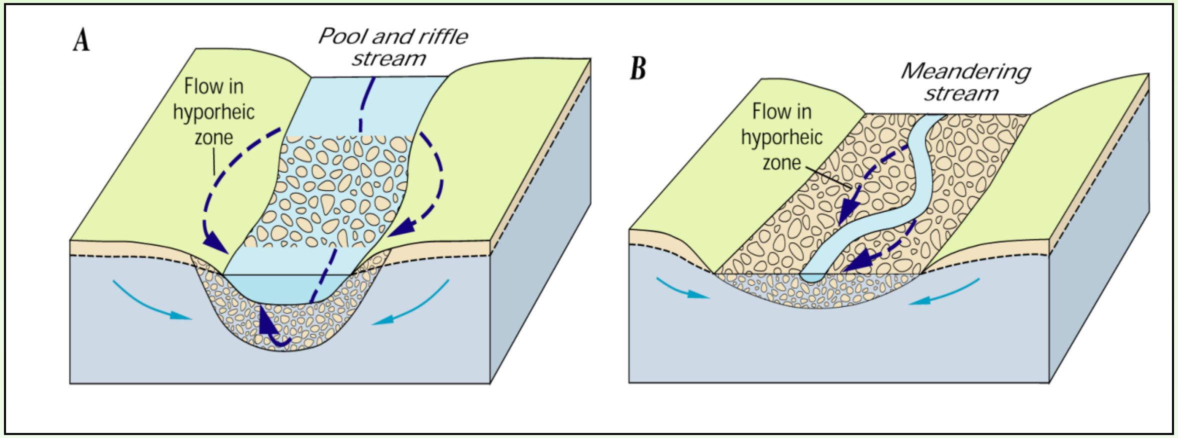
Ground-water surface-water exchange in fluvial settings

Take-home message: Be constantly aware of scale

Hyporheic exchange



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Definition of hyporheic exchange

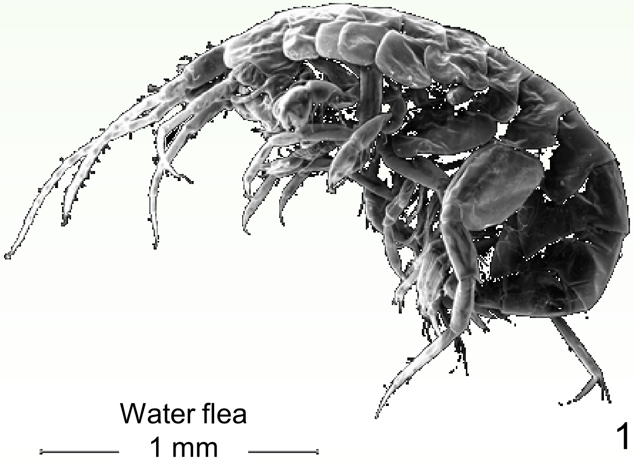
"The region of saturated sediments beneath and beside the active channel and that contains some proportion of surface water that was part of the flow in the surface channel and went back underground and can mix with groundwater" – California Dept. of Water Resources GW glossary

"The subsurface zone where stream water flows through short segments of its adjacent bed and banks is referred to as the hyporheic zone." – USGS Circular 1139

Consider the scale of the process relative to the scale of the measurement.

There are many definitions – these are a couple that we like.

Important ecotone

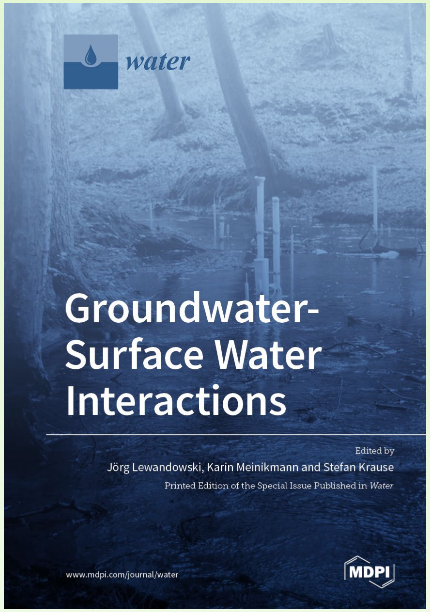


water MDPI

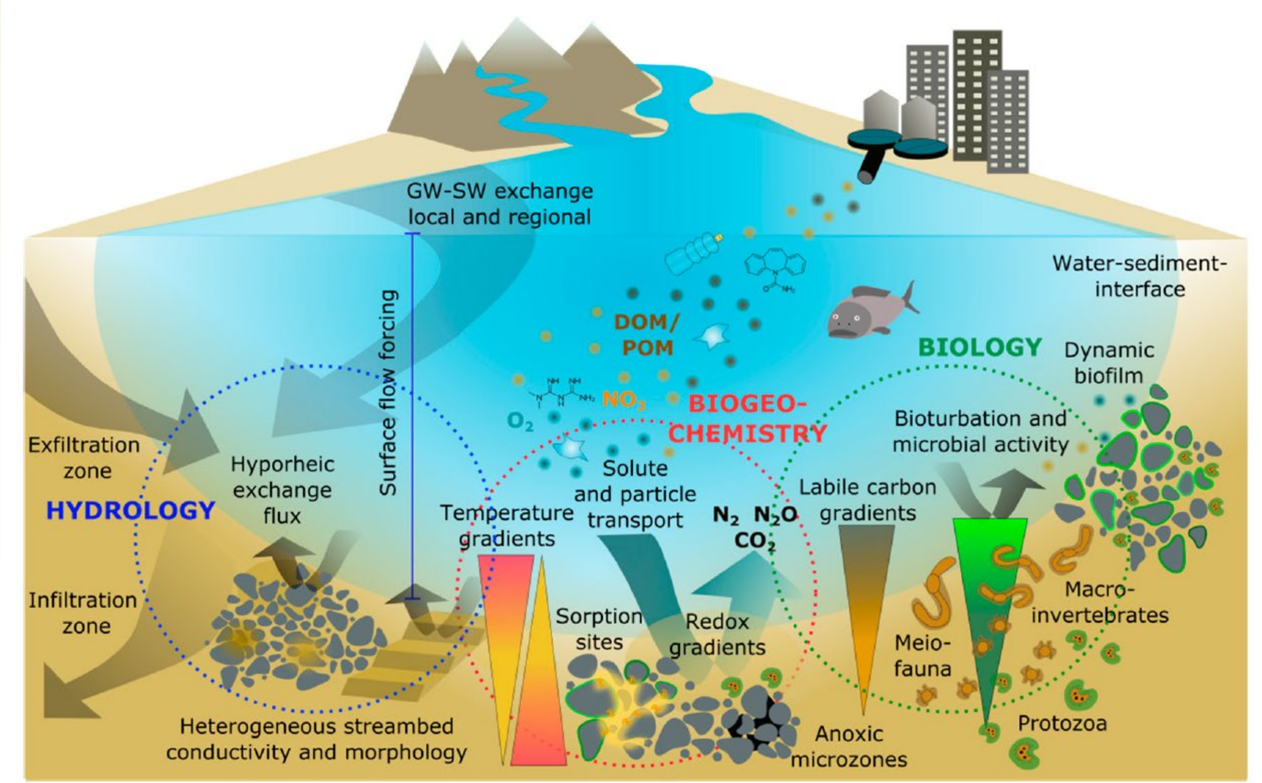
Communication

Is the Hyporheic Zone Relevant beyond the Scientific Community?

Jörg Lewandowski [1,2,*], Shai Arnon [3], Eddie Banks [4], Okke Batelaan [4], Andrea Betterle [5,6], Tabea Broecker [7], Claudia Coll [8], Jennifer D. Drummond [9], Jaime Gaona Garcia [1,10,11], Jason Galloway [1,2], Jesus Gomez-Velez [12], Robert C. Grabowski [13], Skuyler P. Herzog [14], Reinhard Hinkelmann [7], Anja Höhne [1,15], Juliane Hollender [5], Marcus A. Horn [16,17], Anna Jaeger [1,2], Stefan Krause [9], Adrian Löchner Prats [18], Chiara Magliozzi [13,19], Karin Meinikmann [1,20], Brian Babak Mojarrad [21], Birgit Maria Mueller [1,22], Ignacio Peralta-Maraver [23], Andrea L. Popp [5,24], Malte Posselt [8], Anke Putschew [22], Michael Radke [25], Muhammad Raza [26,27], Joakim Riml [21], Anne Robertson [23], Cyrus Rutere [16], Jonas L. Schaper [1,22], Mario Schirmer [5], Hanna Schulz [1,2], Margaret Shanafield [4], Tanu Singh [9], Adam S. Ward [14], Philipp Wolke [1,28], Anders Wörman [21] and Liwen Wu [1,2]



Papers in this special issue of the journal *Water* on GW-SW exchang give a fairly thorough and recent overview of hyporheic exchange and the broad range of processes that are involved and/or affected. This special issue is a nice resource that summarizes recent findings on this topic.

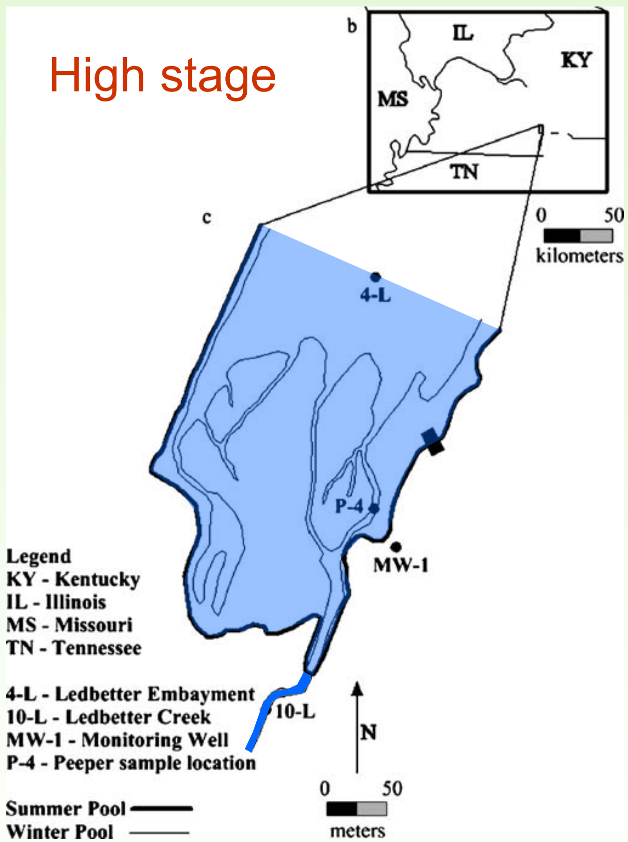


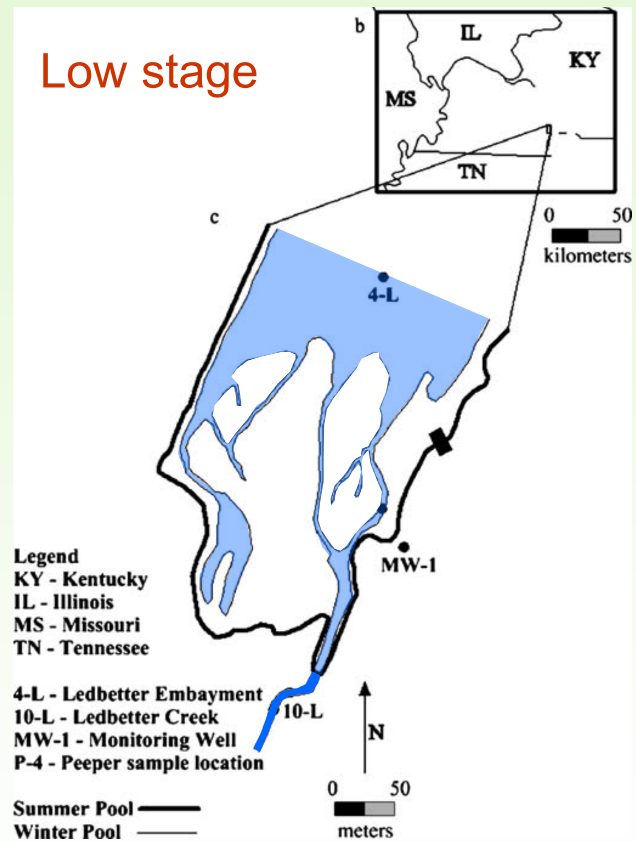
Lewandowski et al., 2020, *Water*

Hypolentic zone?

These types of exchanges also occur in lakes and wetlands, but usually to a lesser extent. In the case of lakes, it was first called hypolentic exchange by Thomas Winter. This subsequent paper used water isotopes to distinguish hypolentic water from hyporheic water, where a river flowed into a reservoir. Hyporheic exchange was created by streambed topography, but hypolentic exchange was created by varying reservoir stage.

Where does hyporheic exchange transition to hypolentic exchange?

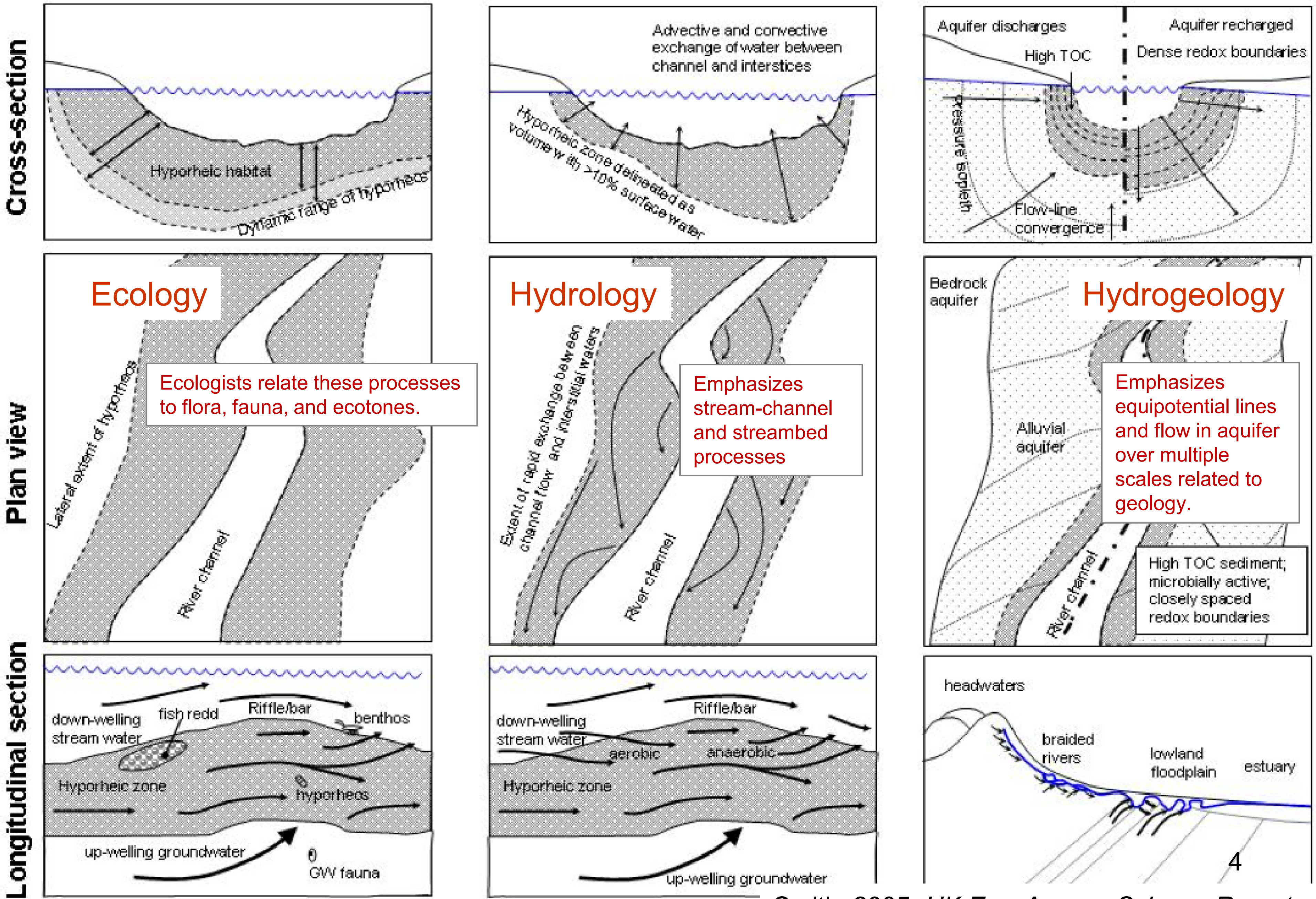




Winter, 2001, *Hydrol. Processes*

Aseltyne et al., 2006, *Hydrogeol. J.*

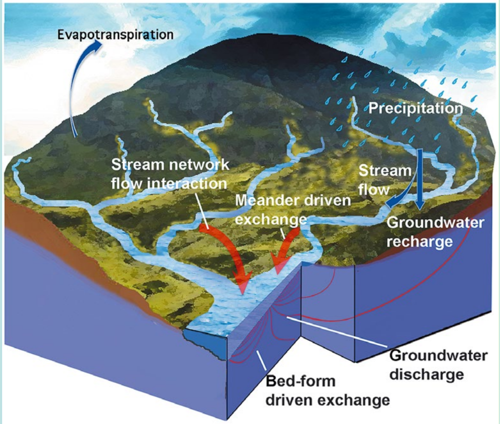
Definition depends on your discipline perspective and the scale of interest



