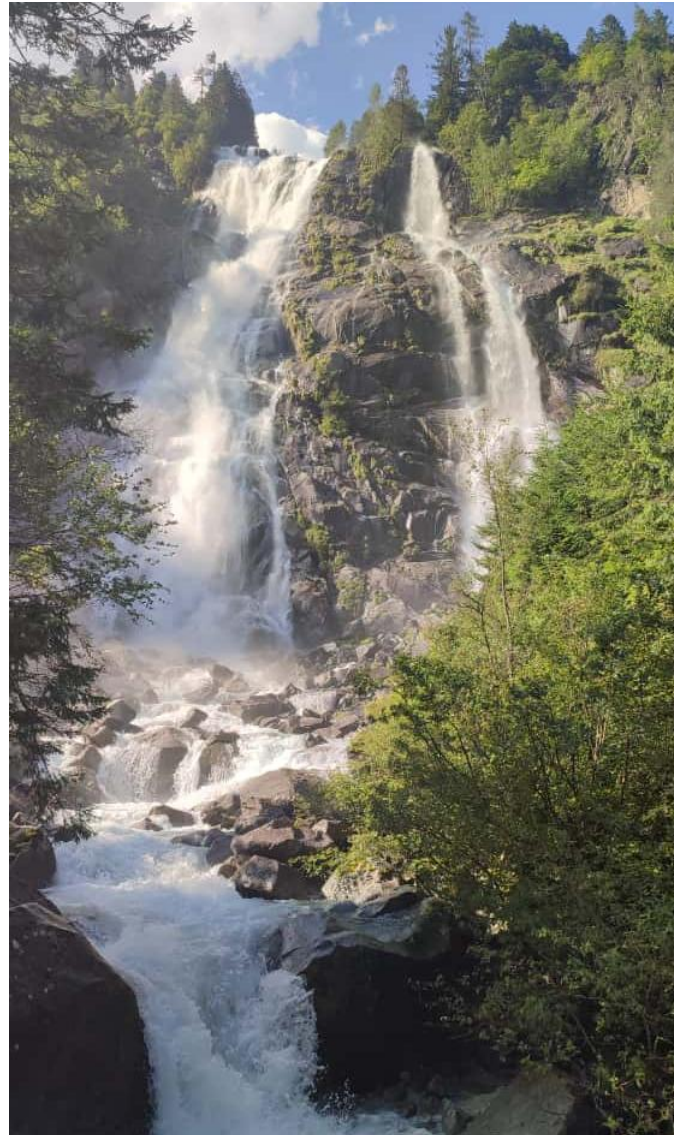
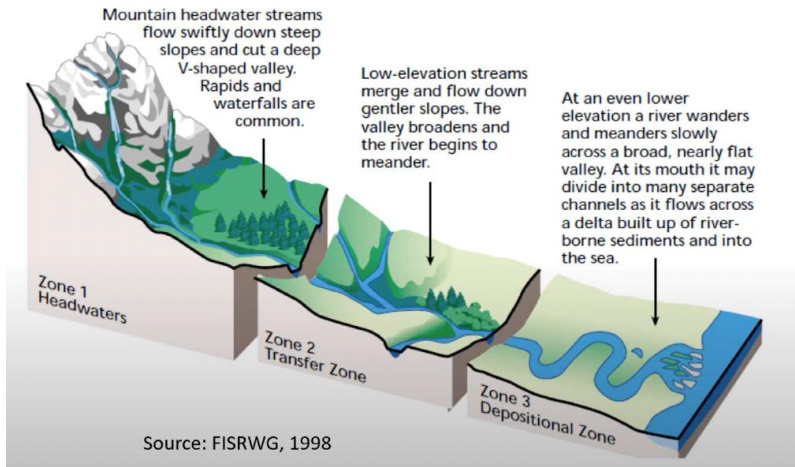
Consequences: connectivity, residence times, vegetation, biodiversity and ecosystem functioning

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

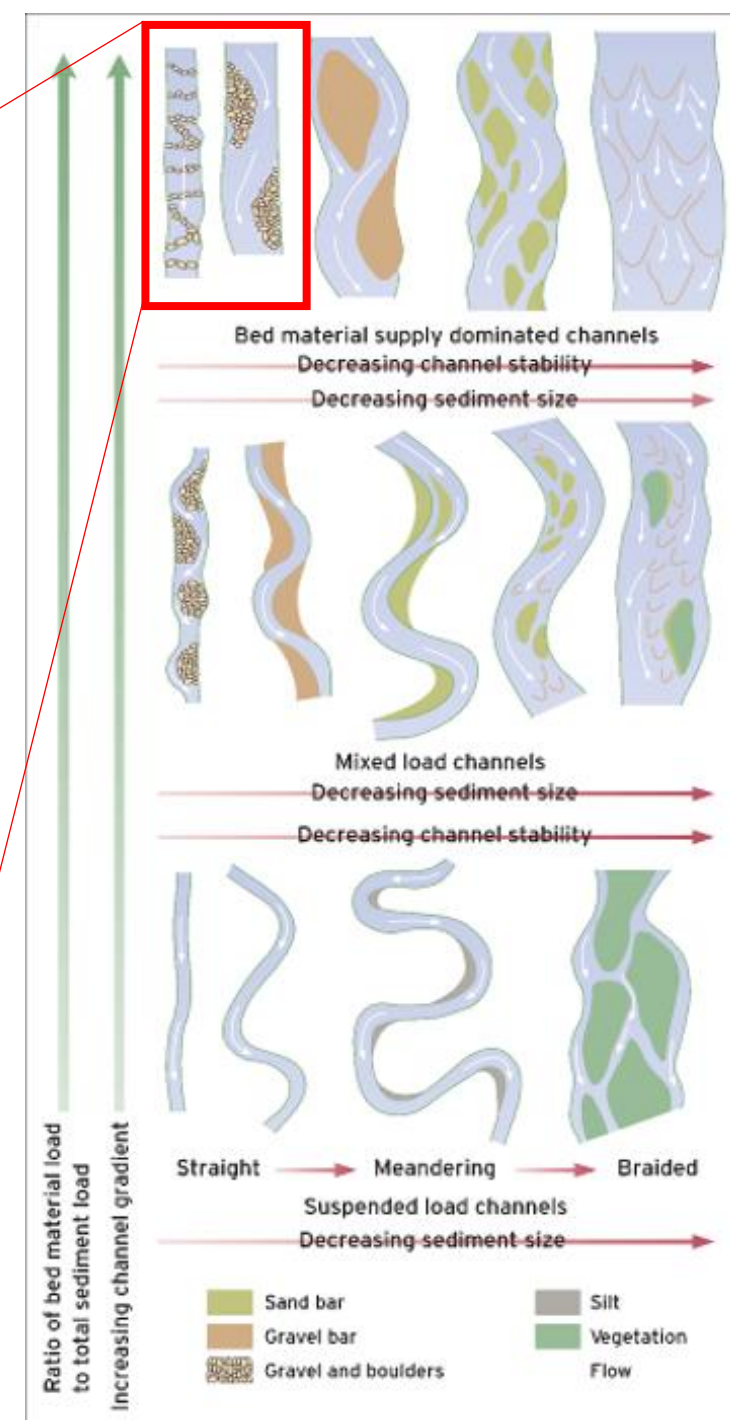
- Low-gradient channels
- Reduced bed load – more suspended load
- Less incised and confined, more dynamic channels
- Reduced sediment size



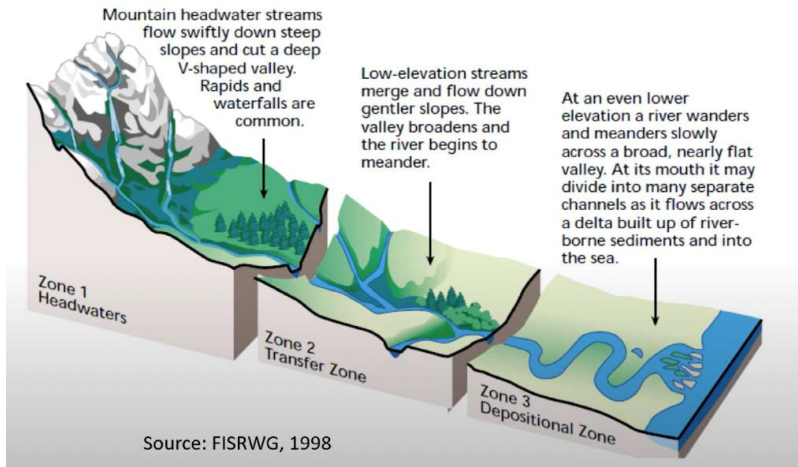
# From braided to meandering streams and rivers



- High Energy (velocity)
- Short Residence Time
- Transport >> Deposition



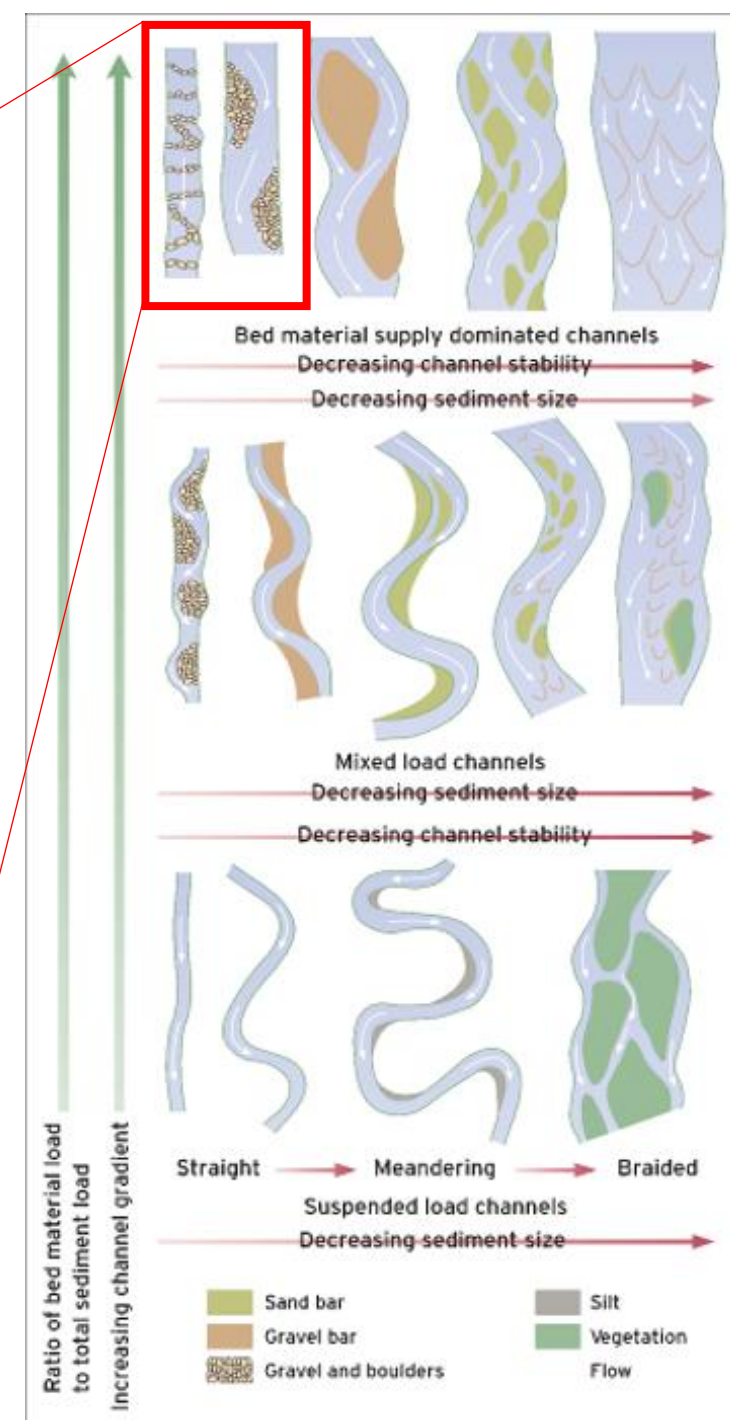
# From braided to meandering streams and rivers