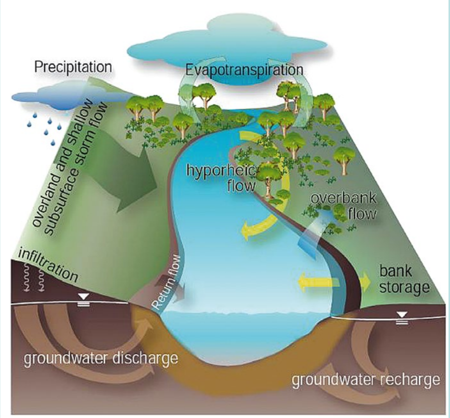
Smith, 2005, *UK Env. Agency Science Report*

Hyporheic exchange occurs at multiple scales

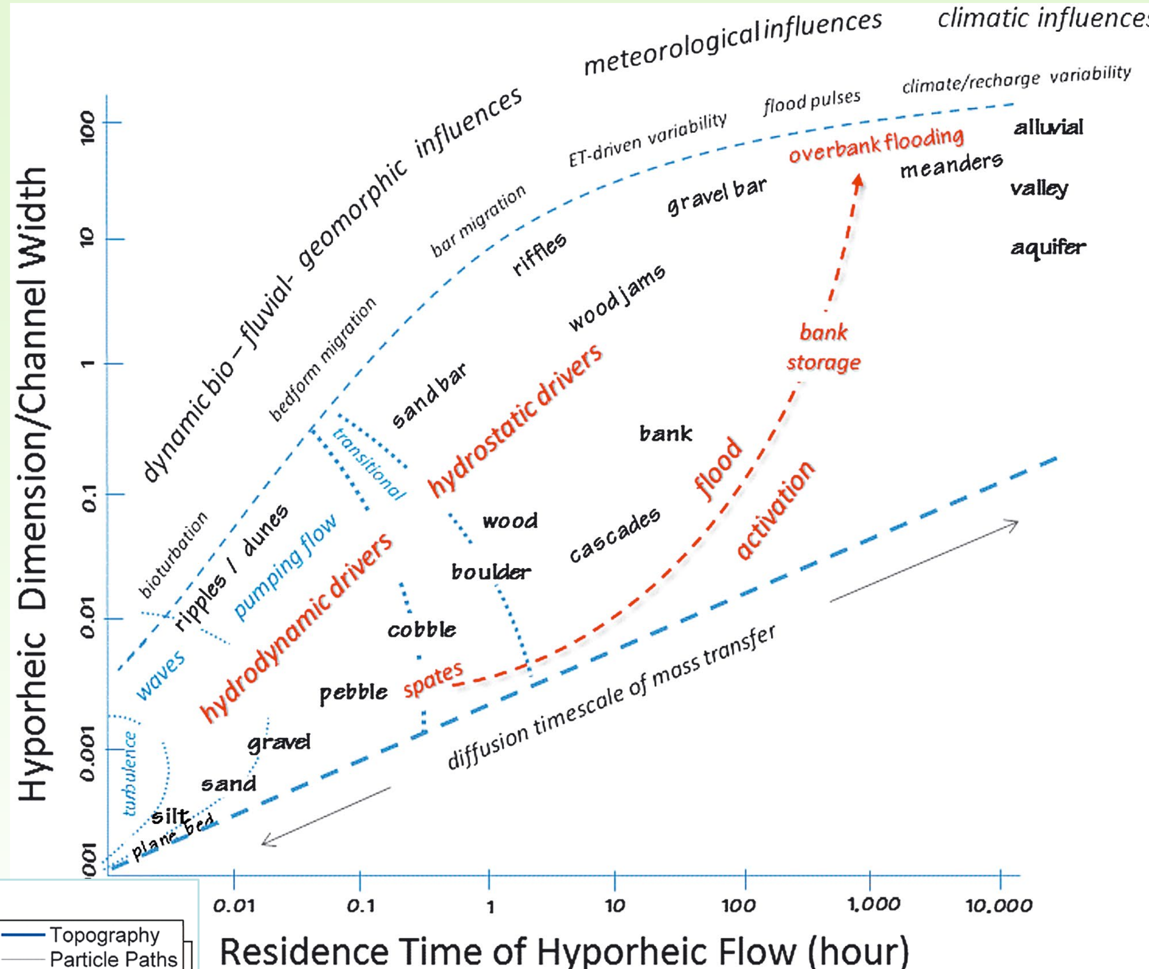
a) Watershed or Basin scale



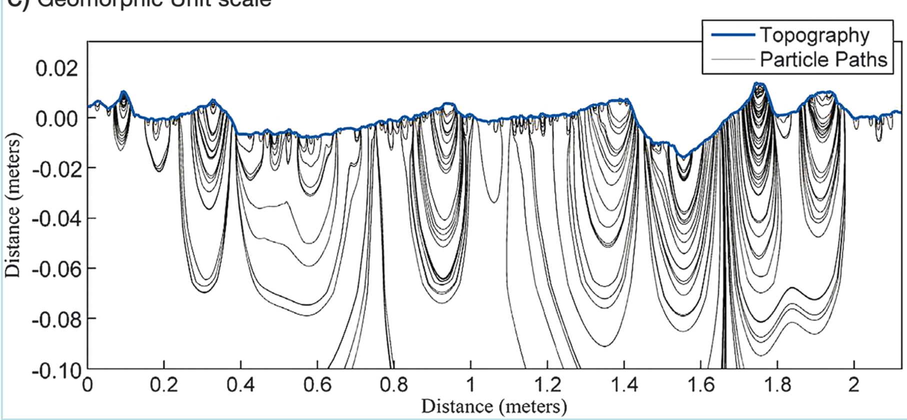
b) River Corridor scale



This scale-time plot provides a nice overview of the scale of many of the processes or events that are relevant to hyporheic exchange.



c) Geomorphic Unit scale



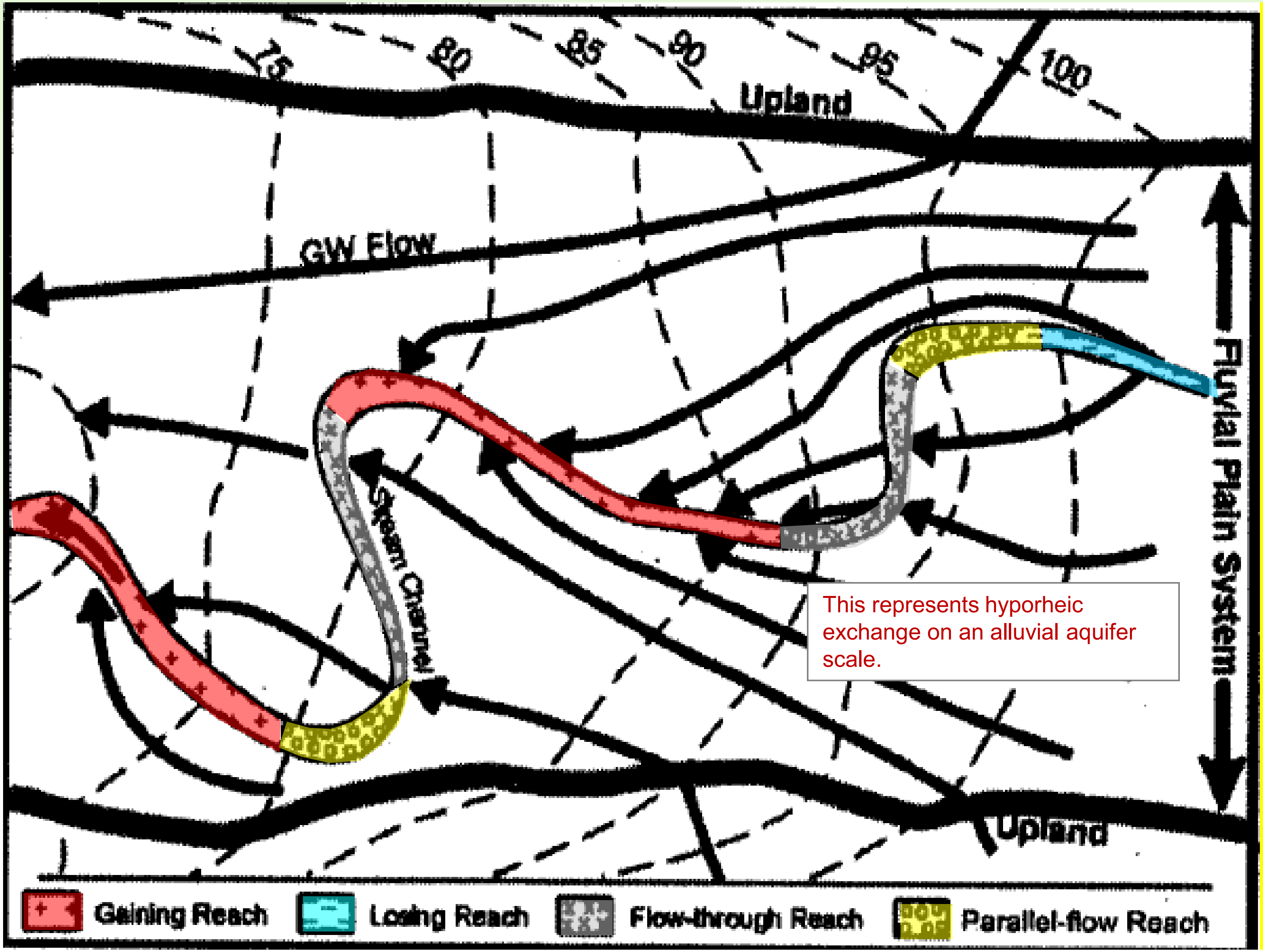
- **Basin scale**
- **Bar scale, meander scale**
- **Pool-riffle scale**
- **Dune, bedform scale**
- **Let's look at a few examples.**

Boano et al., 2014 *Rev. Geophys*.

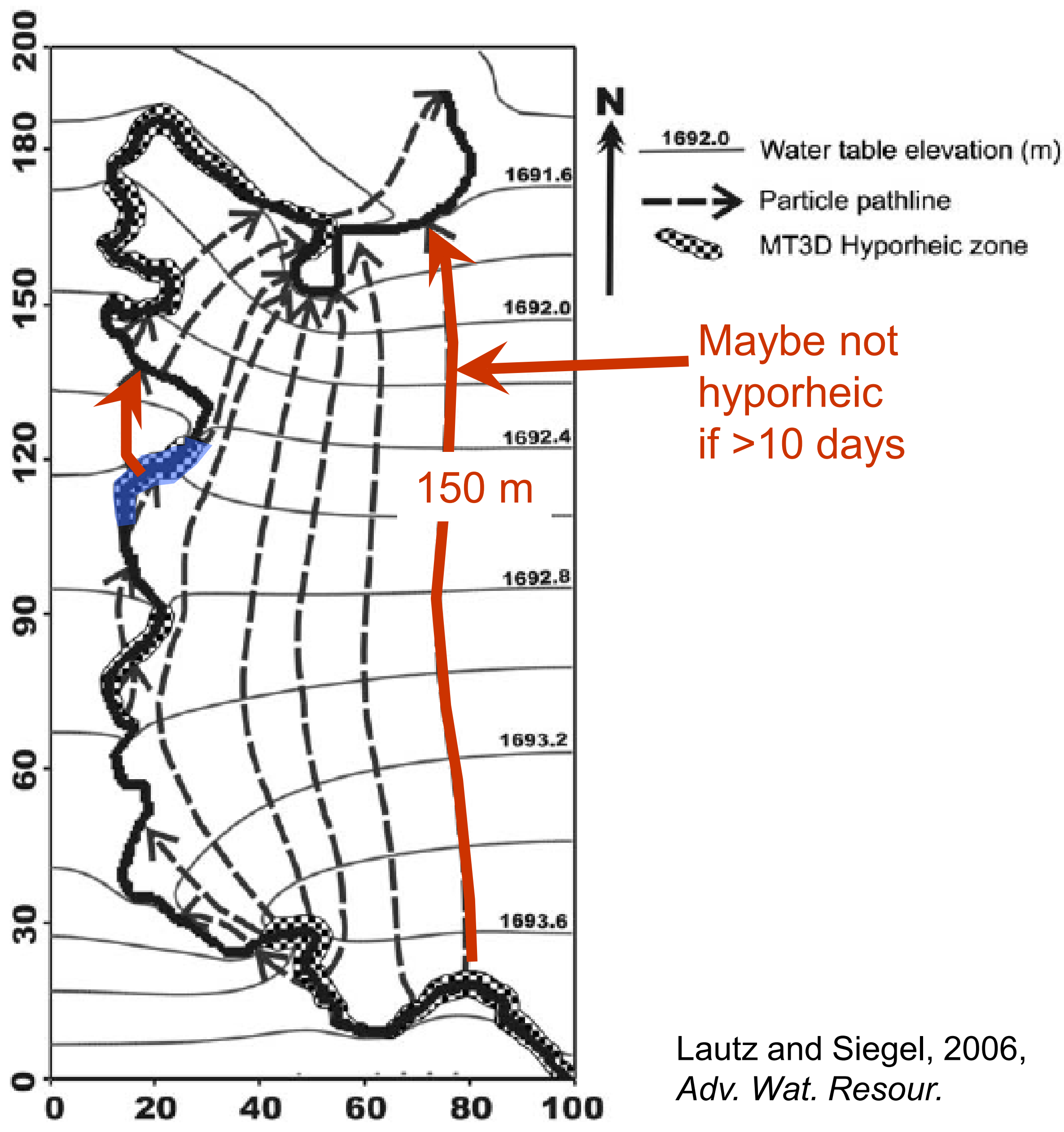
Meander or floodplain scale involves

1. Parallel flow 2. Flow through
3. Gaining reaches 4 Losing reaches

Woessner, 2000, *Ground Water*



This represents hyporheic exchange on an alluvial aquifer scale.