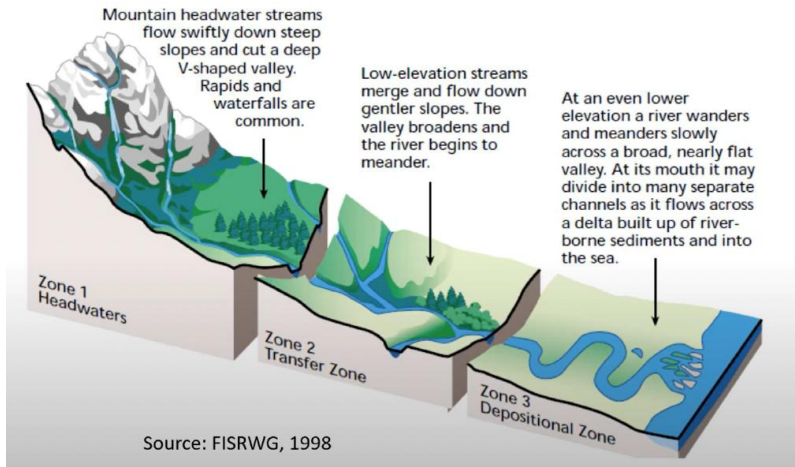
- High Energy (velocity)
- Short Residence Time
- Transport >> Deposition



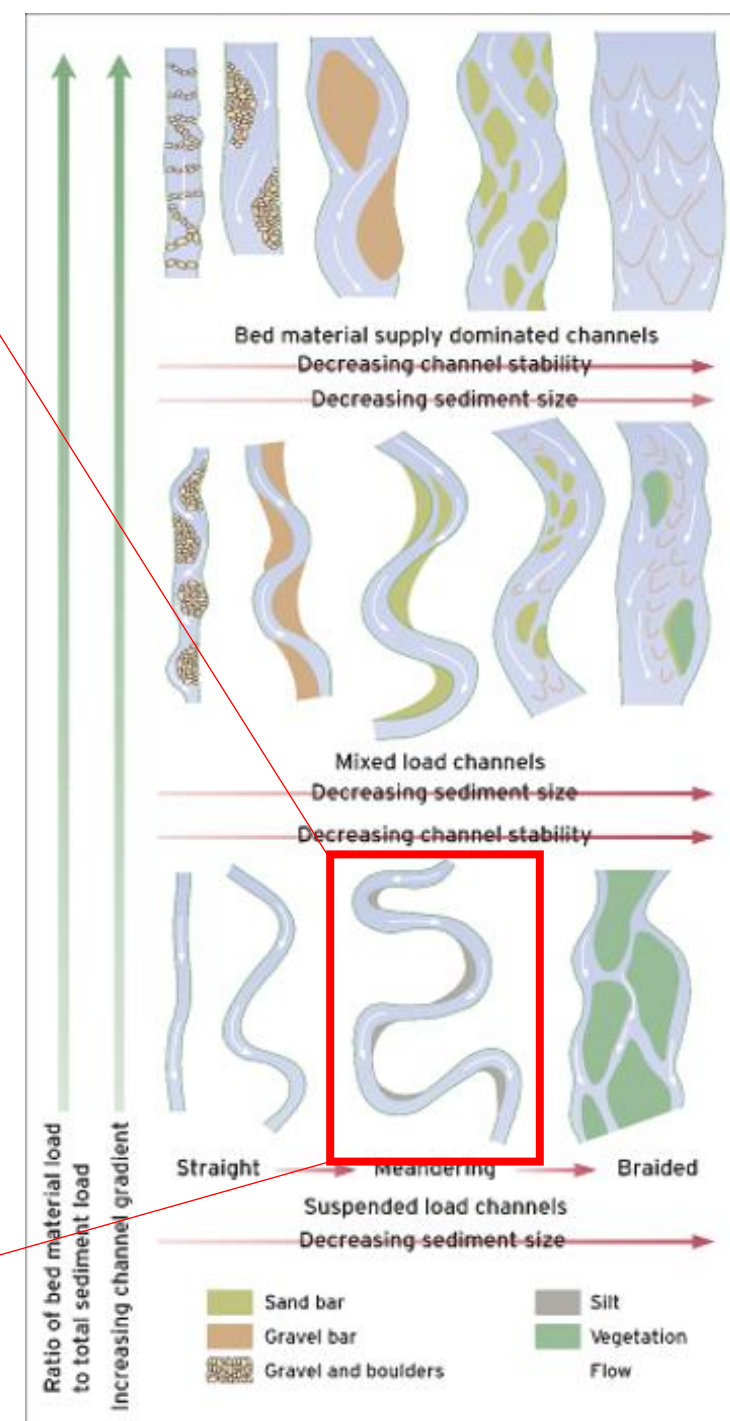
- Erosion
- Debris Flow
- Landslide



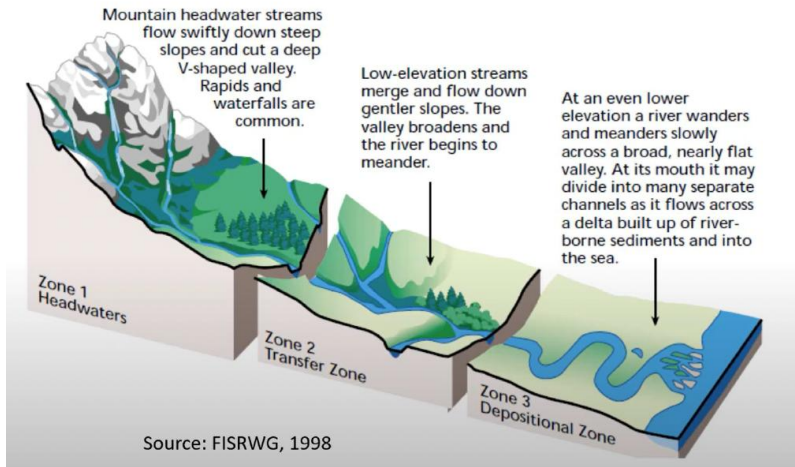
# From braided to meandering streams and rivers



- Low Energy (velocity)
- Long Residence Time
- Transport  $\ll$  Deposition



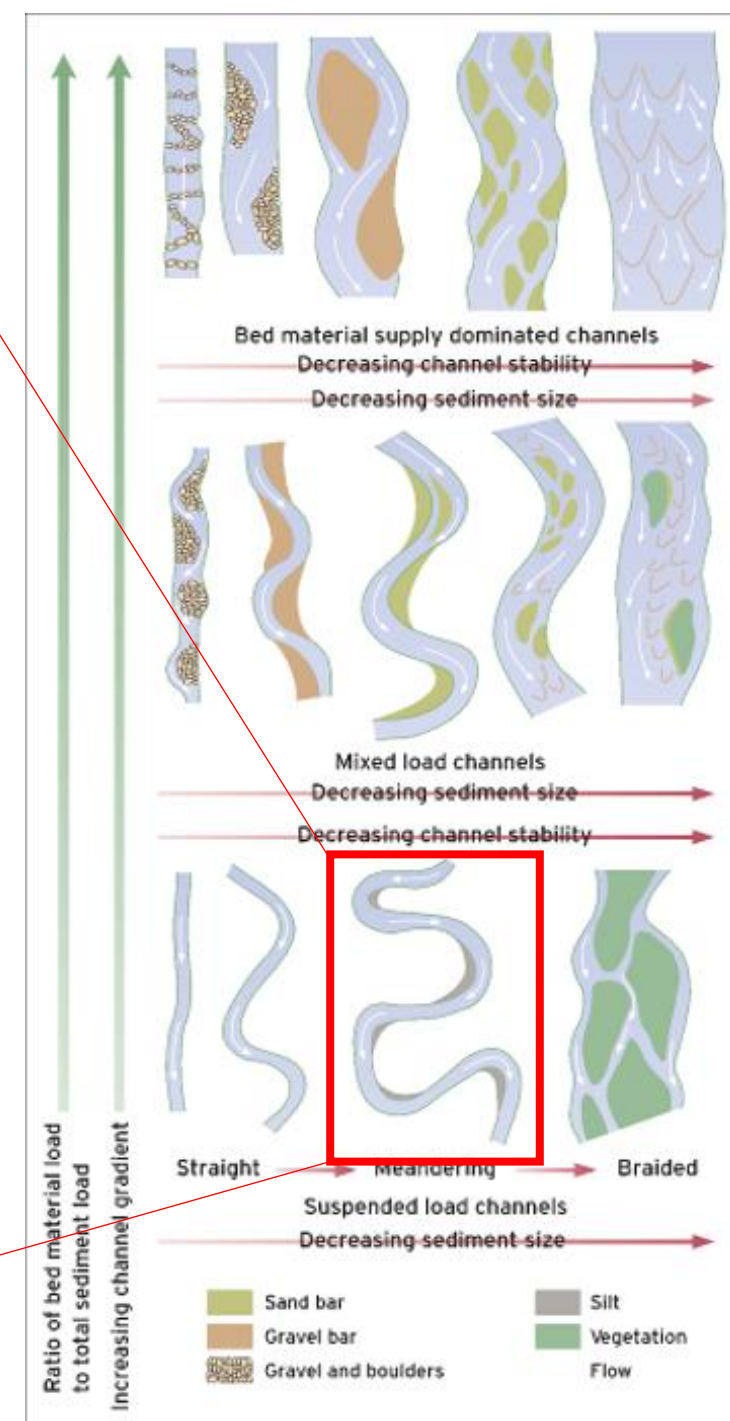
# From braided to meandering streams and rivers