Lautz and Siegel, 2006, *Adv. Wat. Resour.*

Exchange depends on perspective and definition

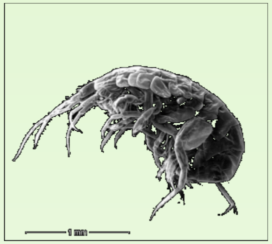
Larger-scale exchange based on MODFLOW calibrated to wells

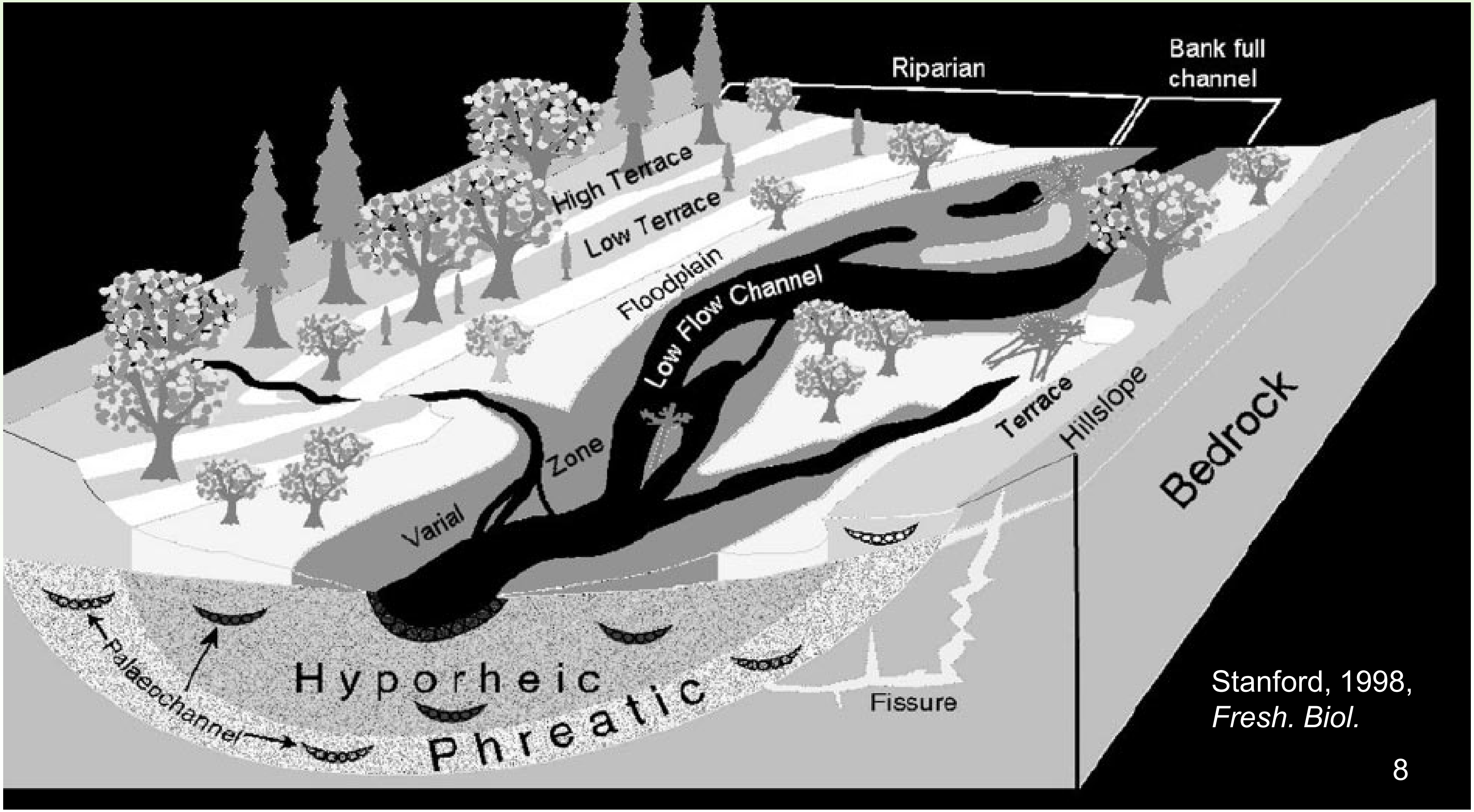
Local-scale exchange based on new definition (10% surface water within a 10-day travel time

We keep developing new definitions that depend on the perspective of the scientist, this one based on hydrology and geochemistry. The authors used MODFLOW to determine hyporheic zone based on travel times.

Hyporheic zone based on hyporheos
Benthic invertebrates can be found several km away from thalweg

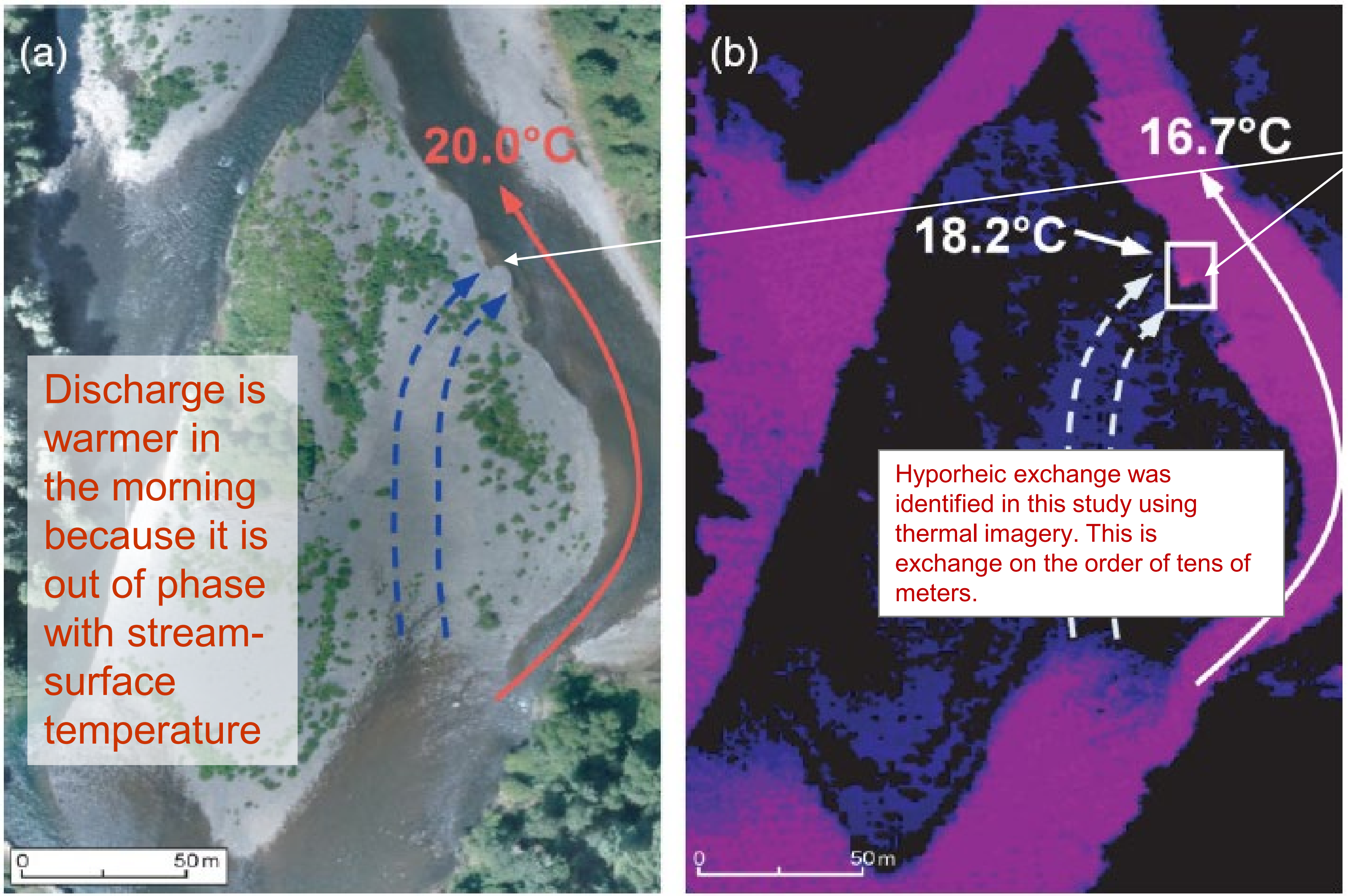
This definition is based on the presence of animals in alluvial sediments that normally are associated with streambed sediments. Sometimes they can be found hundreds of meters away from the active stream channel. Aren't you glad the scale distance in the figure to the right is 1 mm and not 1 m?





Stanford, 1998, *Fresh. Biol.*

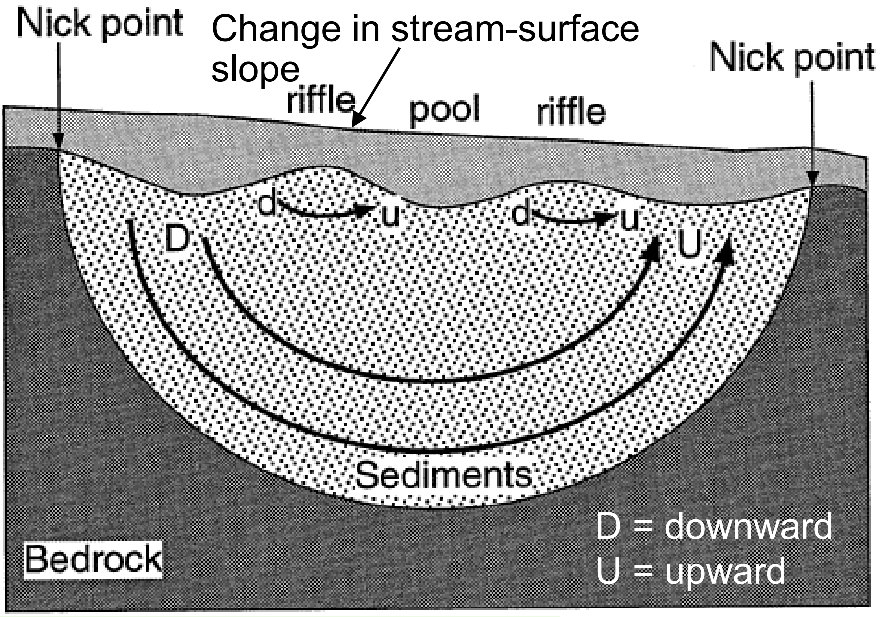
Bar-scale hyporheic exchange



Focused discharge

Burkholder et al., 2008, *Hydrol. Process.*

Pool-riffle scale

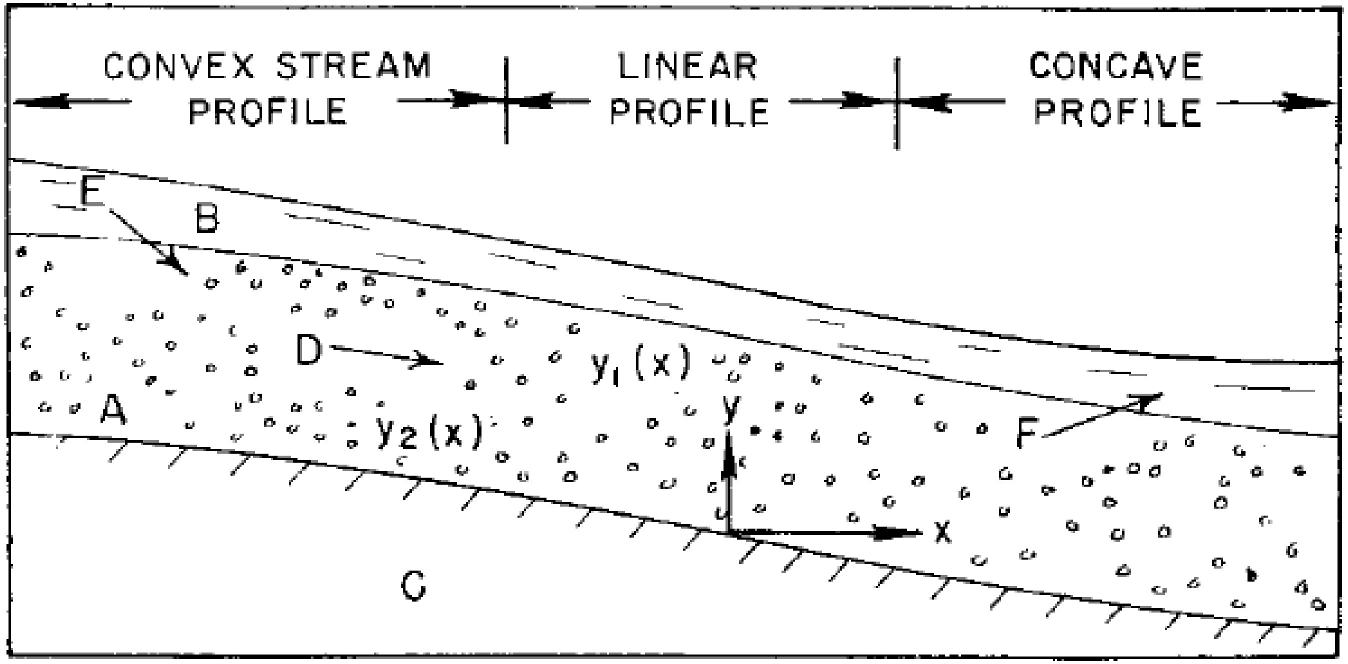


- Downward seepage at downstream ends of pools
- Upward seepage at upstream ends of pools
- A mix of downward, upward, and bed-parallel seepage in riffles

Brunke and Gonser, 1997, *Fresh. Biol.*

The concept of the downstream streambed profile affecting hyporheic exchange has been around for a long time

They didn't call it hyporheic exchange when this was published in 1968.



Vaux, 1968, *Fishery Bulletin*

This is an early publication that illustrates the hyporheic zone.

Nick point: an abrupt change in slope

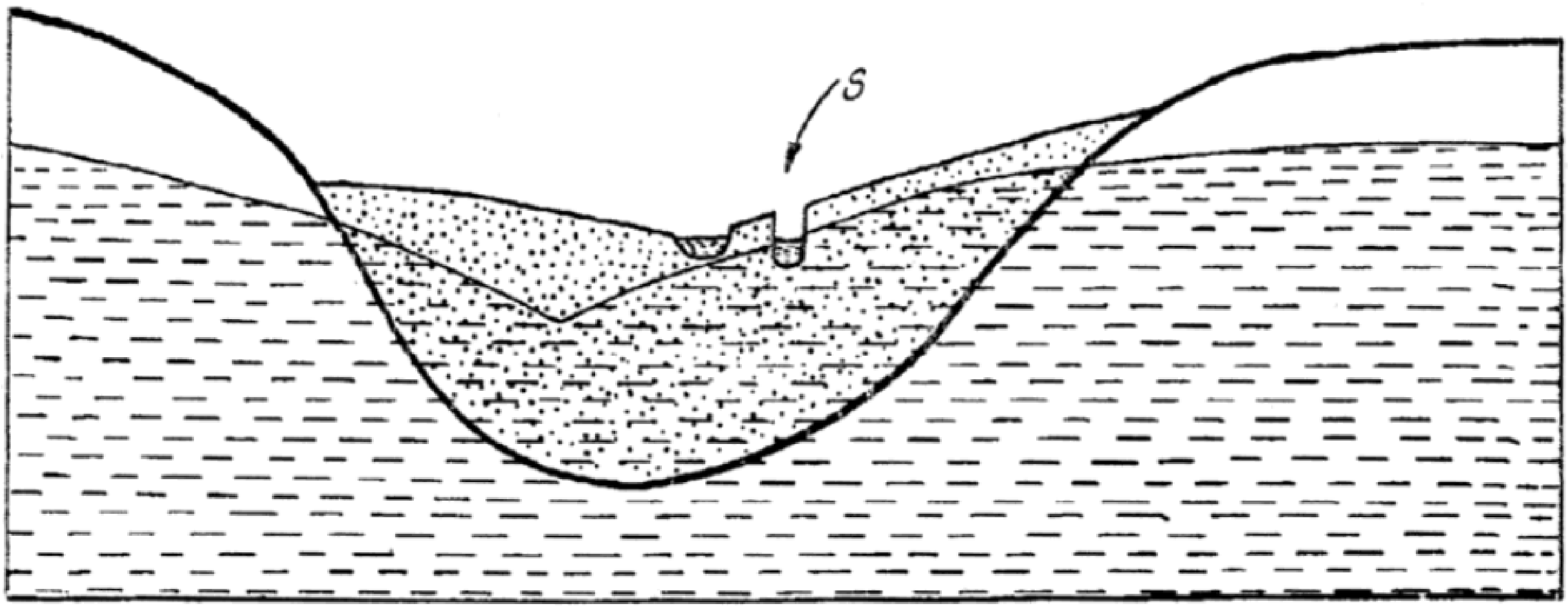
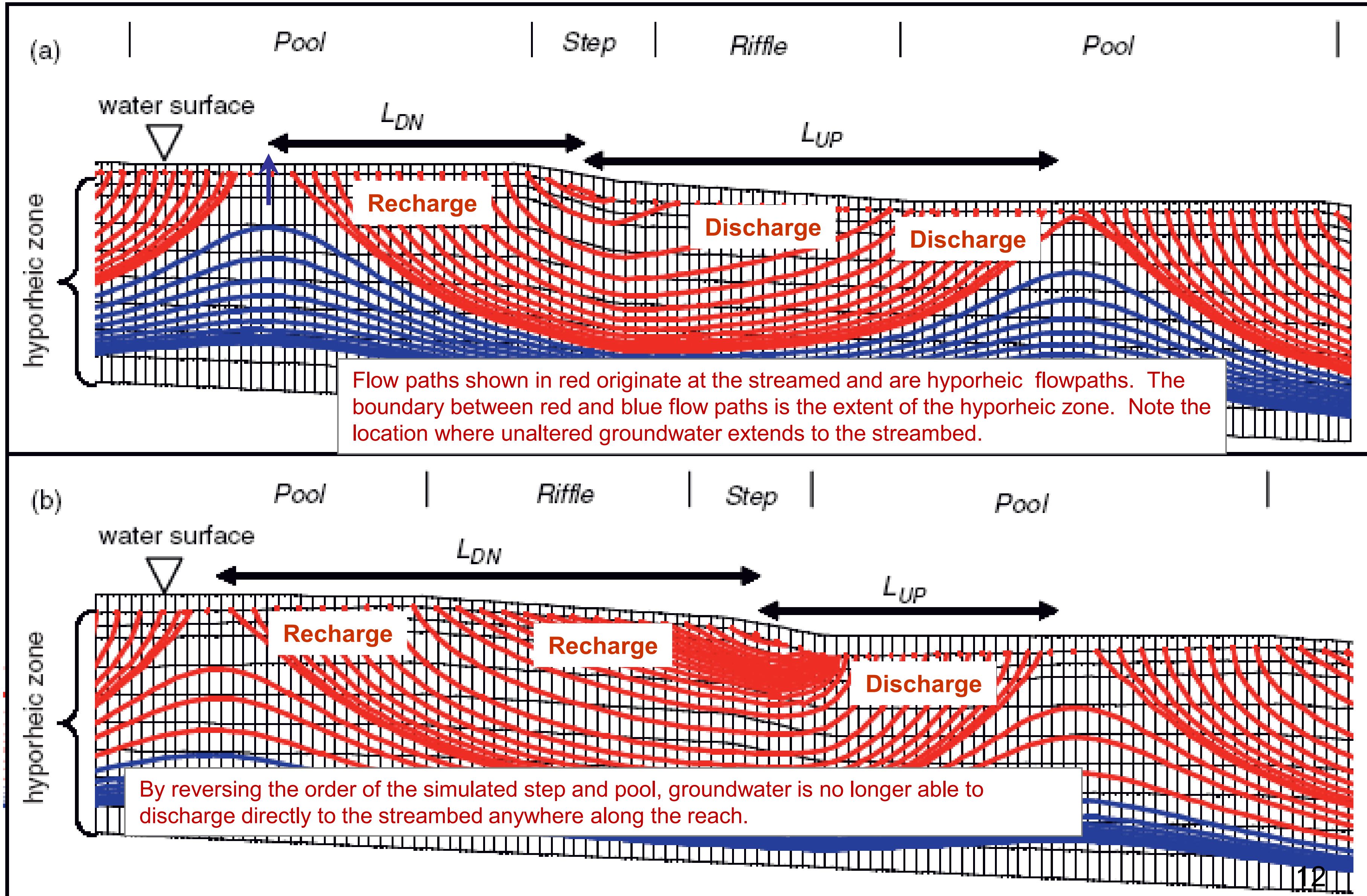


Figure 1. Permeable valley floor; hyporheic water comes both from the stream and the phreatic groundwater (modified after Imbeaux). S, excavation site.

But the earliest mention of the hyporheic zone was by Orghidan in 1959, translated from German to English by Daniel Kaser, 2010.

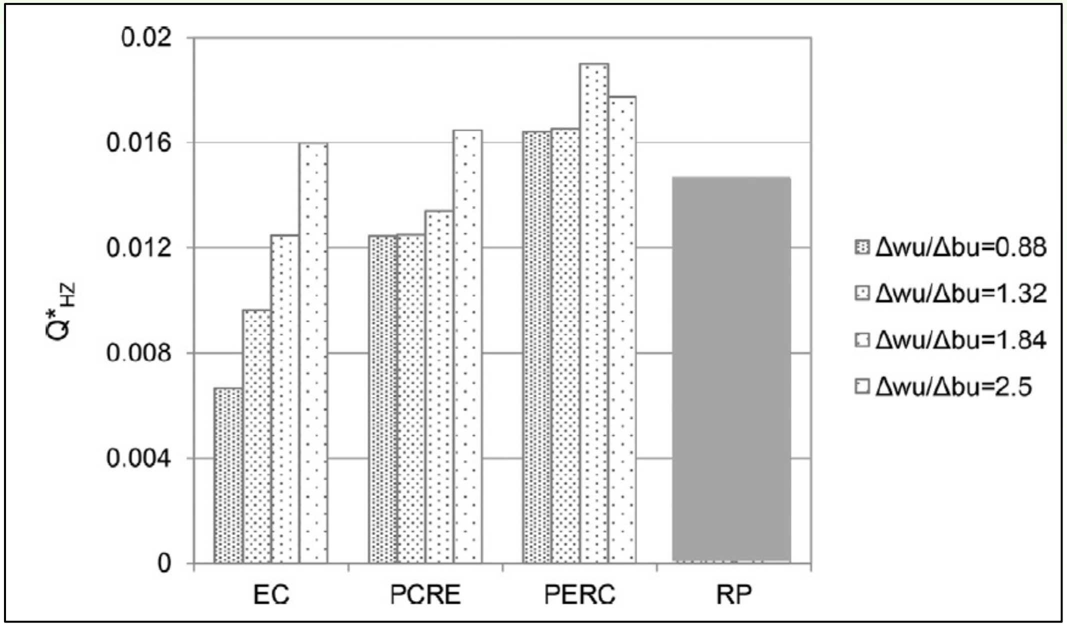
Direction of exchange depends on the degree and sequence of changes in bed slope



Gooseff et al., 2006, *Hydrological Processes*

Changes in stream width can also induce hyporheic exchange

Variations in stream width can also induce hyporheic exchange, although the influence is generally less than changes in bed slope. The greatest hyporheic exchange occurs when the pool is wide and the riffle is narrow (PERC).

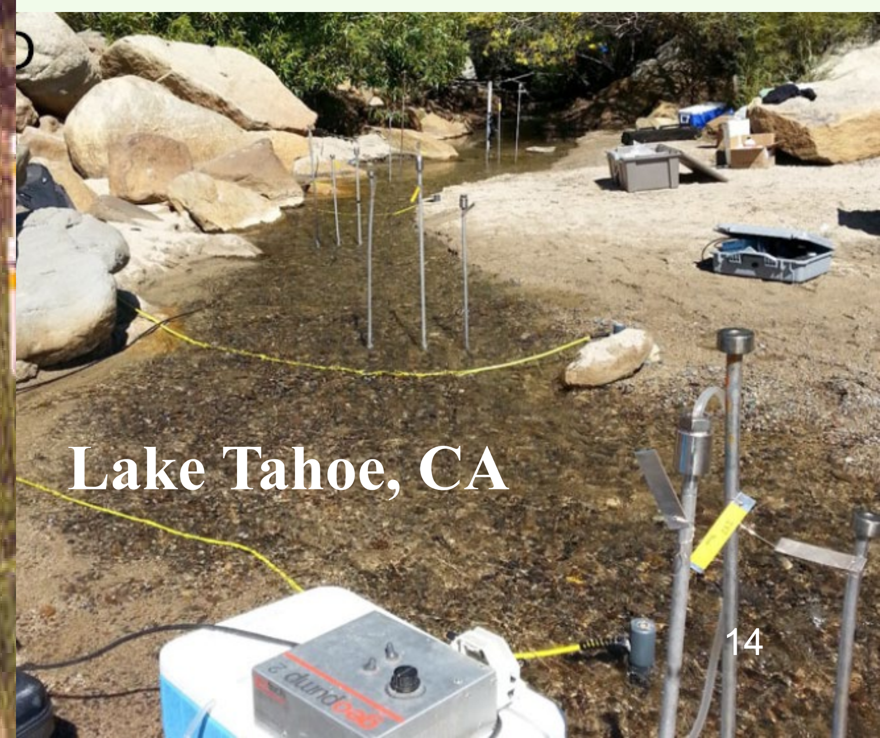


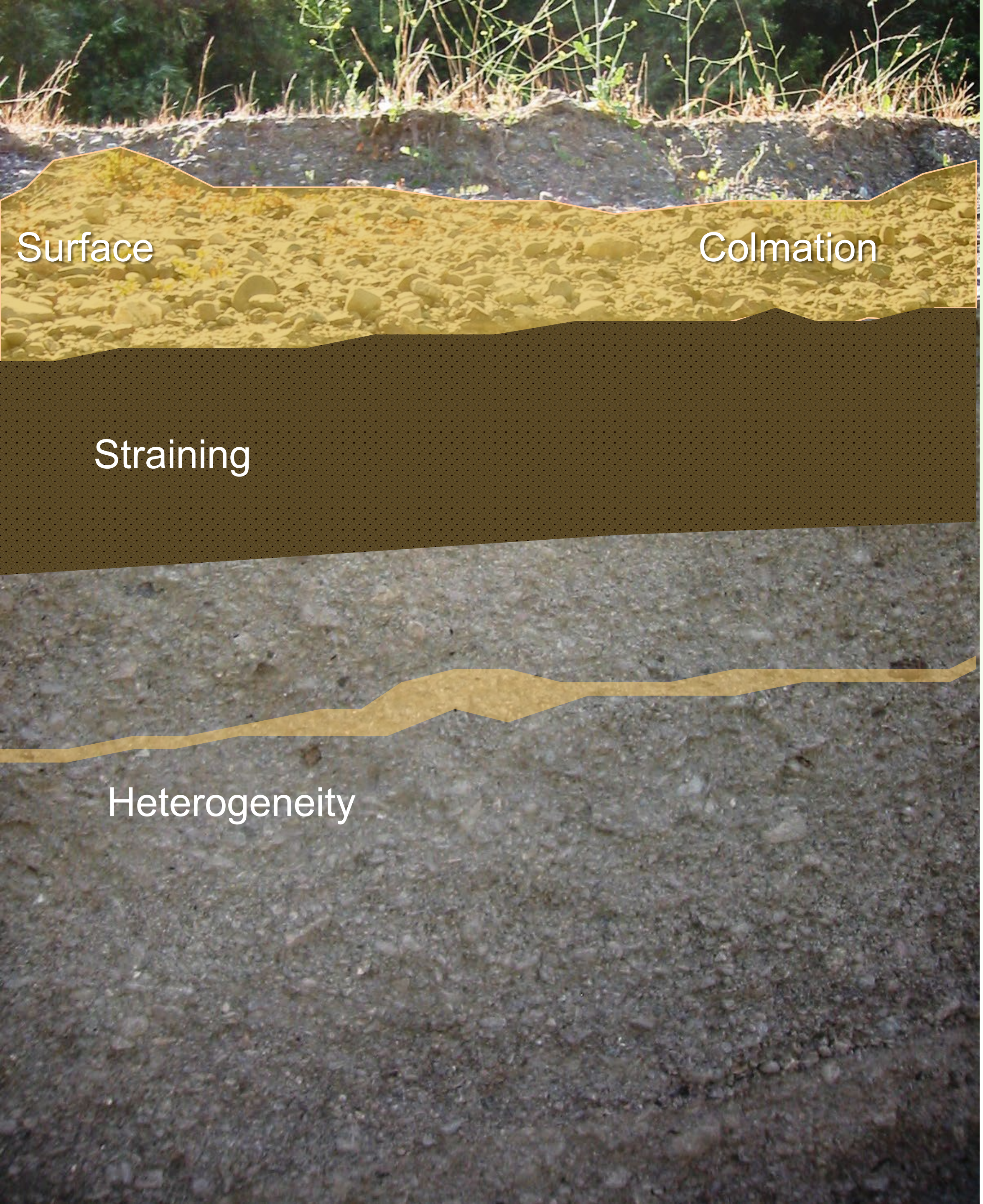
wu = width undulation
bu = bed slope undulation
EC = expansion-constriction
PCRE = pool constricted, riffle expanded
PERC = pool expanded, riffle constructed
RP = riffle-pool

Movahedi et al., 2021, *Advances in Water Resources*

Quantification of hyporheic exchange and determination of flowpaths can require intensive instrumentation in and adjacent to the stream

There now are many studies on a scale of cm to m in the literature.





Depth of hyporheic exchange is dependent on changes in *K* with depth

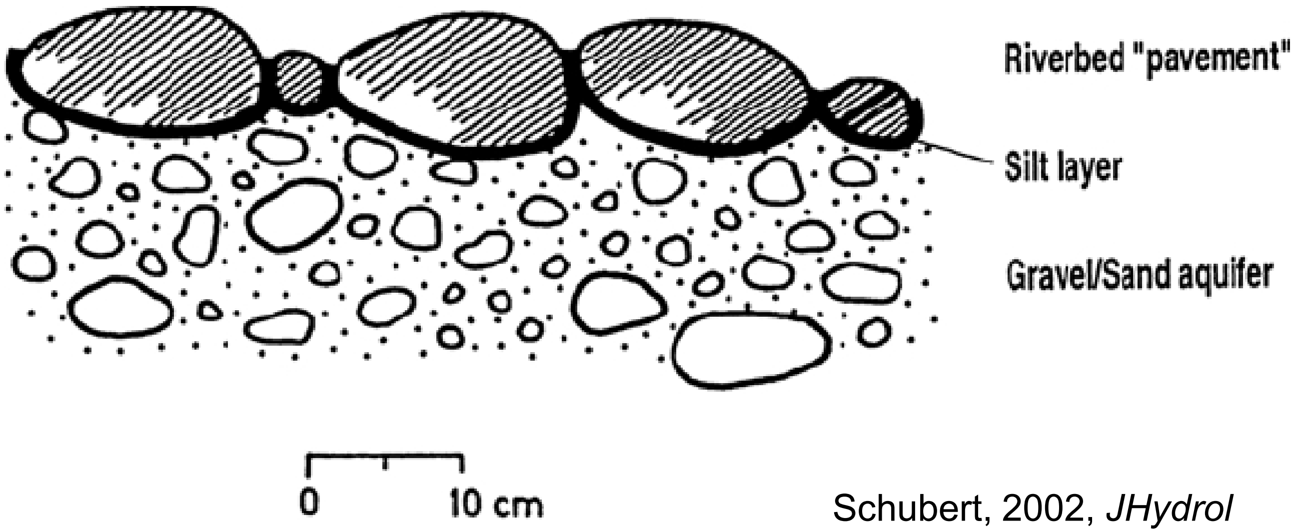
The vertical extent of hyporheic exchange also depends on the vertical distribution of *K* in the bed sediments. If low-K sediments are present at or near the surface, the volume and vertical extent of hyporheic exchange will be reduced. If low-*K* sediments are present deeper in the streambed sediments, hyporheic exchange may not be affected. In many fluvial systems, the presence, absence, and distribution of low-K sediments can change over short time scales.