- Low Energy (velocity)
- Long Residence Time
- Transport  $\ll$  Deposition

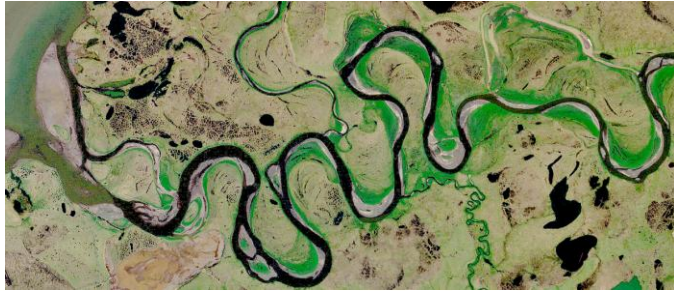


- Conflict with land use (urbanisation, agriculture)
- Channelisation
- Flood

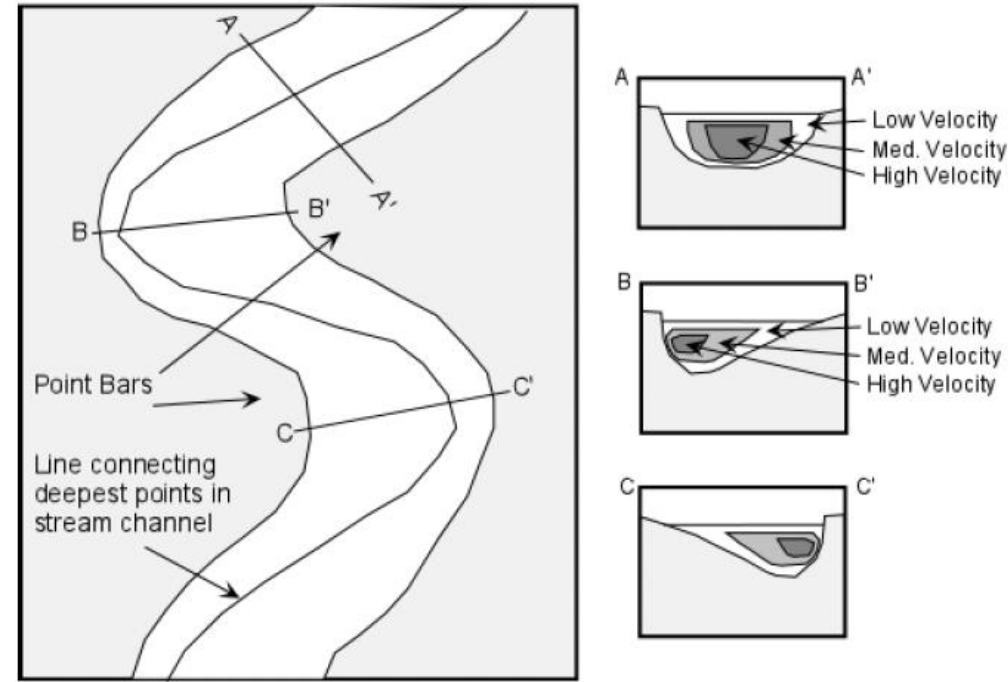


<https://www.youtube.com/watch?v=dHERpWgA84Y>

# Meander formation

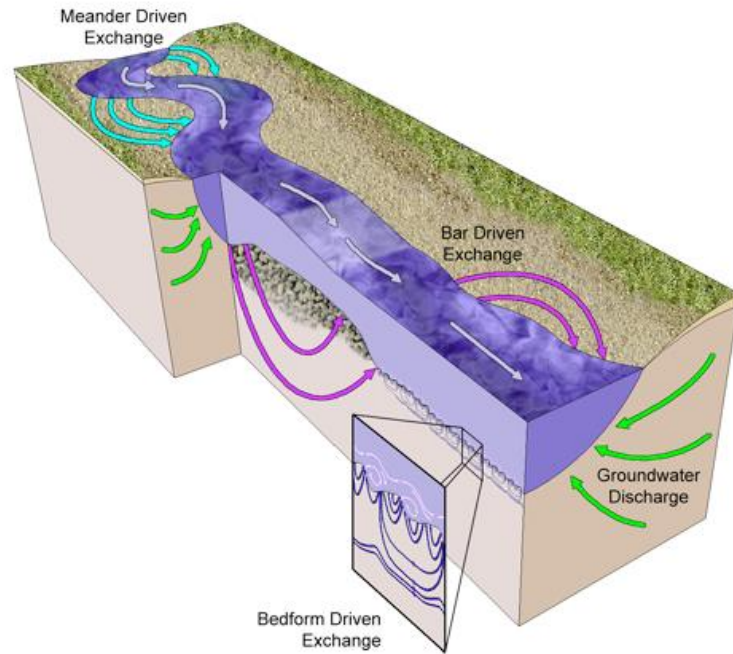


Meandering Channels



- 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 and stability of parent material

# Hyporheic exchange

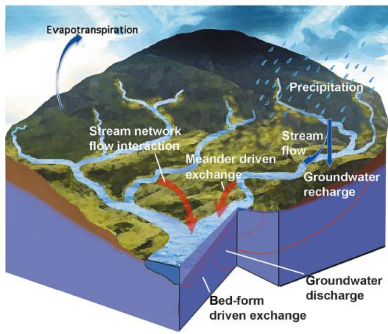


# Hyporheic exchange across spatial and temporal scales

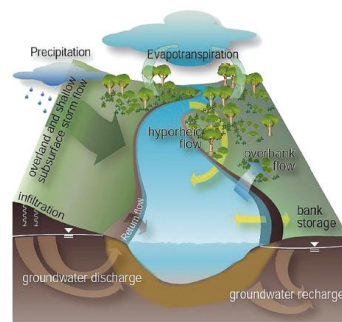


- Residence times
- Biogeochemical reaction rates

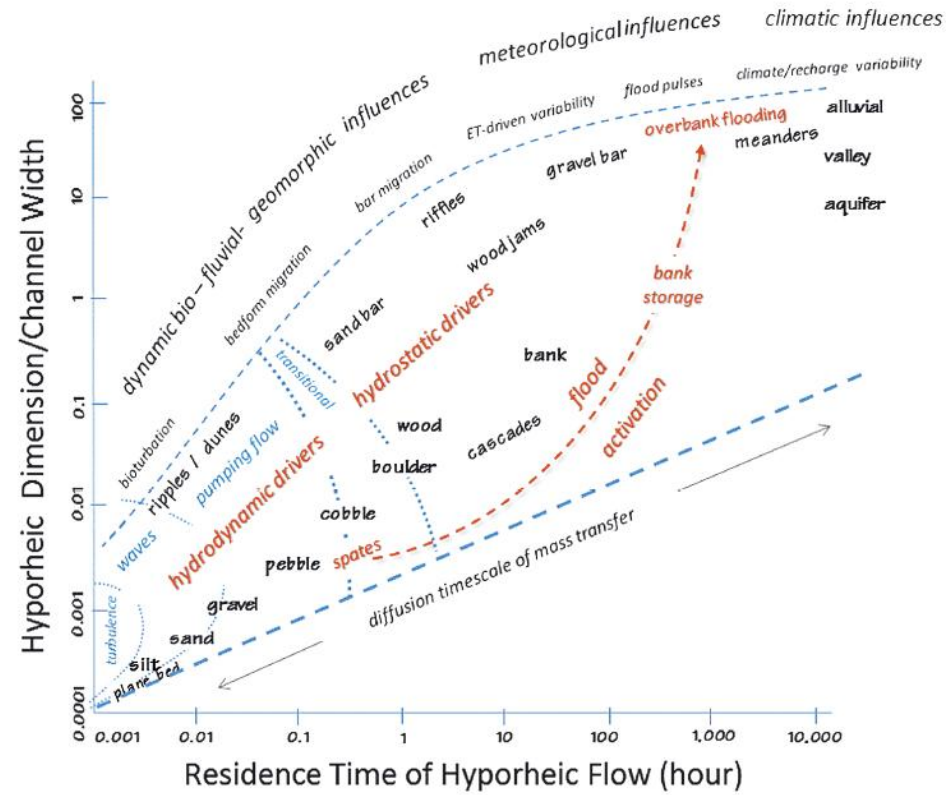
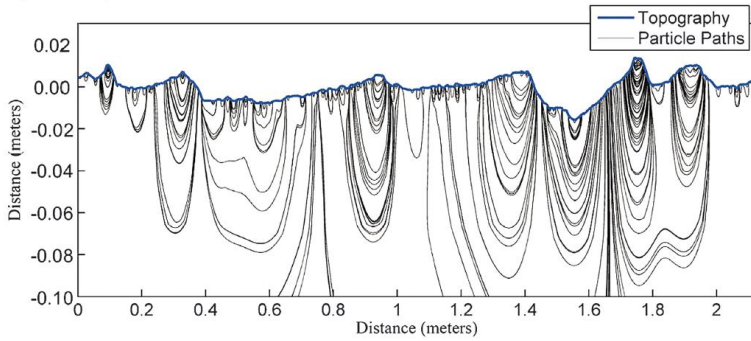
a) Watershed or Basin scale