Colmation is the clogging of sediments with fine-grained particles. Colmation can be focused at the surface (surface colmation) or vertically distributed in the bed (straining). Remember that D-10 grain-size is often the most important for controlling *K*.

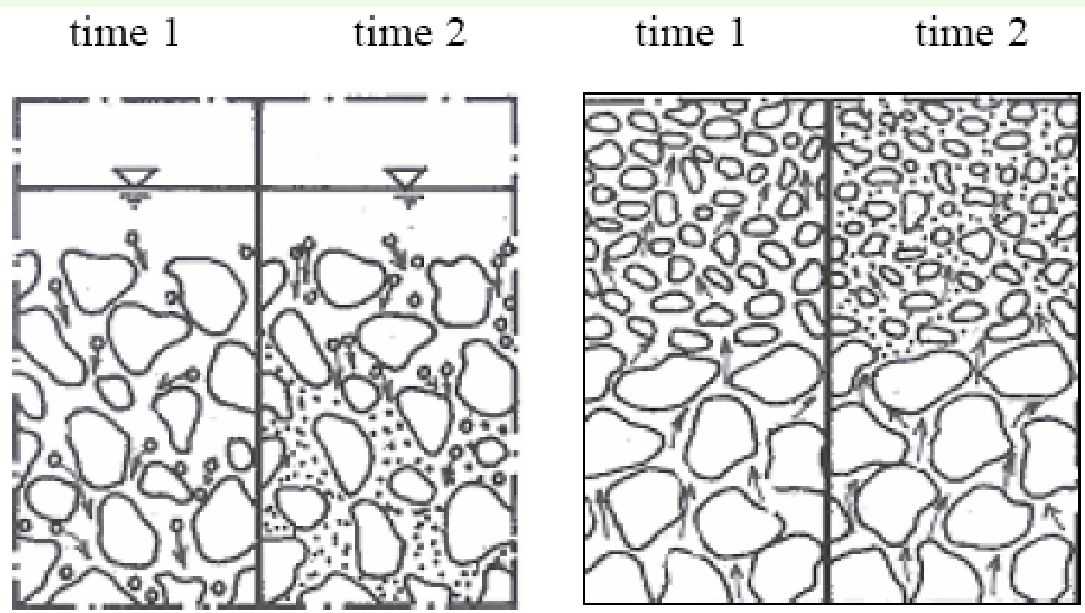
Examples of surface colmation

Here is an example of surface colmation. A layer of clayey silt deposited on a sand bed has dried after declining stream stage exposed the bed. Clay in the colmation layer has shrunk, causing the silt-clay mix to curl and expose the sand beneath. Here the colmation layer is perhaps 1 to 3 mm thick.

In this photo, a depression created by walking on the exposed but still wet streambed extends through the colmation layer to the sand and gravel beneath. Here the colmation layer appears to be about 1 cm thick.



Schubert, 2002, *JHydrol*



(B) **Internal** colmation

(C) contact colmation

Straining

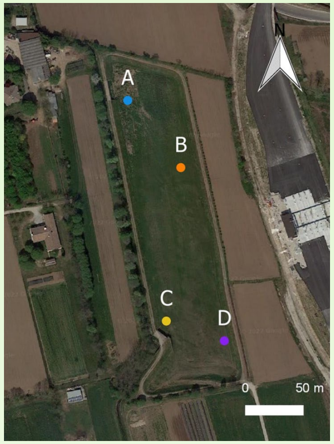
Surface colmation

Velickovic, 2005, *Arch&Civil Eng.*

- Colmation can greatly limit hyporheic exchange until the streambed is re-mobilized
- Where surface armor is large and extensive and old, only a big flood can remobilize the bed

- Type of colmation depends on the ratio of the size of the clogging particles to the particles on the bed

- Biological processes can enhance colmation and make bed more cohesive (e.g., algal mat)
- Or they can reduce colmation and allow greater exchange



Infiltration basin in **Italy**

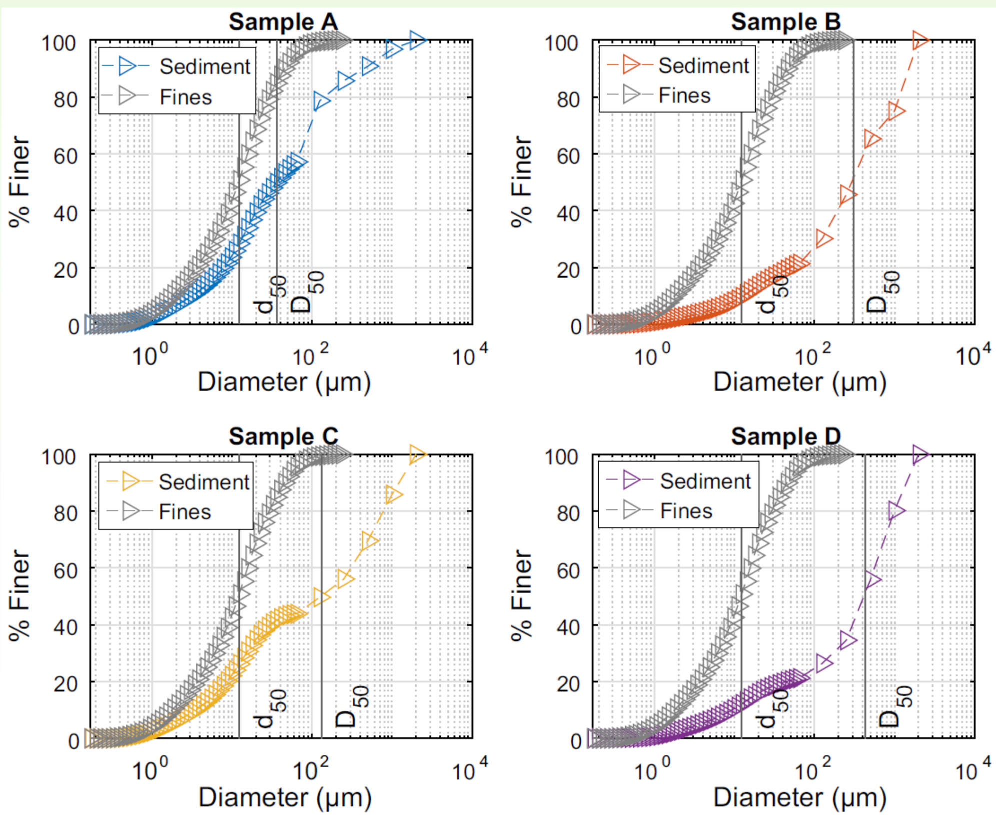
Modeled clogging depth and extent based on d_{50}/D_{50}

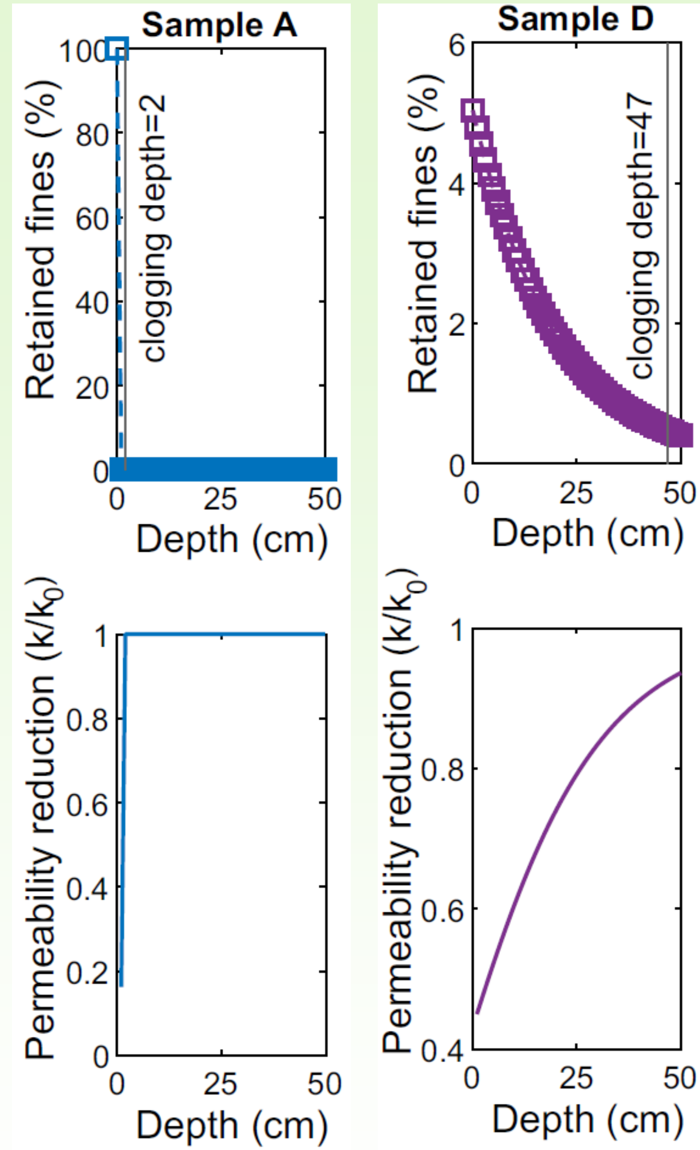
Infiltrating fines is clayey silt (d_{50} = 12 μm)

Sample A is medium silt (D_{50} = 37 μm)

Sample D is medium sand (D_{50} = 0.4 mm)

Where fines infiltrate a silt bed, all the clogging is in the top 2 cm. Where fines infiltrate a sand bed, the fines are distributed across the top 50 cm of the bed. By 0.5 m depth, *K* is reduced by 92 percent.





Lippera et al., 2023, *HJ*

Why does colmation matter?

One reason is many drinking-water supplies induce flow from surface water to municipal wells (river-bank filtration or RBF). Colmation reduces the process.

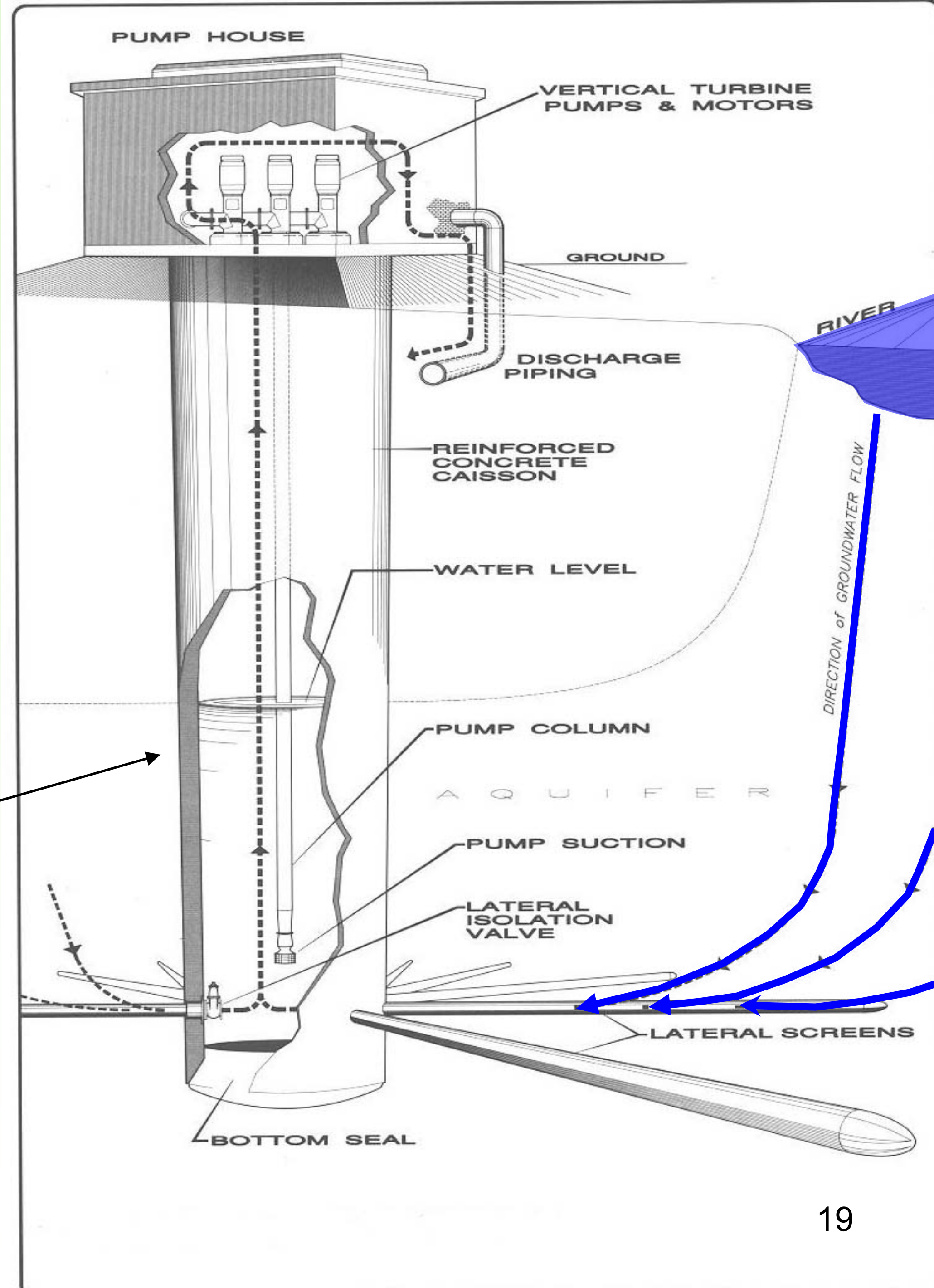
River bank filtration (RBF)