b) River Corridor scale



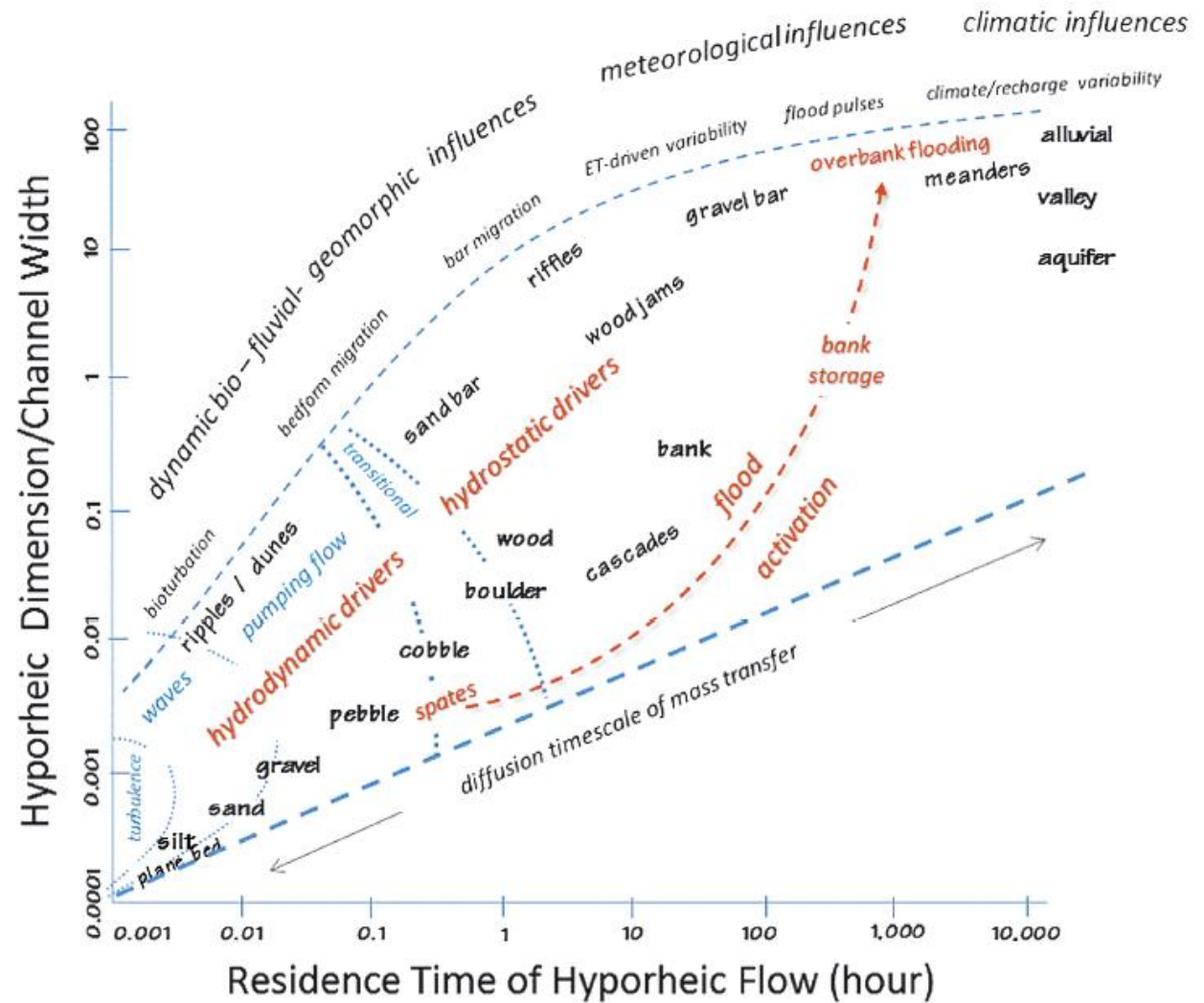
c) Geomorphic Unit scale





There are both static and dynamic contributors to hyporheic flow

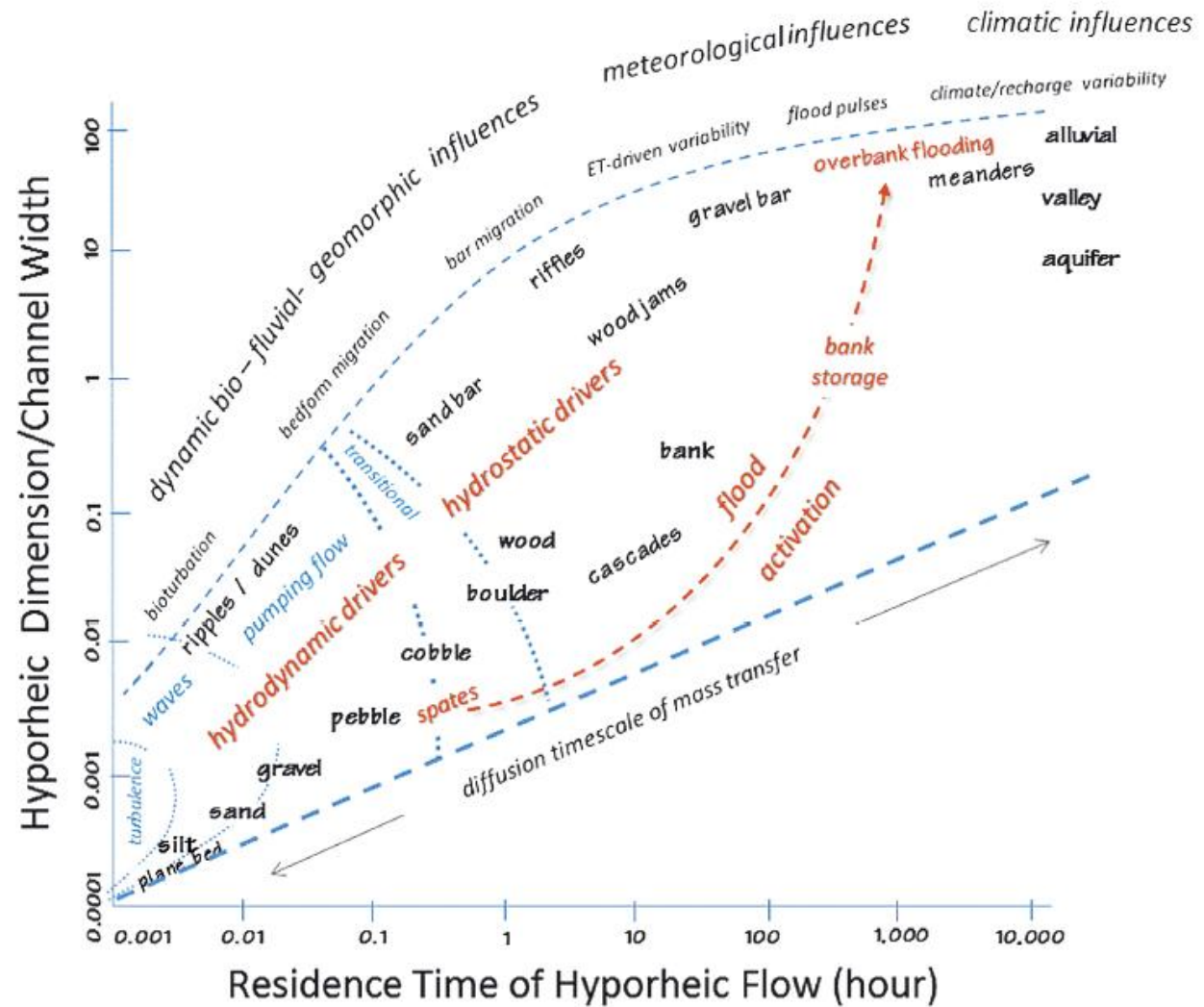
- At a point on the streambed the “hydrostatic” component represents the contribution to total hydraulic head given by water height regardless of flow.
- The “hydrodynamic” component represents the forces arising from surface water flow around roughness features on the streambed and the resulting momentum 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.



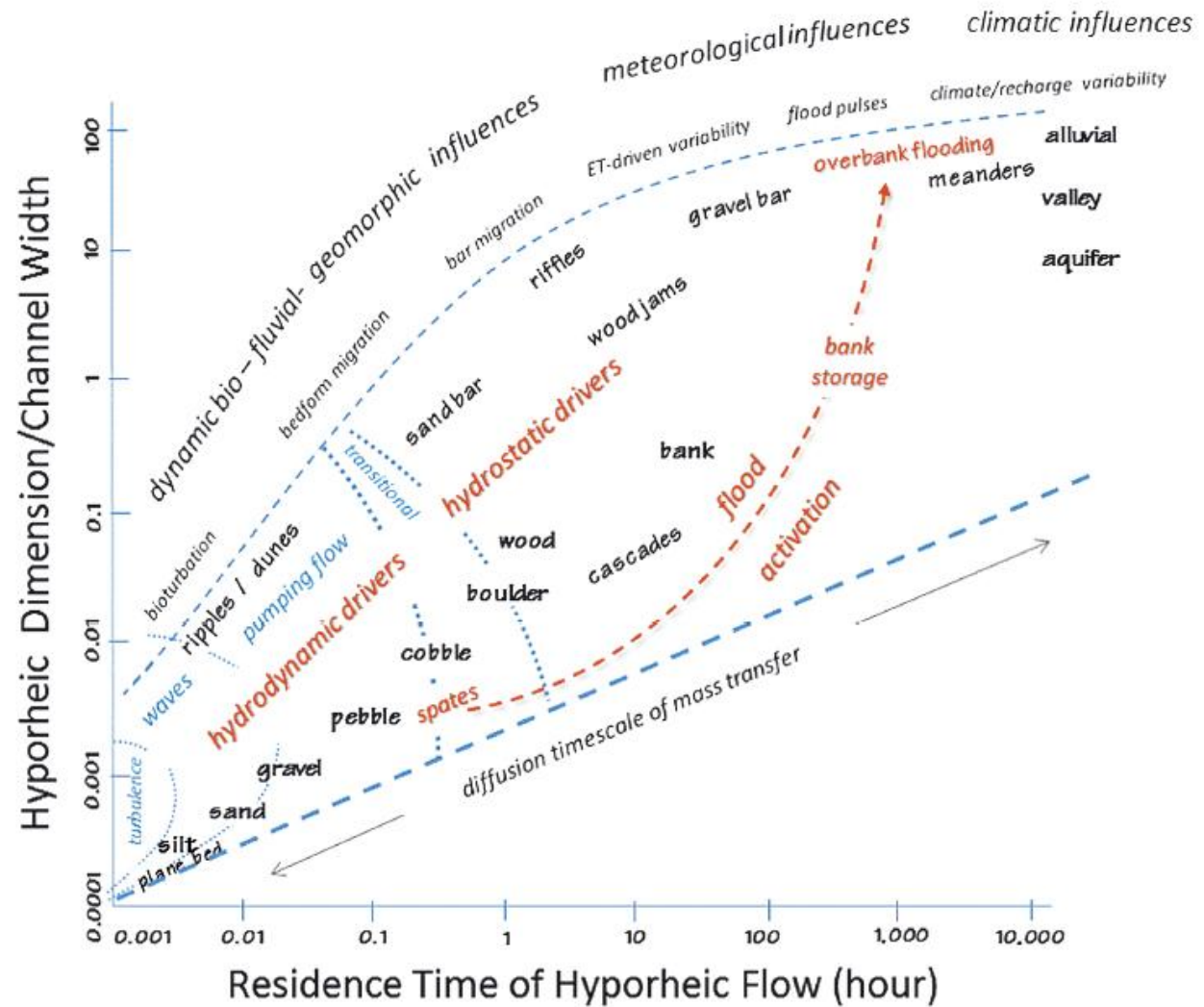
- Hydrostatic conditions in streams imply that the hydraulic head at the streambed interface is equal to the height of overlying surface water.
- Hydrostatically influenced hyporheic flow will therefore be affected by the variability in the height and slope of the streamwater surface and its effect on 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.



**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.



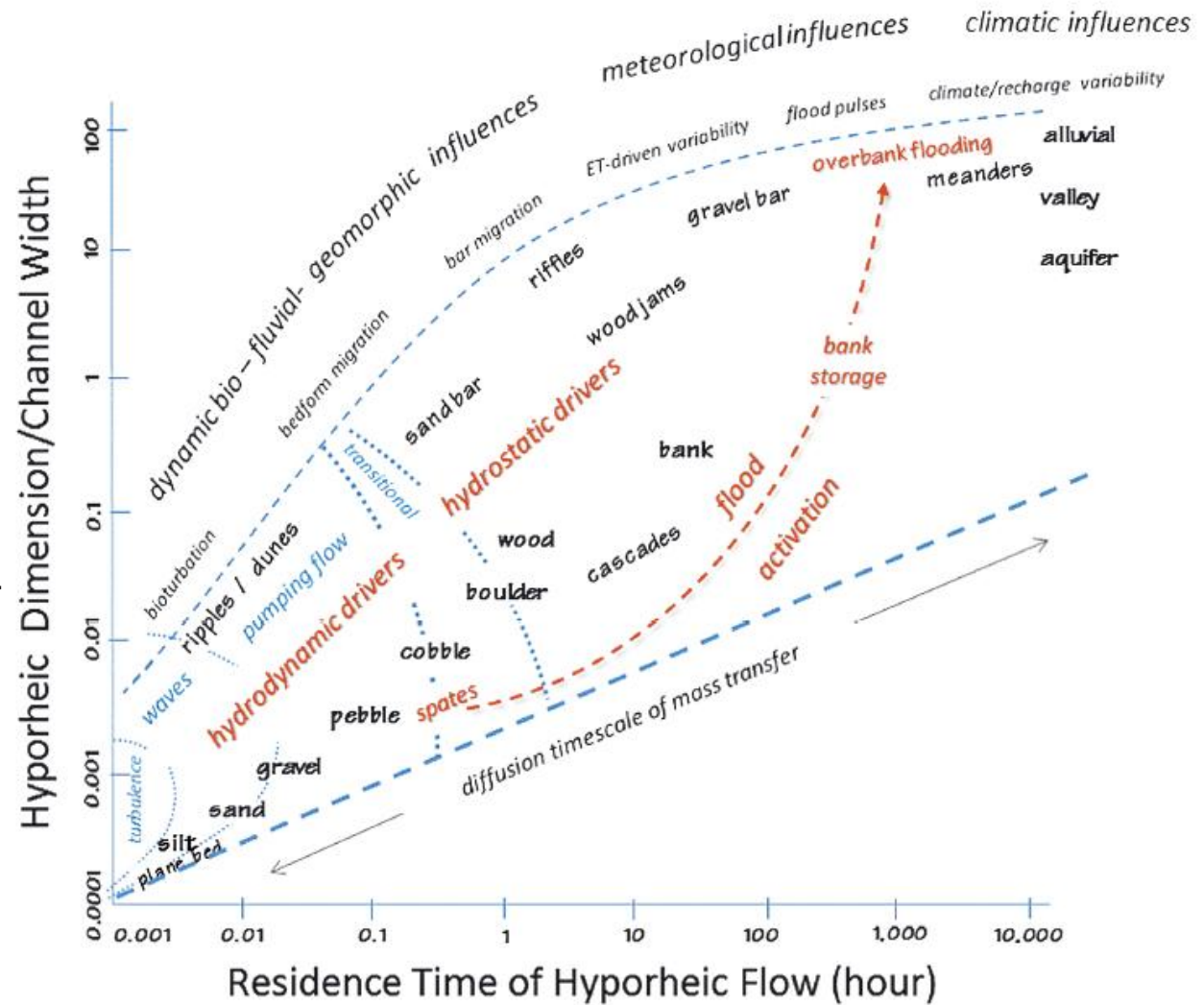
- Hydrodynamically driven hyporheic flow has its greatest influence at finer scales of variability in streamwater velocity flowing over submerged bedforms, which affects momentum transfer to the streambed.
- Hydrodynamic forces tend to be most influential in driving shallow hyporheic flows through pathways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



**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.



- 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 → resetting of the system