RBF supplies 16% of potable water for Germany

7% of potable water for The Netherlands

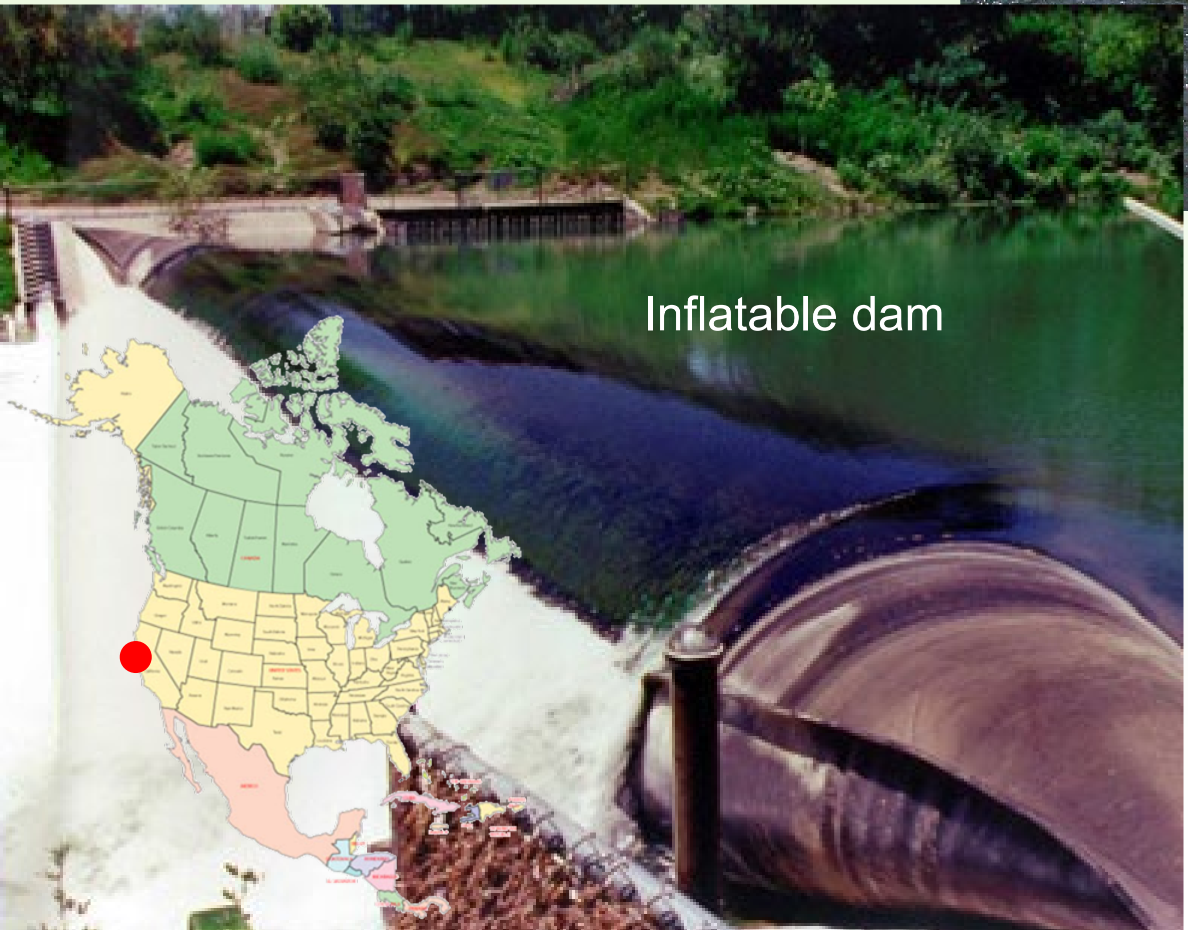
Ranney collector well

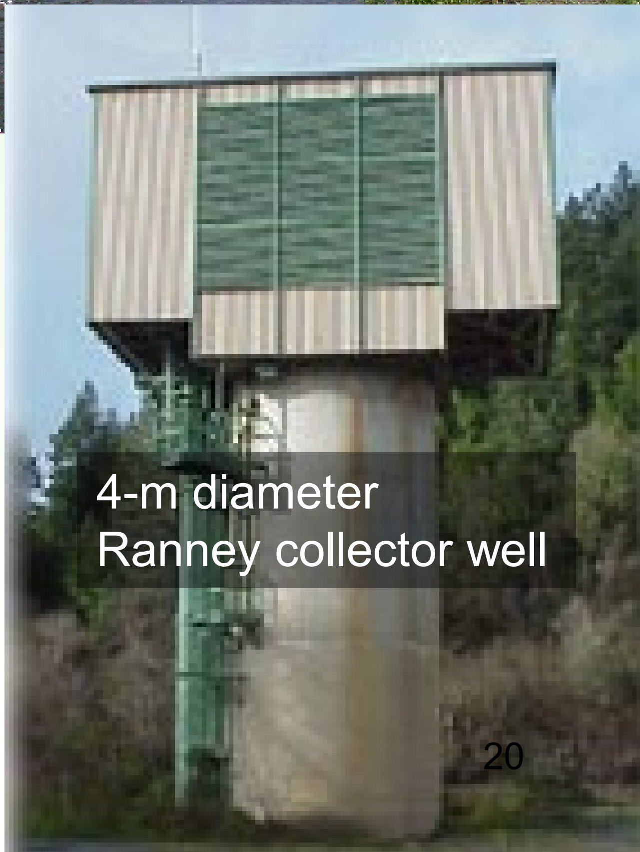
- Large diameter, high volume well
- Laterals extend beneath the river to induce flow from the river to the well
- Water-treatment requirements are often less restrictive because we assume bacteria and viruses in surface water are filtered by the sediments before they reach the well.



Sonoma County Water Agency, Russian River, CA

- Produce 300,000 m^3/day
- Inflatable dam raises river stage 3 m
- Still can't get enough water because the riverbed is becoming clogged





Induced infiltration depends on algae accumulation, basin stage, and accumulation of fine-grained sediments

(Here we are using seepage meters to determine areal distribution of seepage)

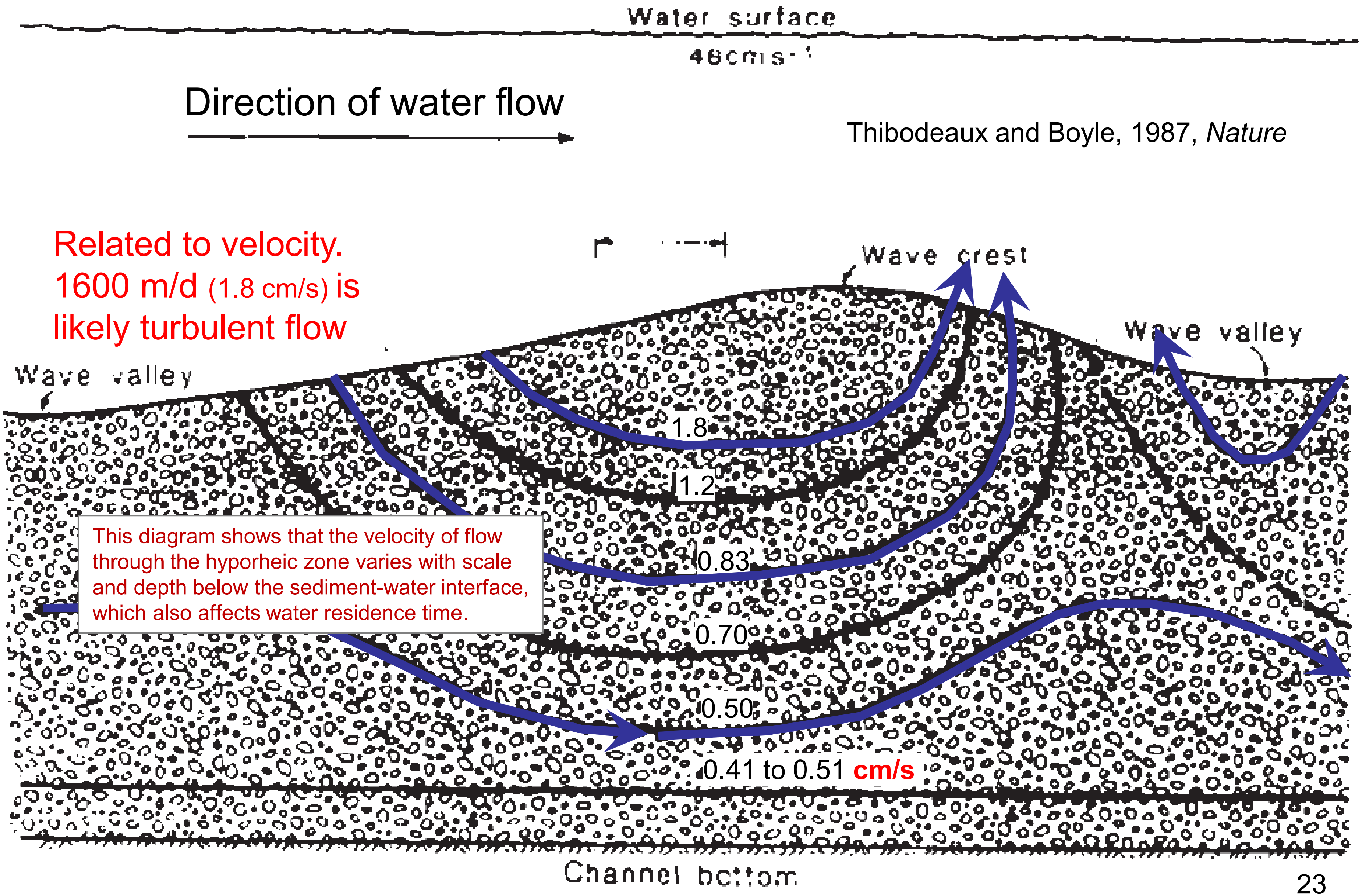
Dealing with colmation

This infiltration basin was drained because infiltration rates had decreased. The scraper in the photograph is removing the fine-grained sediments that had accumulated at the basin surface. Following removal, the basin will be filled again with river water and infiltration to ground water and the nearby pumping well will be much faster until the bed once again becomes clogged..

Bedform scale – Bedforms drive convective exchange in bed sediments

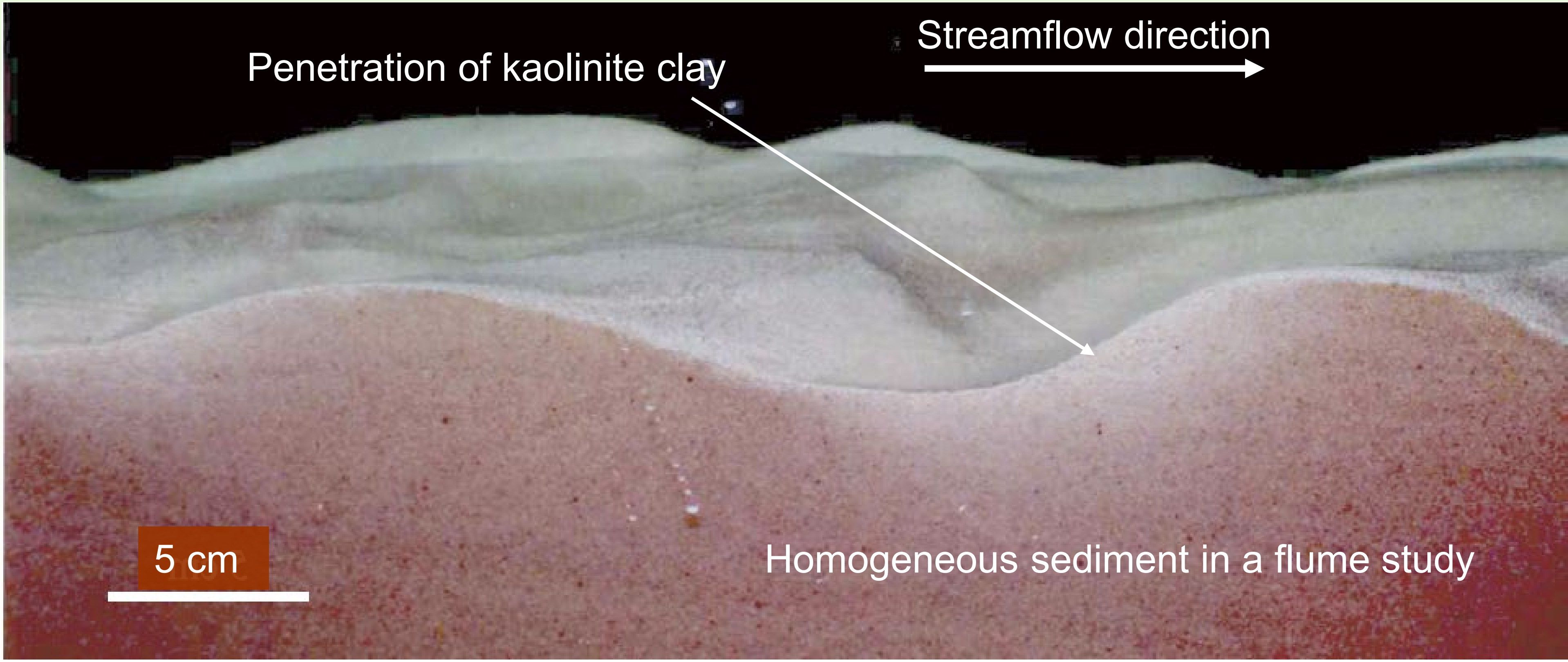
Thibodeaux and Boyle, 1987, *Nature*

Related to velocity.
1600 m/d (1.8 cm/s) is
likely turbulent flow



This diagram shows that the velocity of flow through the hyporheic zone varies with scale and depth below the sediment-water interface, which also affects water residence time.

Sediment and chemicals are transported along hyporheic flowpaths along with the water

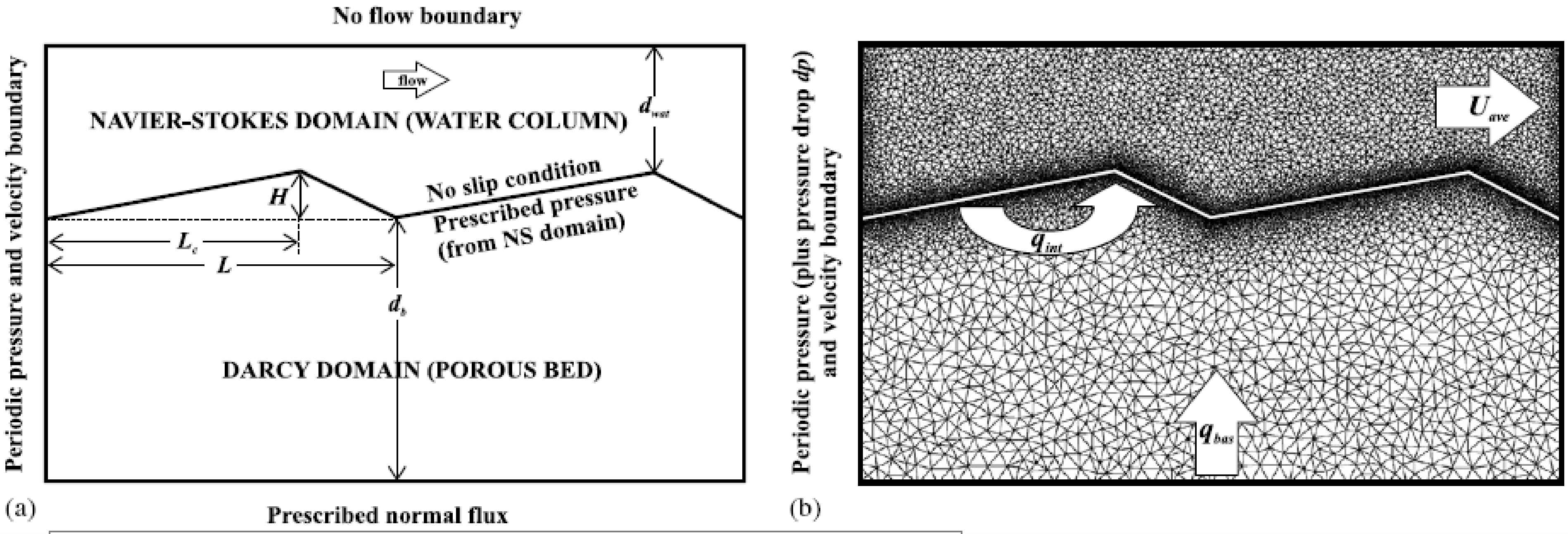


Note that flow here is from left to right. White clay particles penetrate 5 cm or more into medium-grain sand, shown here as pink. This indicates that sediment, and any chemicals sorbed to sediment particles, can move through hyporheic sediments along with the water.

Packman and Mackay, 2003, *WRR*

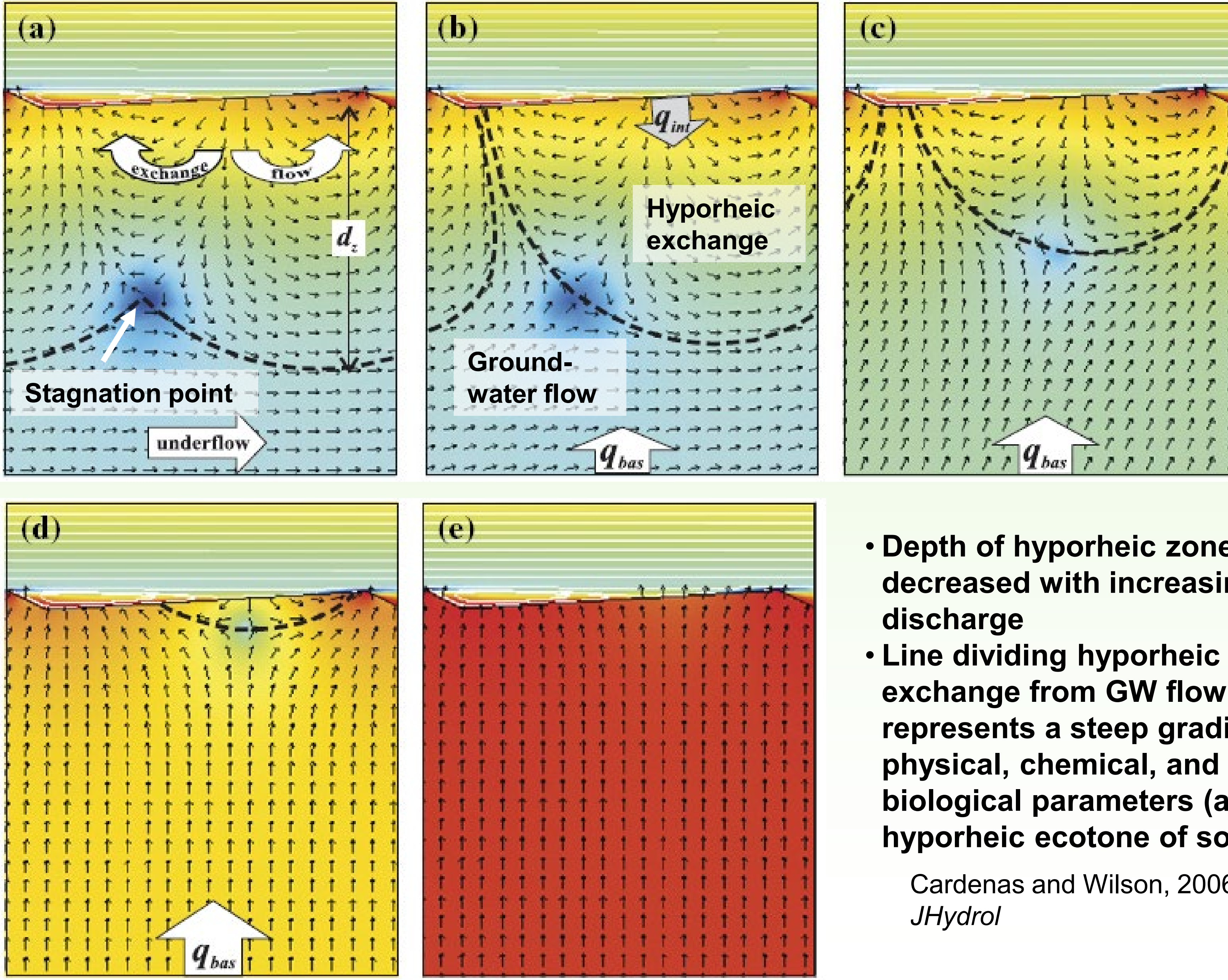
Modeling of hyporheic exchange with changing GW discharge

- Modeled laminar flow in porous medium and turbulent flow in stream
- Looked at the influence of bedform on inducing hyporheic exchange
- Held surface-water velocity constant



Bayani Cardenas has contributed much to the hyporheic literature. In this paper, he and his thesis advisor, John Wilson, coupled a surface-water hydrodynamics model with a groundwater-flow model to study the effect of groundwater discharge on the boundary between hyporheic water and unaltered groundwater.

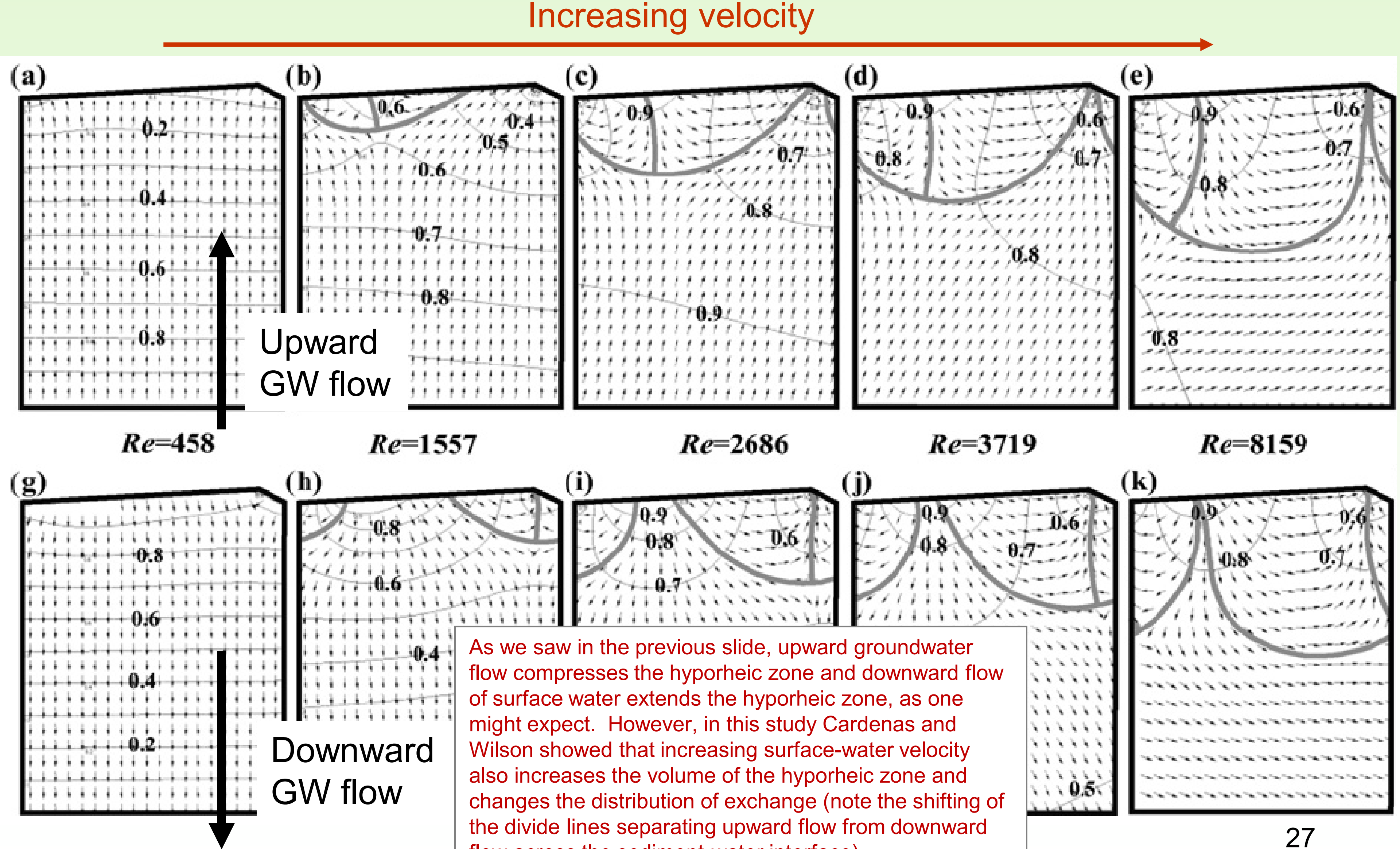
Cardenas and Wilson, 2006, *JHydrol*



- **Depth of hyporheic zone decreased with increasing GW discharge**
- **Line dividing hyporheic exchange from GW flow represents a steep gradient for physical, chemical, and biological parameters (a hyporheic ecotone of sorts)**

Cardenas and Wilson, 2006, *JHydrol*

Hyporheic zone also depends on surface-water velocity, *K*, and direction of seepage



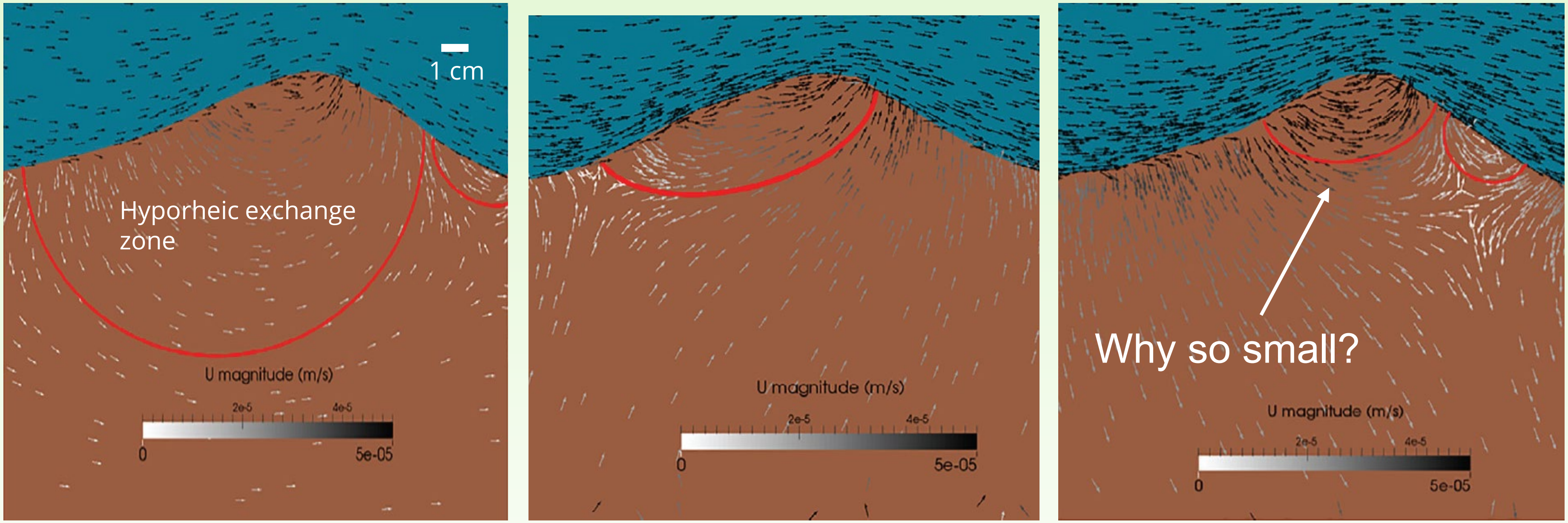
As we saw in the previous slide, upward groundwater flow compresses the hyporheic zone and downward flow of surface water extends the hyporheic zone, as one might expect. However, in this study Cardenas and Wilson showed that increasing surface-water velocity also increases the volume of the hyporheic zone and changes the distribution of exchange (note the shifting of the divide lines separating upward flow from downward flow across the sediment-water interface).

Cardenas and Wilson, 2007, *JHydrol*

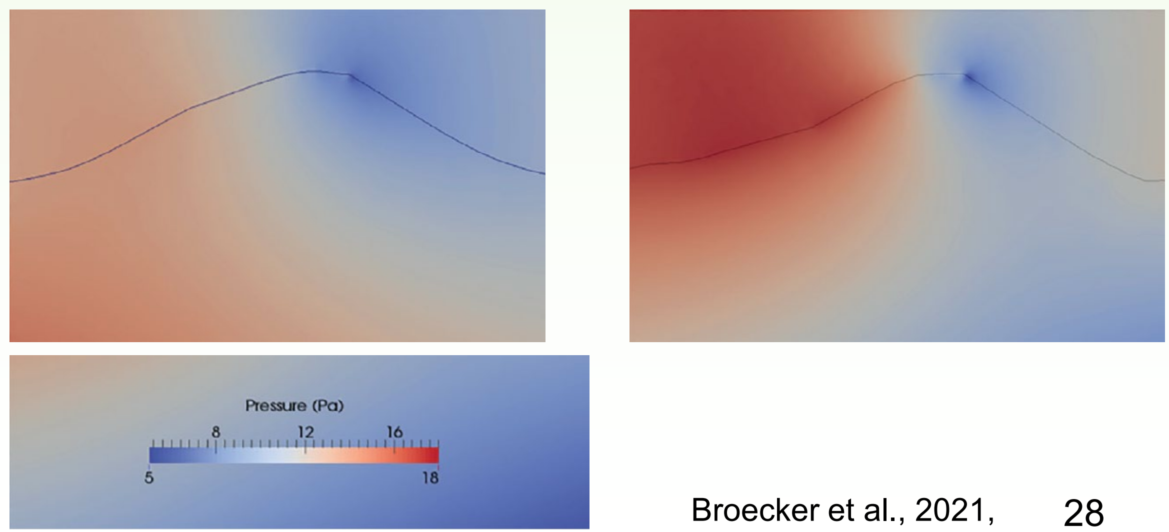
Hyporheic zone also depends on where the water that enters the porous media ends up

Authors used OpenFOAM to simulate both surface-water and groundwater flow domains at a bed ripple scale.