**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.

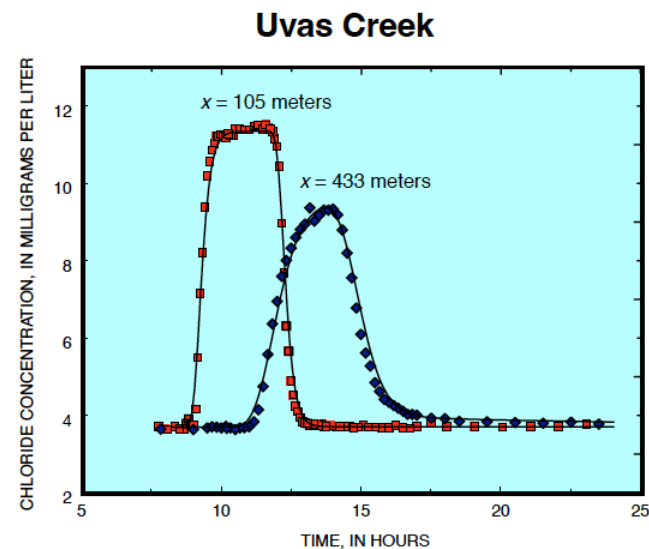
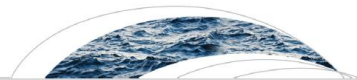
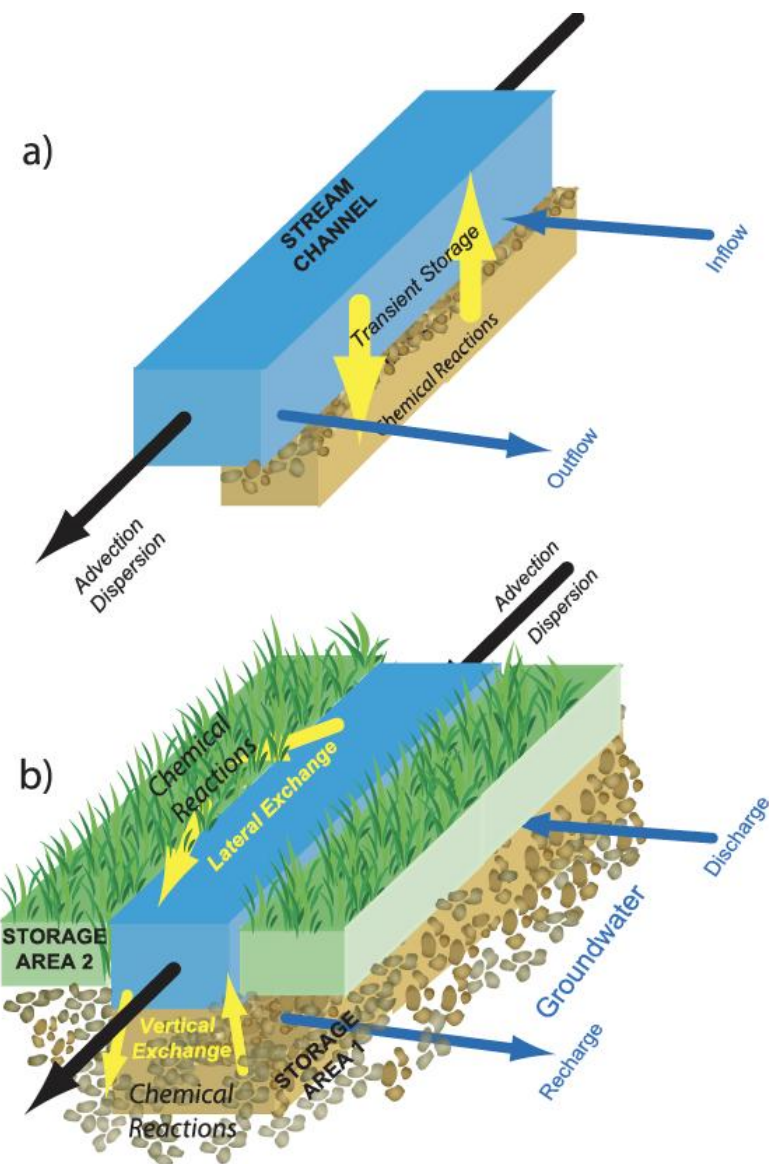


Figure 3. Simulated (solid lines) and observed (symbols) chloride concentrations in Uvas Creek, California.

## 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

- 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

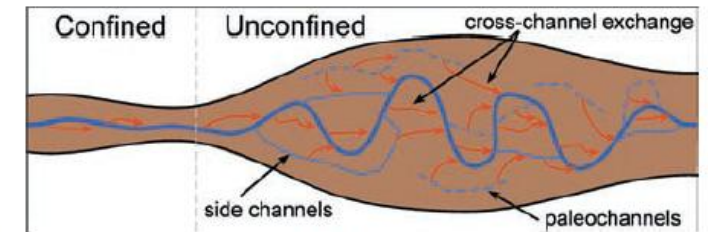


Fig. 5. Differences in lateral complexity of head gradients and hyporheic exchange in confined versus unconfined alluvial valleys.

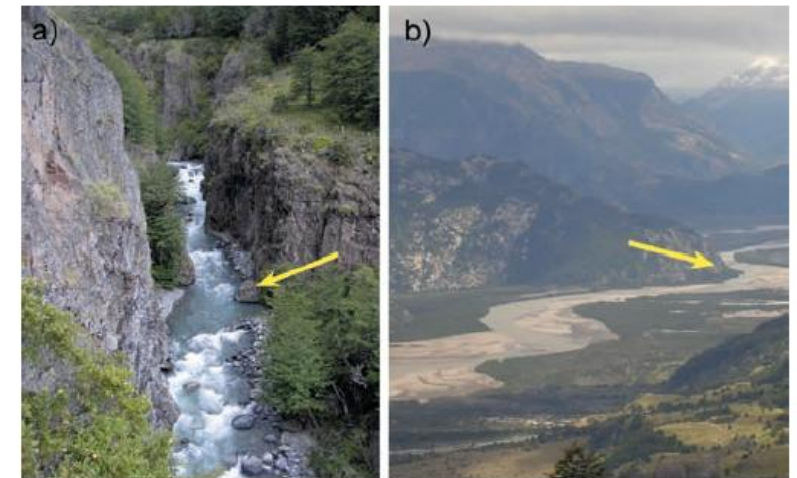
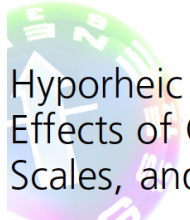


Fig. 6. Photographs of (a) confined and (b) unconfined channels. Arrows indicate bedrock projections that locally constrict alluvial area.



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

John M. Buffington<sup>1\*</sup> and Daniele Tonina<sup>2</sup>

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

- 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

High turnover length  
Low mixing  
Low residence time

Low turnover length  
High mixing  
Elevated residence time

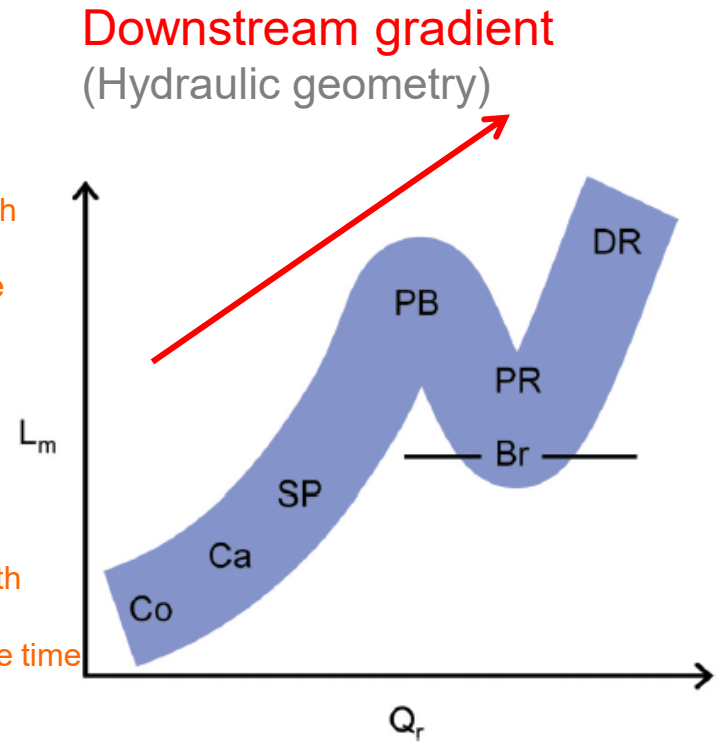
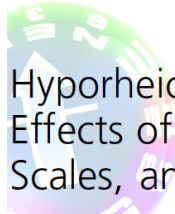


Fig. 8. Conceptual plot of length scales for complete mixing of river and hyporheic waters ( $L_m$ ) as a function of river discharge ( $Q_r$ ) and channel type (Co = colluvial, Ca = cascade, SP = step-pool, PB = plane-bed, PR = pool-riffle, BR = braided, DR = dune-ripple).



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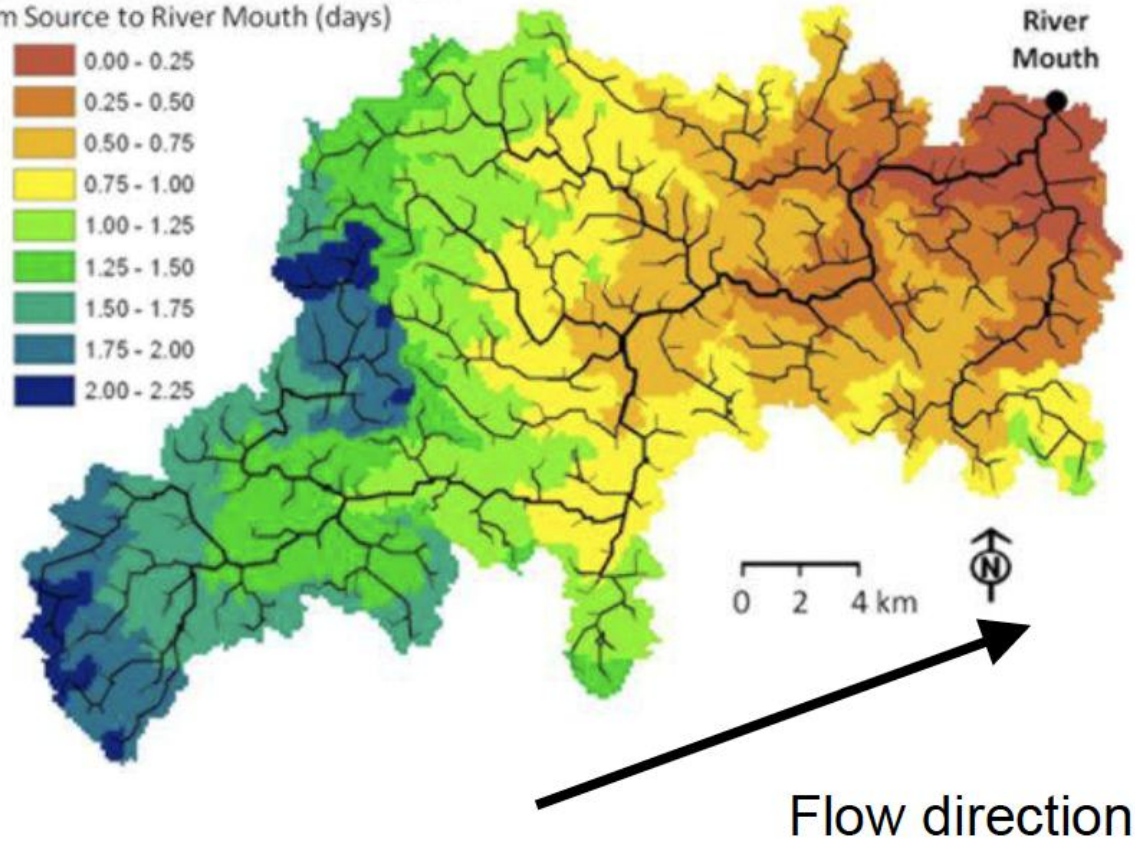
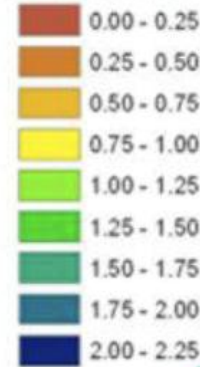
$Q_r$  stream flow (discharge)

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- Discharge ( $Q$ ) changing predictably from up- to downstream
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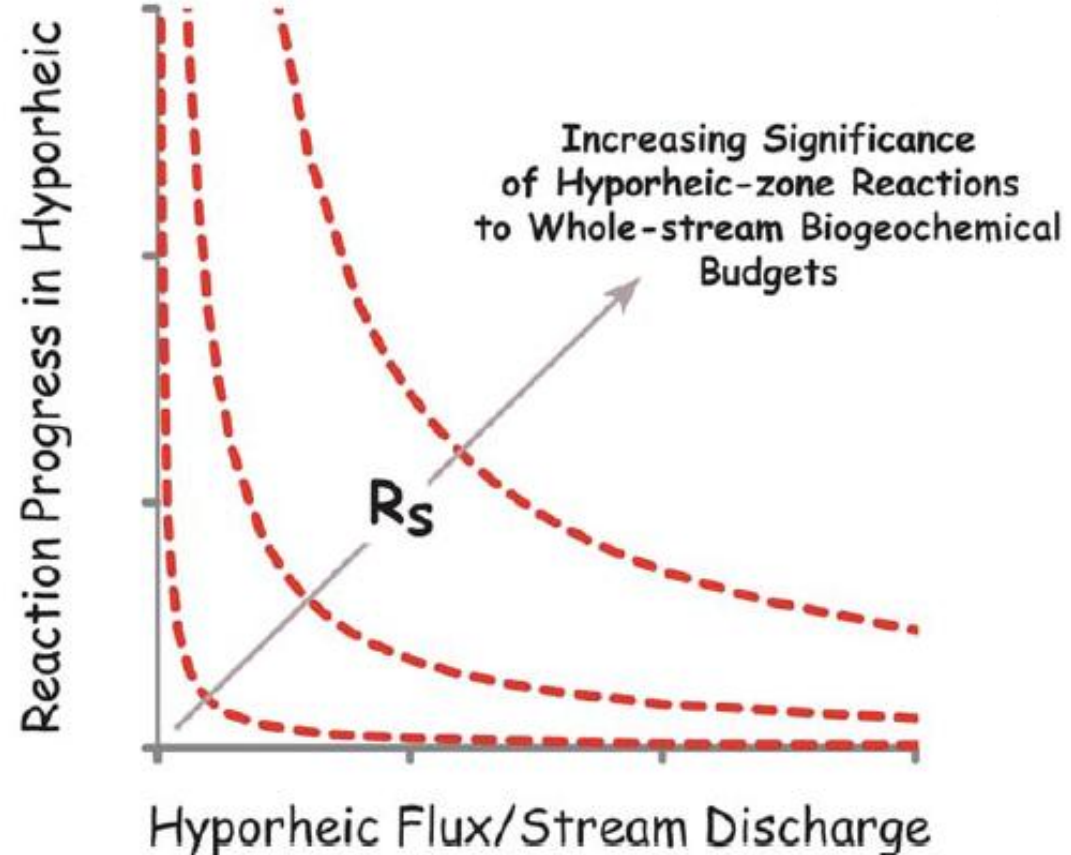
Total Cumulative Residence Time in HTS from Source to River Mouth (days)



# 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  $R_s$ , comprised of average hyporheic flow path-scale factors and reach-scale hydrologic factors.
- The dashed lines are isolines with increasing values of  $R_s$  toward the upper right denoting the fraction of the reactant removed per characteristic (dimensionless) distance travelled in the stream.



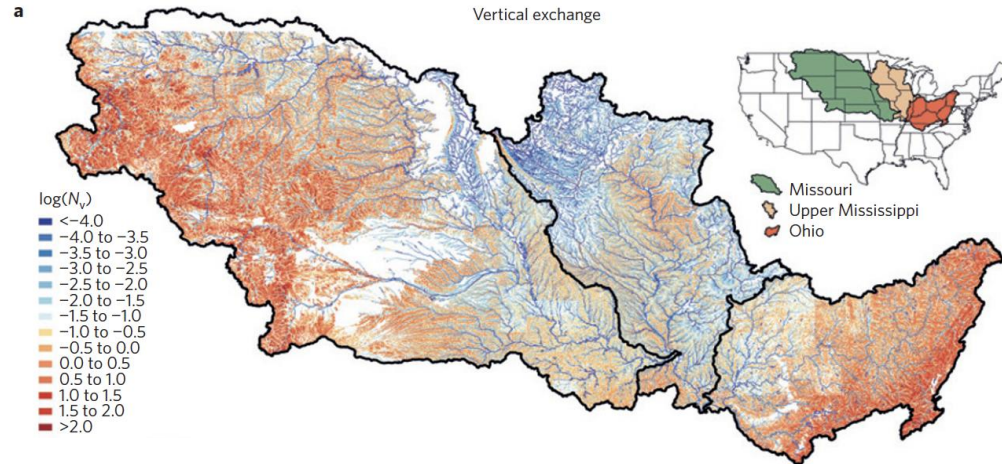
# Consequences of hyporheic flow and storage

## Reaction Significance Factor

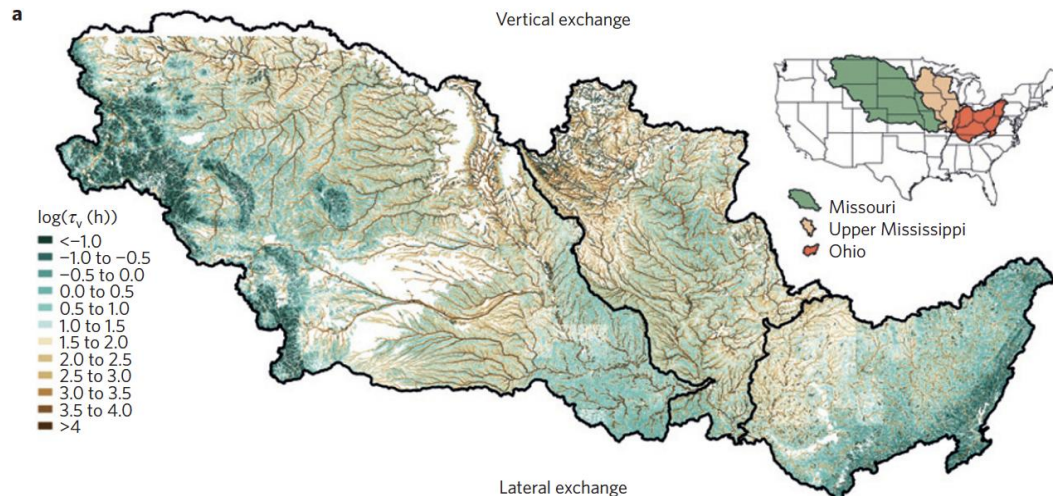
### Denitrification in the Mississippi River network controlled by flow through river bedforms

Jesus D. Gomez-Velez<sup>1,2\*</sup>, Judson W. Harvey<sup>1</sup>, M. Bayani Cardenas<sup>3</sup> and Brian Kiel<sup>3</sup>

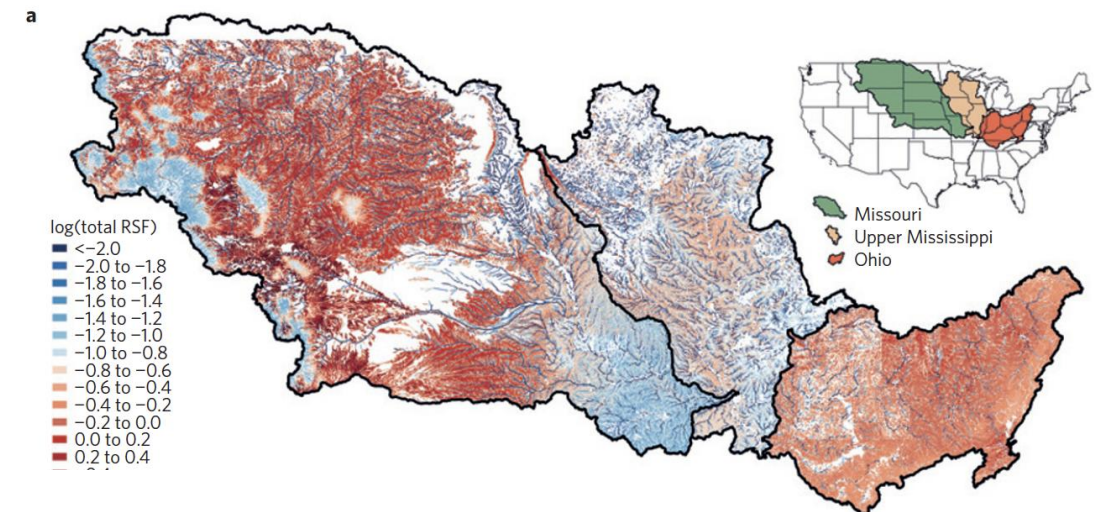
Promoting the development of permeable bedforms at the streambed—and thus vertical hyporheic exchange — is effective at enhancing river denitrification in large river basins



## Median hydrological turnover length

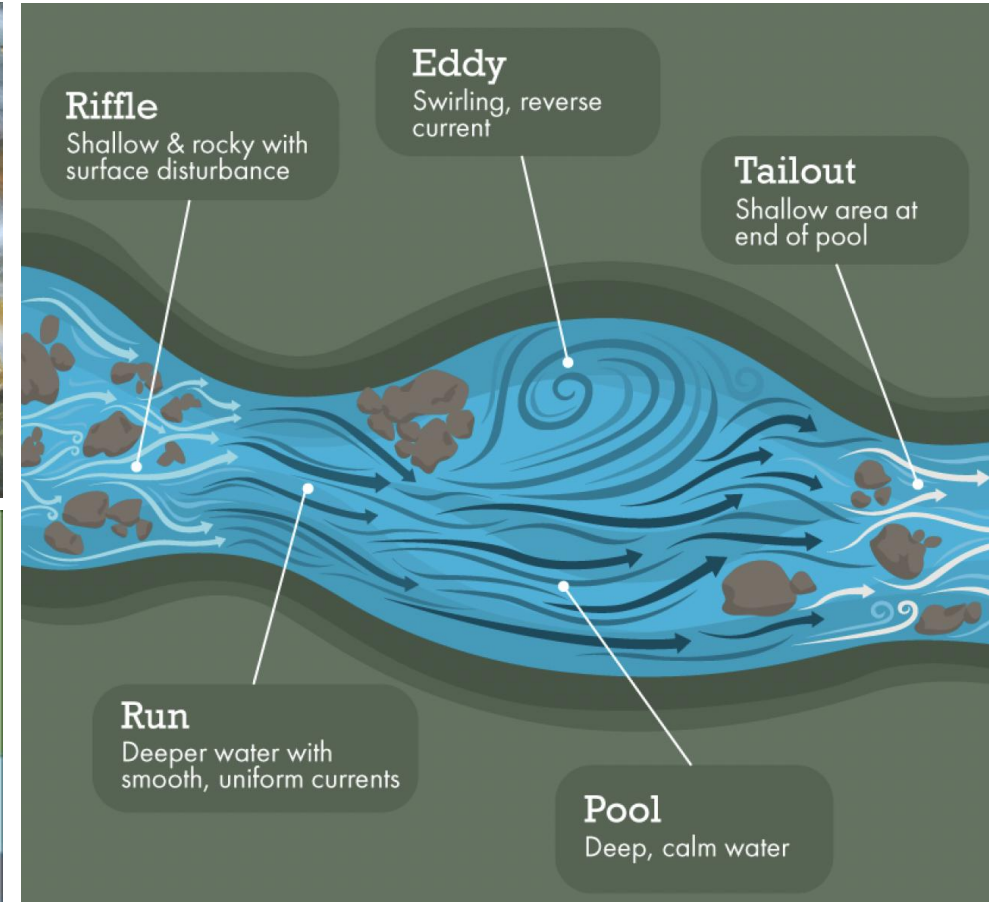
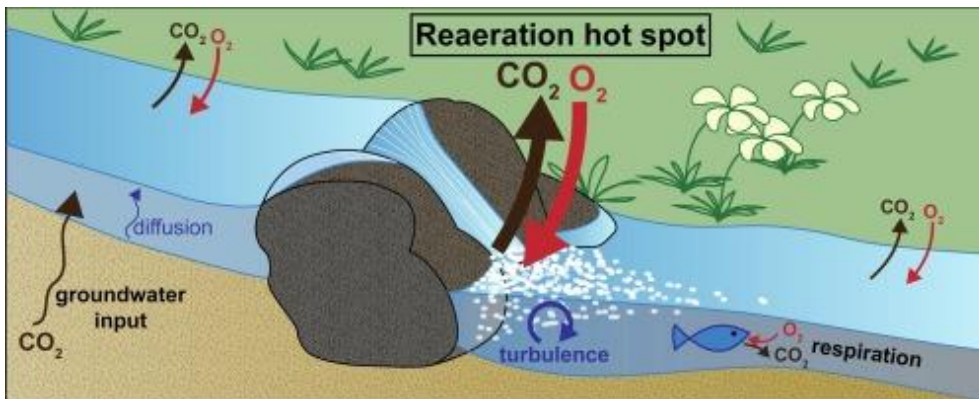
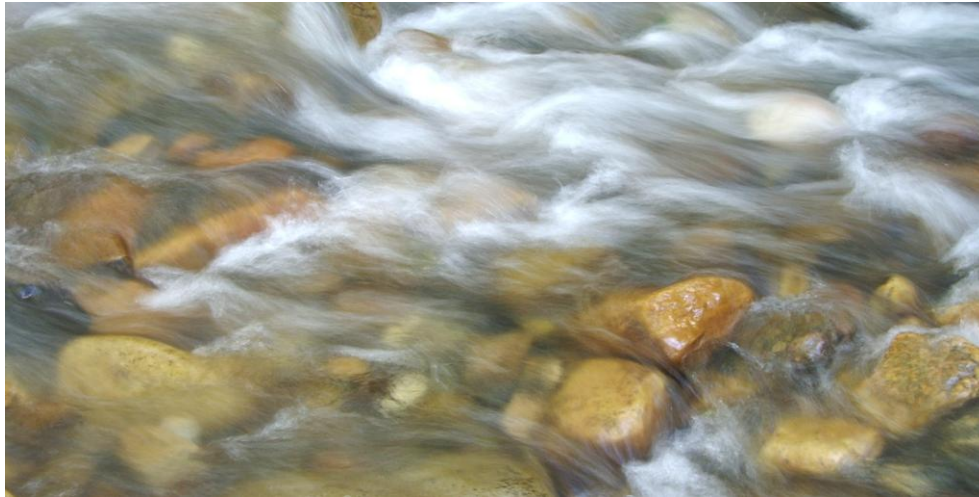


## Median hyporheic residence time



## Reaction Significance Factor for denitrification

# Streambed topographic heterogeneity and gas exchange

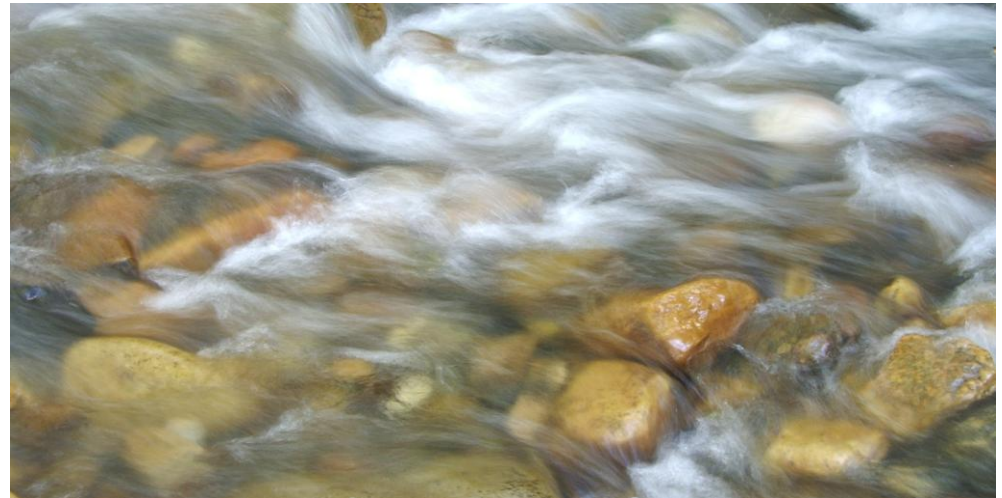


- Oxygenation — biodiversity & fish population; degradation and purification
- GHG emissions

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

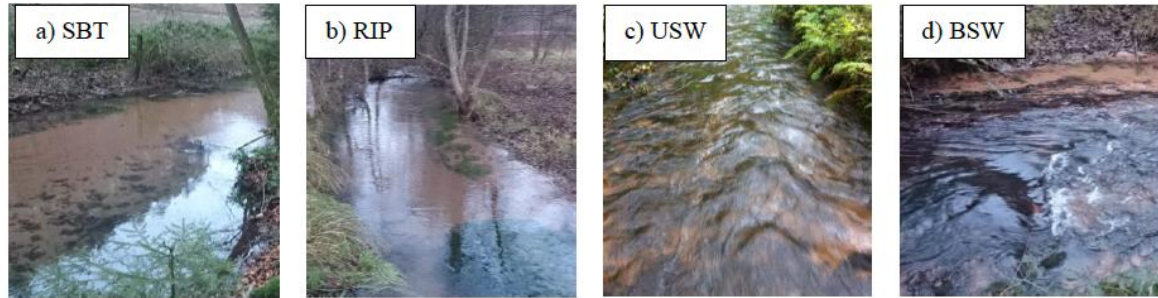
$$k = \alpha (\varepsilon \nu)^{1/4} Sc^{-n}$$

$\nu$  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  $\alpha$  is a scaling coefficient

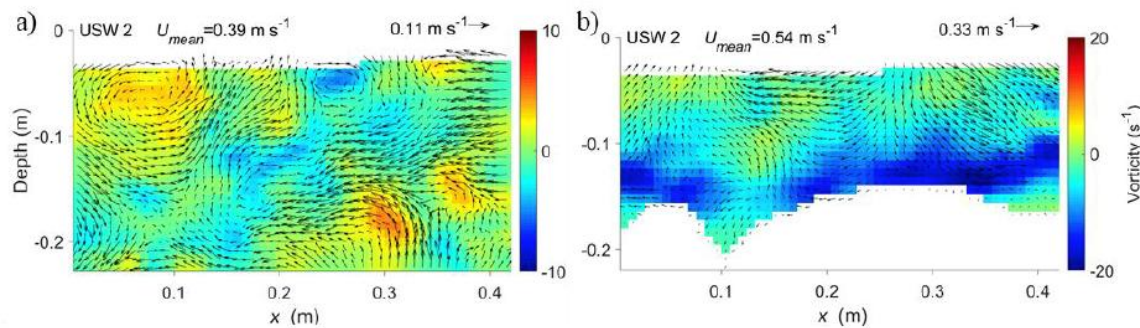


## Hydrodynamic control of gas-exchange velocity in small streams

Andreas Lorke<sup>1\*</sup>, Pascal Bodmer<sup>1</sup>, Kaan Koca<sup>1</sup> and Christian Noss<sup>1</sup>

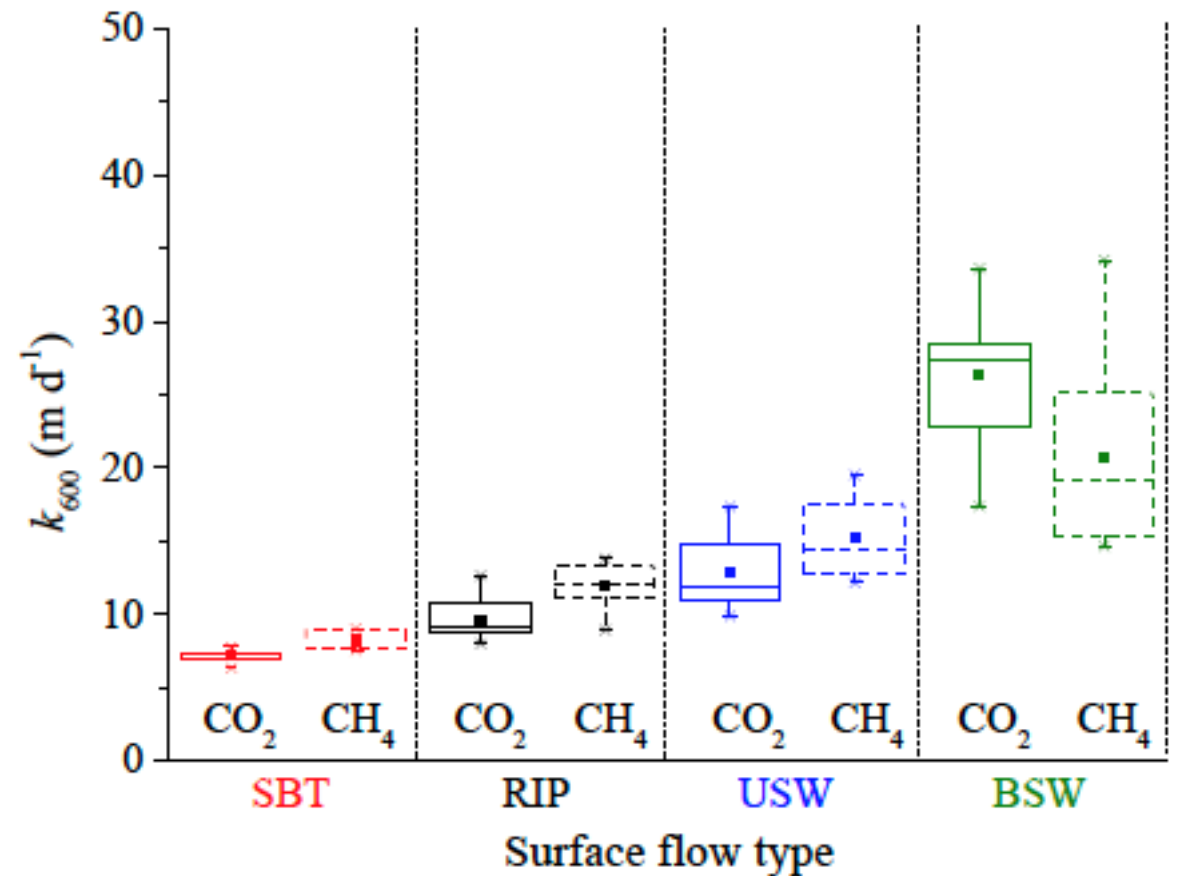


**Figure 1:** Study sites at the Wellbach featuring different surface flow types: a) Smooth boundary turbulence (SBT), b) rippled flow (RIP), c) unbroken standing wave (USW) and d) broken standing wave (BSW).



**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 ( $\omega$ , Eq. 8) scales with the angular velocity of clockwise (blue color) and counterclockwise (red color) rotating eddies in the planar field of view.

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



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

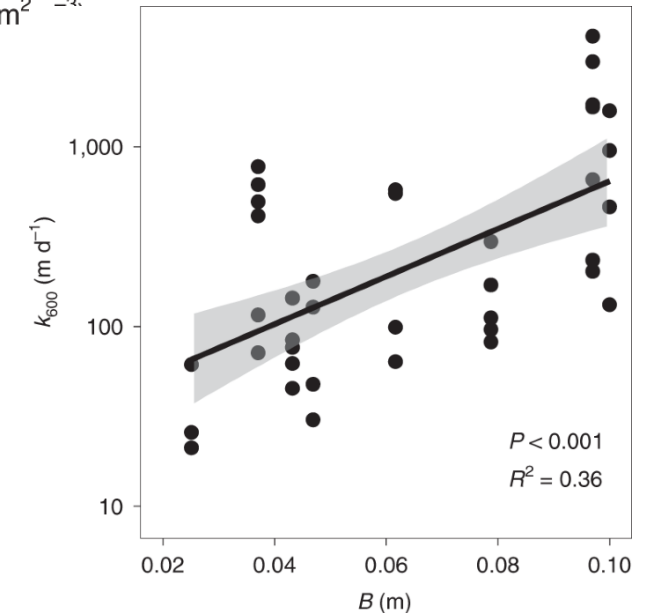
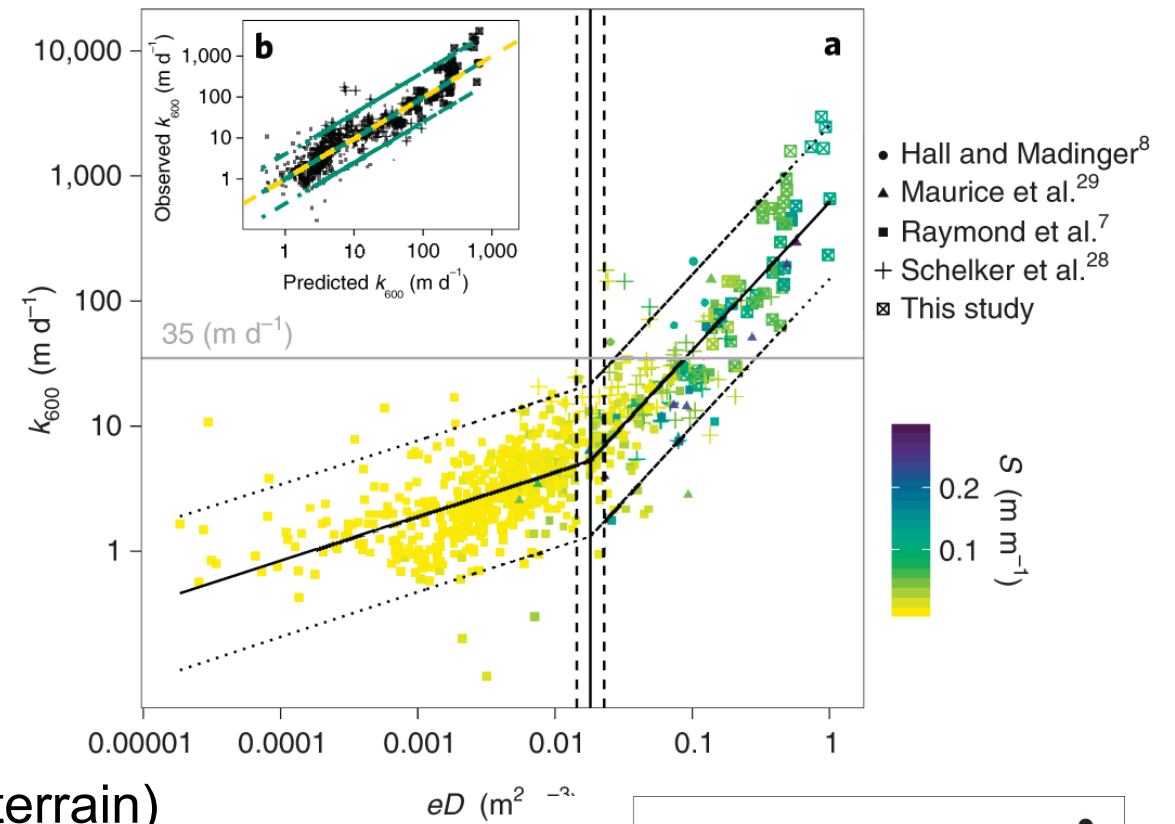
Amber J. Ulseth<sup>1,4\*</sup>, Robert O. Hall Jr.<sup>2</sup>, Marta Boix Canadell<sup>1</sup>, Hilary L. Madinger<sup>3,5</sup>, Amin Niayifar<sup>1</sup> and Tom J. Battin<sup>1</sup>

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 dissipated to water surface (low submergence)



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

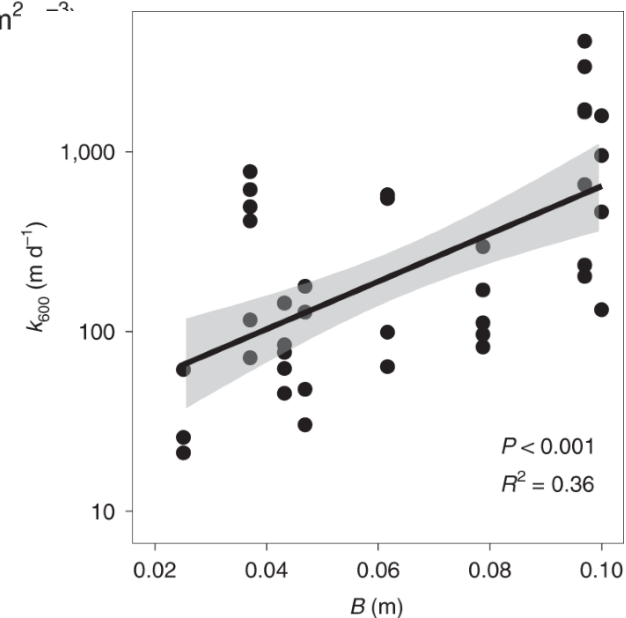
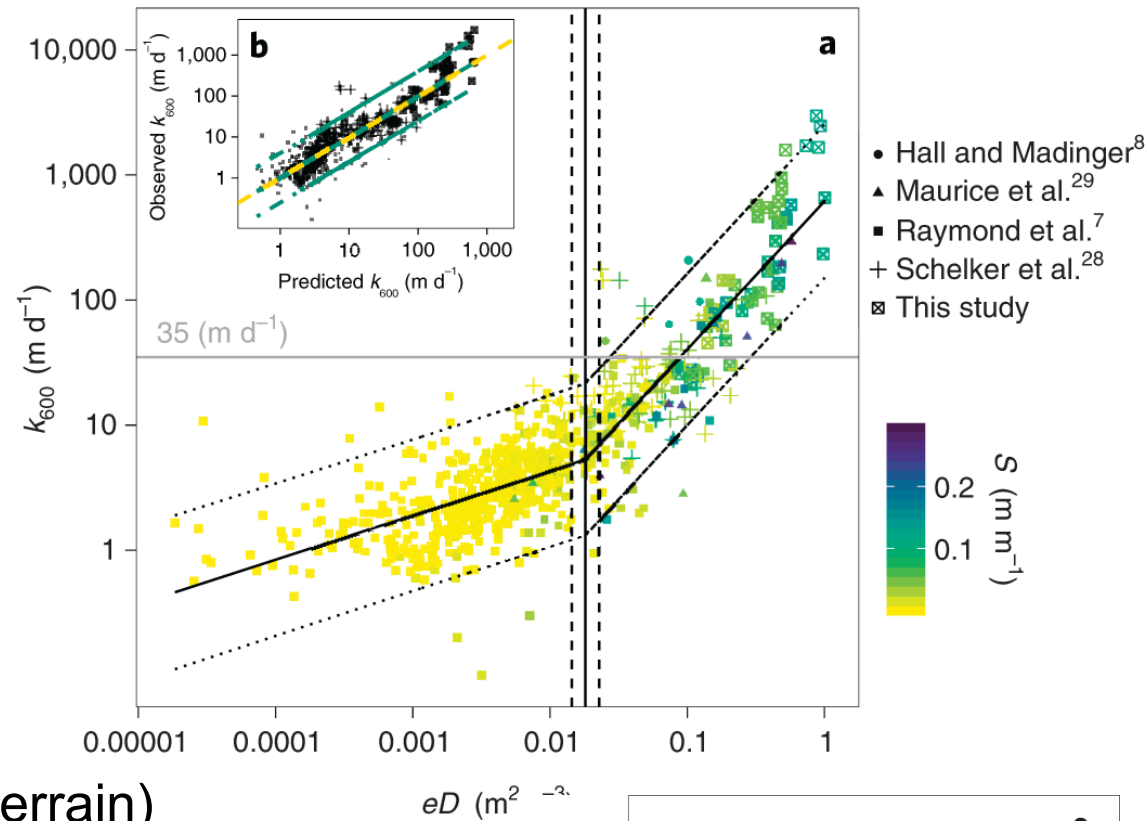
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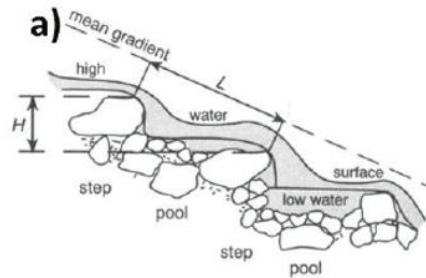
Breakpoint:

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

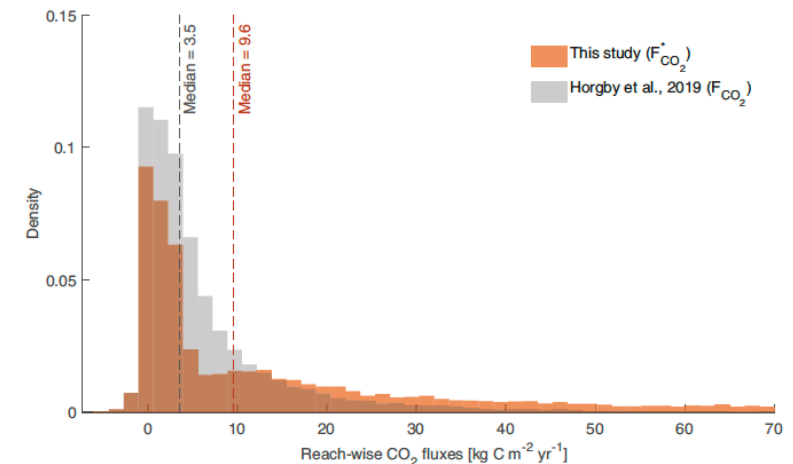
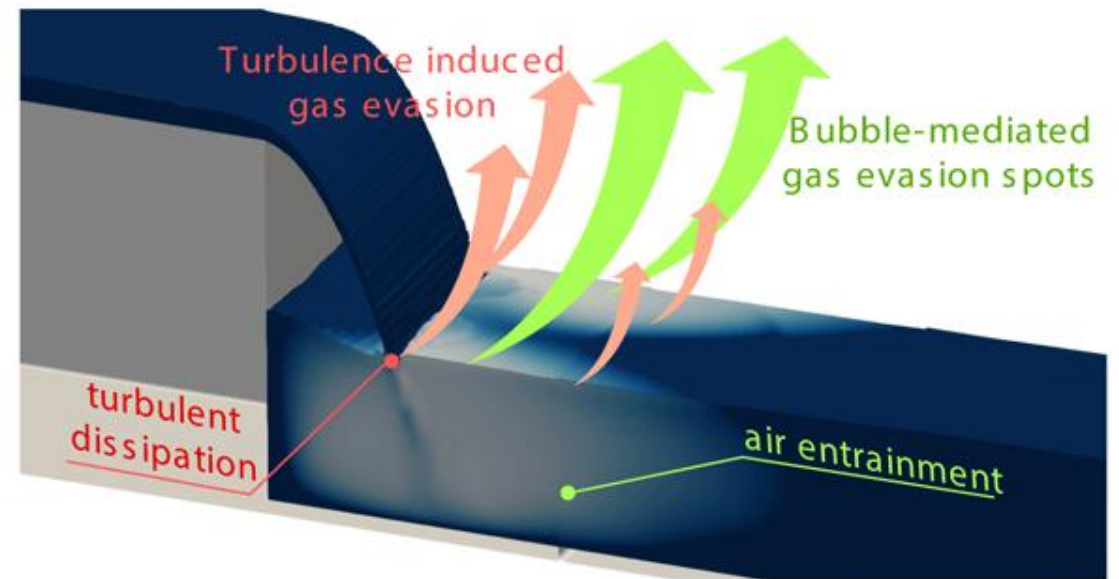


# Steps dominate gas evasion from a mountain headwater stream

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Gianluca Botter<sup>1</sup>✉, Anna Carozzani<sup>1</sup>, Paolo Peruzzo<sup>1</sup> & Nicola Durighetto<sup>1</sup>

- Step-pool geomorphology (as frequent in mountain catchments) increases turbulent dissipation and air entrainment (white water)
- Increases gas exchange velocity
- Potentially increasing CO<sub>2</sub> evasion fluxes



**Fig. 5 | Effect of steps on CO<sub>2</sub> emissions from Swiss mountain streams.** Frequency distribution of reach-wise CO<sub>2</sub> fluxes estimated by Horgby et al.<sup>6</sup>,  $F_{CO_2}$  (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.<sup>6</sup> and this study, respectively. Note that the tail of the frequency distribution including the steps reaches values up to  $F'_{CO_2} \approx 500 \text{ kg C m}^{-2} \text{ yr}^{-1}$ .

# 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