No vertical gradient | Upward flux at +49 cm/day | Downward flux at -49 cm/day



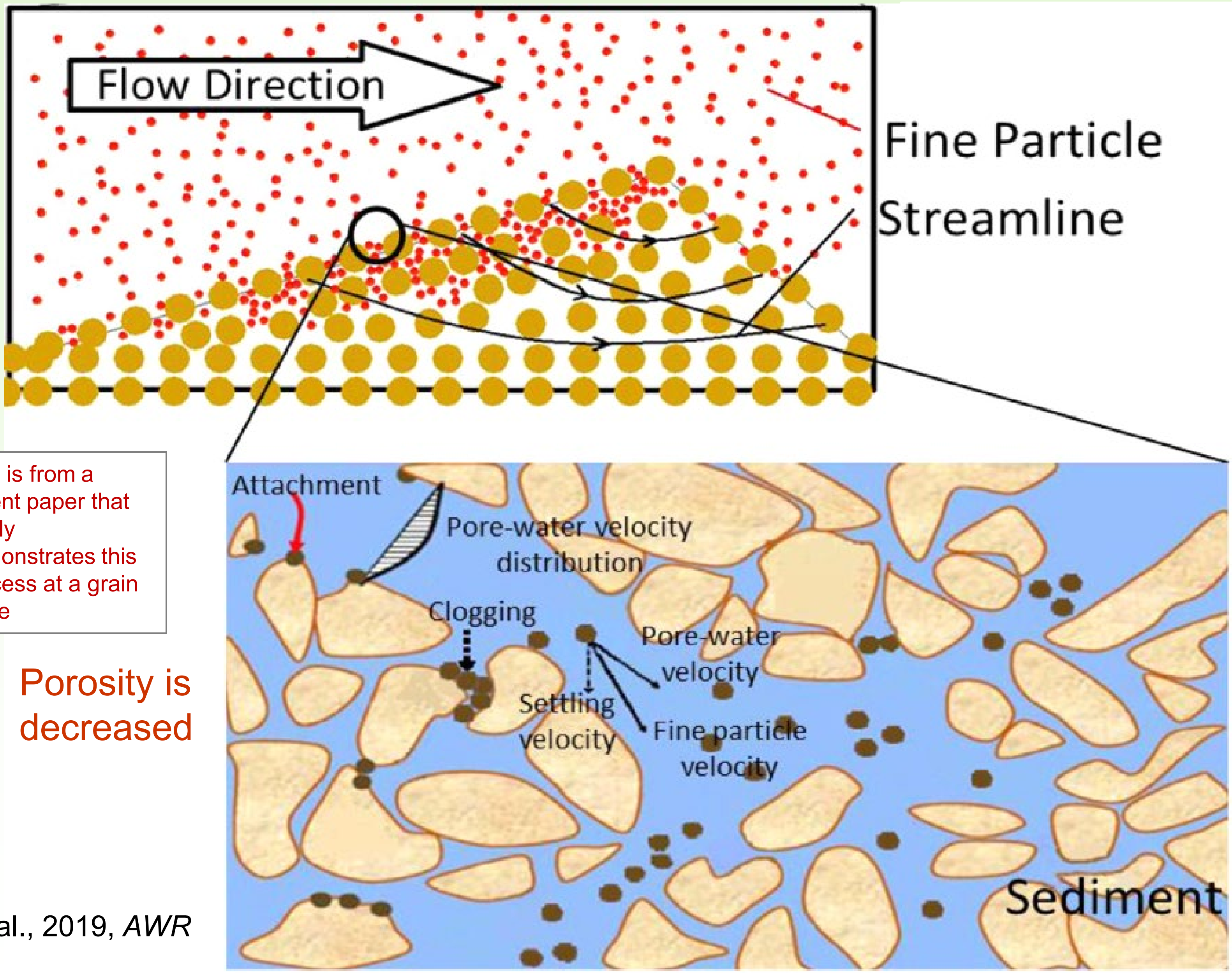
More powerful, more recent modeling tools lead to better understanding



The volume of the hyporheic zone is reduced (compressed) by upward flux through the groundwater flow domain, which makes logical sense. But why is the hyporheic zone for downward flux smaller than the neutral condition? It's because more of the groundwater flow paths continue downward through the groundwater flow domain rather than flowing back into the stream.

Broecker et al., 2021, *Groundwater*

But, as mentioned before, clogging (colmation) can reduce hyporheic exchange



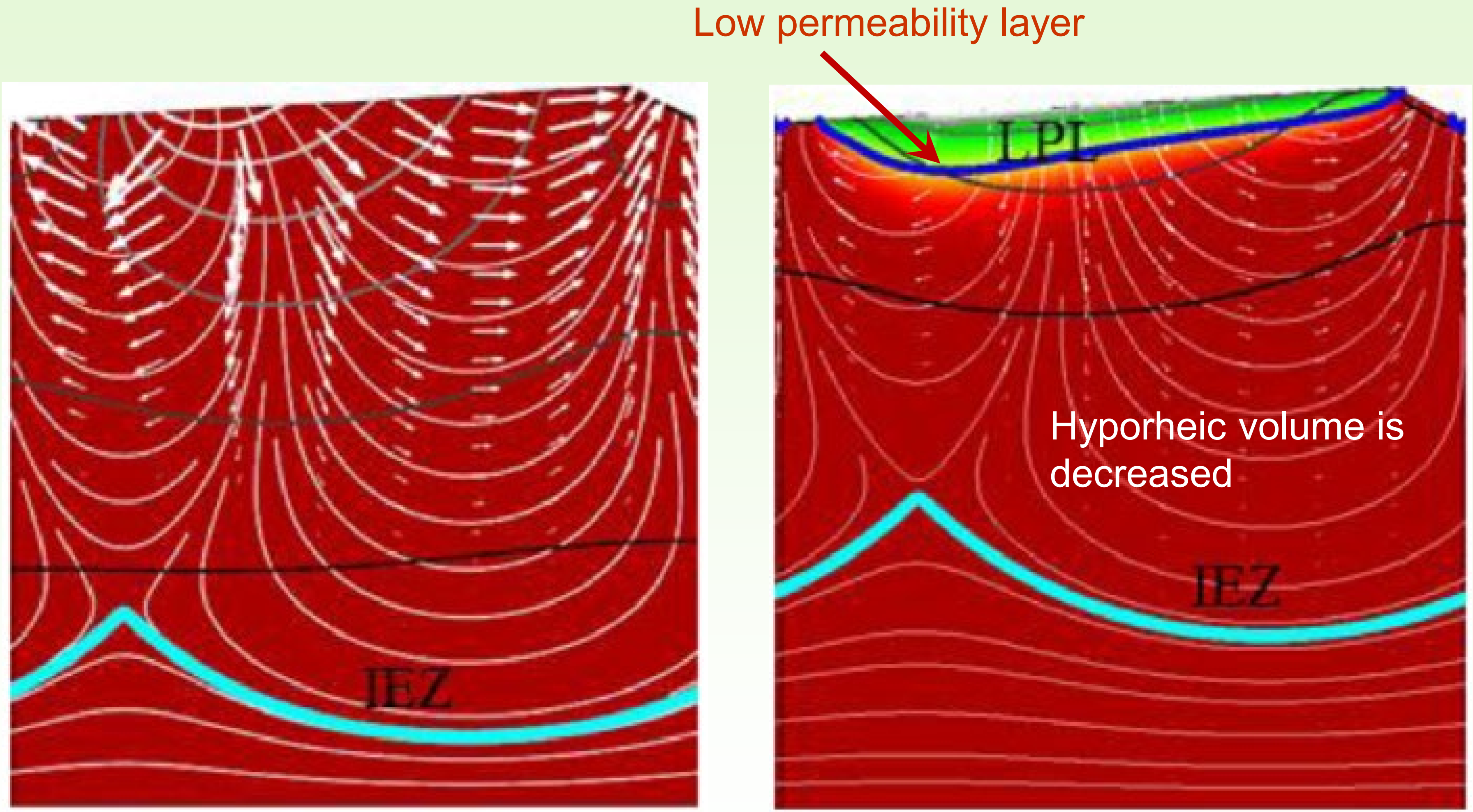
This is from a recent paper that nicely demonstrates this process at a grain scale

Porosity is decreased

Jin et al., 2019, *AWR*

Near total clogging could occur in 1 to 20 hours

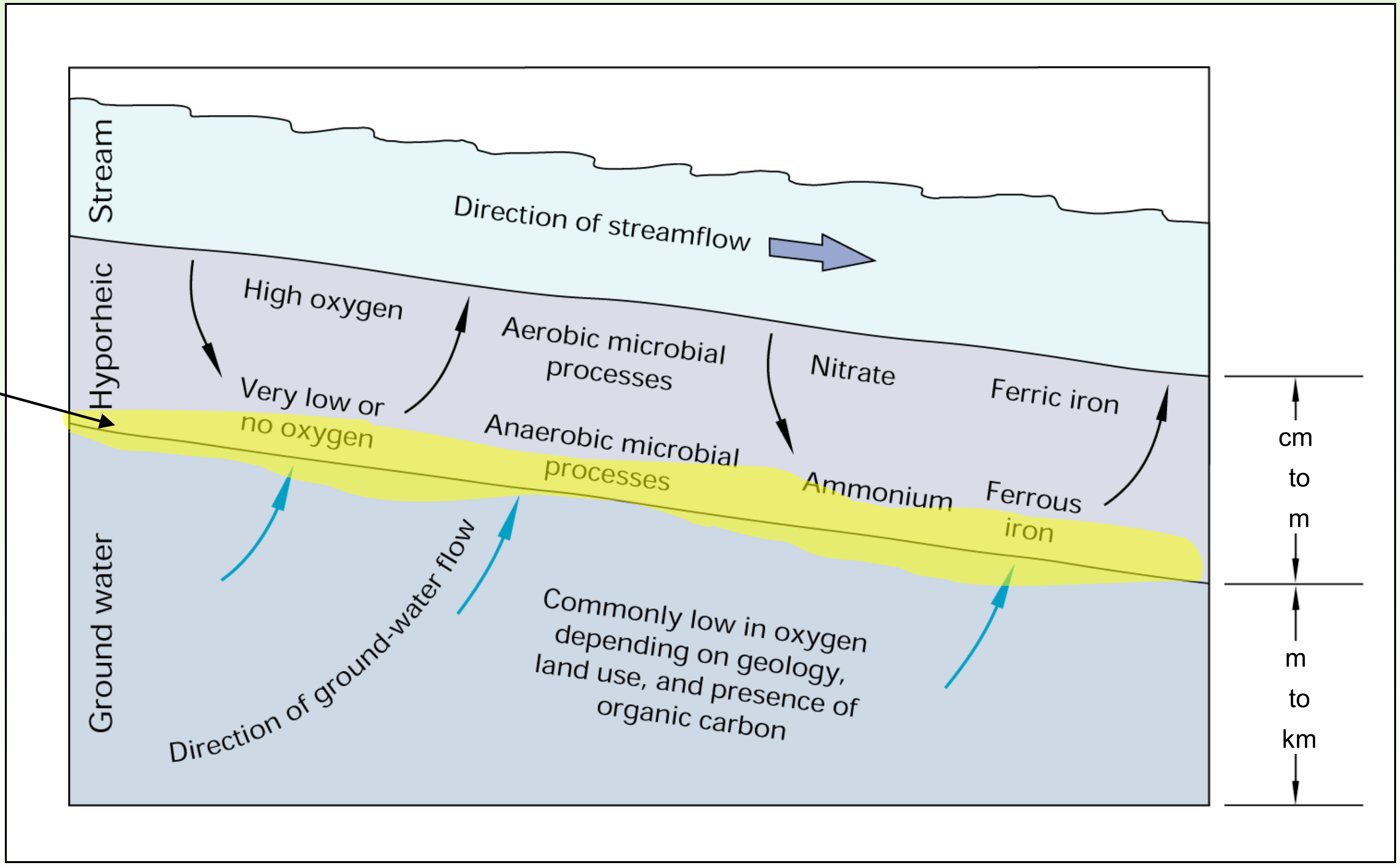
Clogging yes, but how long does it take? These results indicate clogging after a flushing flow that resets a sediment bed could occur within a day.



Jin et al., 2019, *AWR*

Biological and geochemical (ecological) perspective

Large gradients



Microbial activity and chemical transformations commonly are enhanced in the hyporheic zone compared to those that take place in ground water and surface water. This diagram illustrates some of the processes and chemical transformations that may take place in the hyporheic zone. Actual chemical interactions depend on numerous factors including aquifer mineralogy, shape of the aquifer, types of organic matter in surface water and ground water, and nearby land use.

Spawning redds

Another impetus that is driving much research by ground-water hydrologists, fluvial geomorphologists, and ecologists is whether fish create their spawning redds in areas of ground-water discharge. Whether they do or not seems to be species dependent. These measurements are particularly difficult to make because the streambed substrate often is very coarse. This is a rapidly growing research area.

Alexander and Caissie. 2003. *Ground Water*

Brown and Ford. 2002. *River Research and Applications*

Moir et al. 2002. *Geomorphology*

Morrison et al. 2002. *Journal of Hydrology*

Soulsby et al. 2001. *Regulated Rivers: Research & Management*

Baxter and Hauer. 2000. *Journal of Fisheries and Aquatic Science*

Baxter and McPhail. 1999. *Canadian Journal of Zoology*

Garrett et al. 1998. *Journal of Fisheries Management*

Pitlick and Van Steeter. 1998. *Water Resources Research*

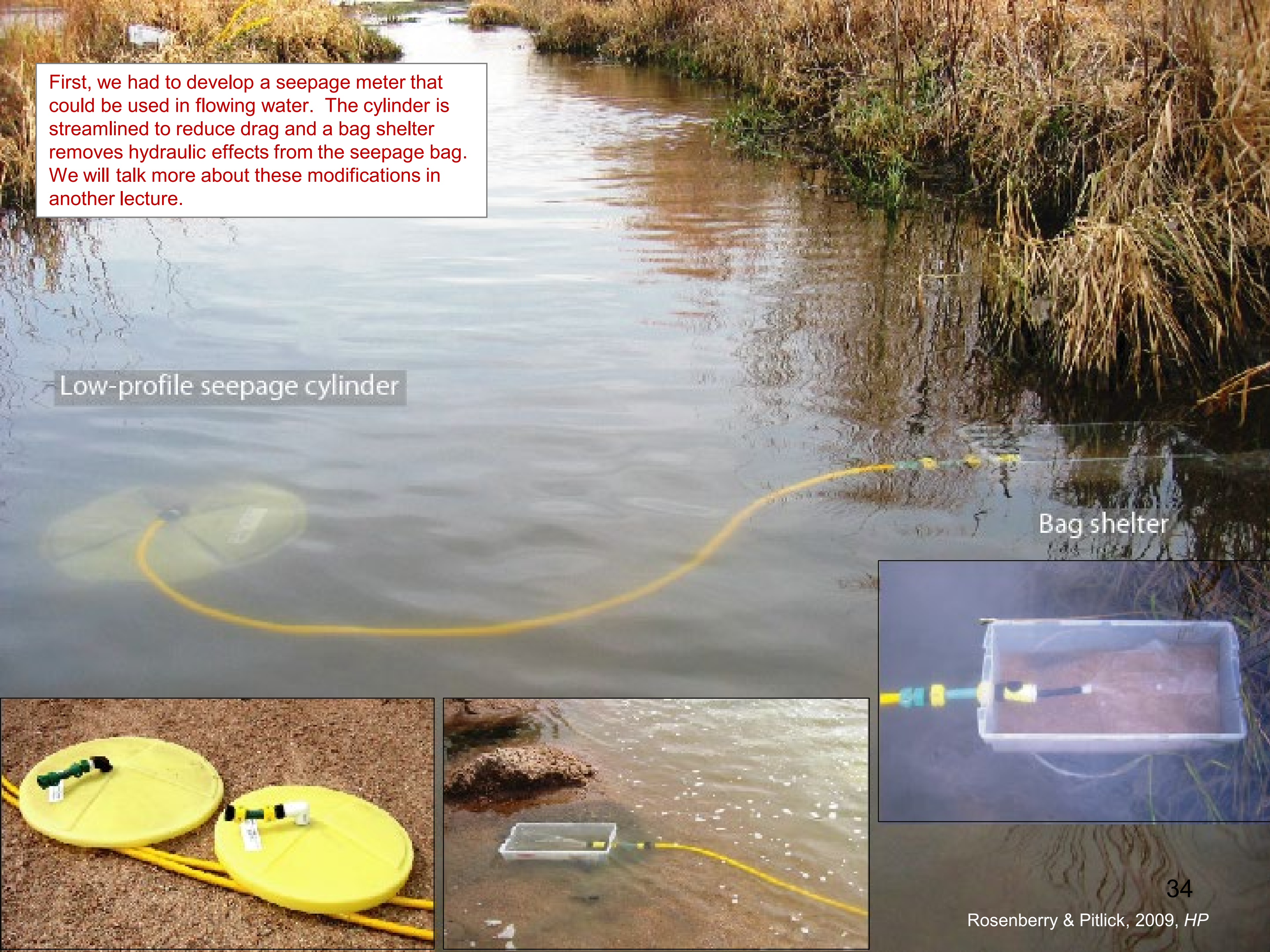
Ridgway and Blanchfield. 1998. *Ecology of Freshwater Fish*

Field example of reach-scale hyporheic exchange

Rosenberry & Pitlick, 2009, *HP*

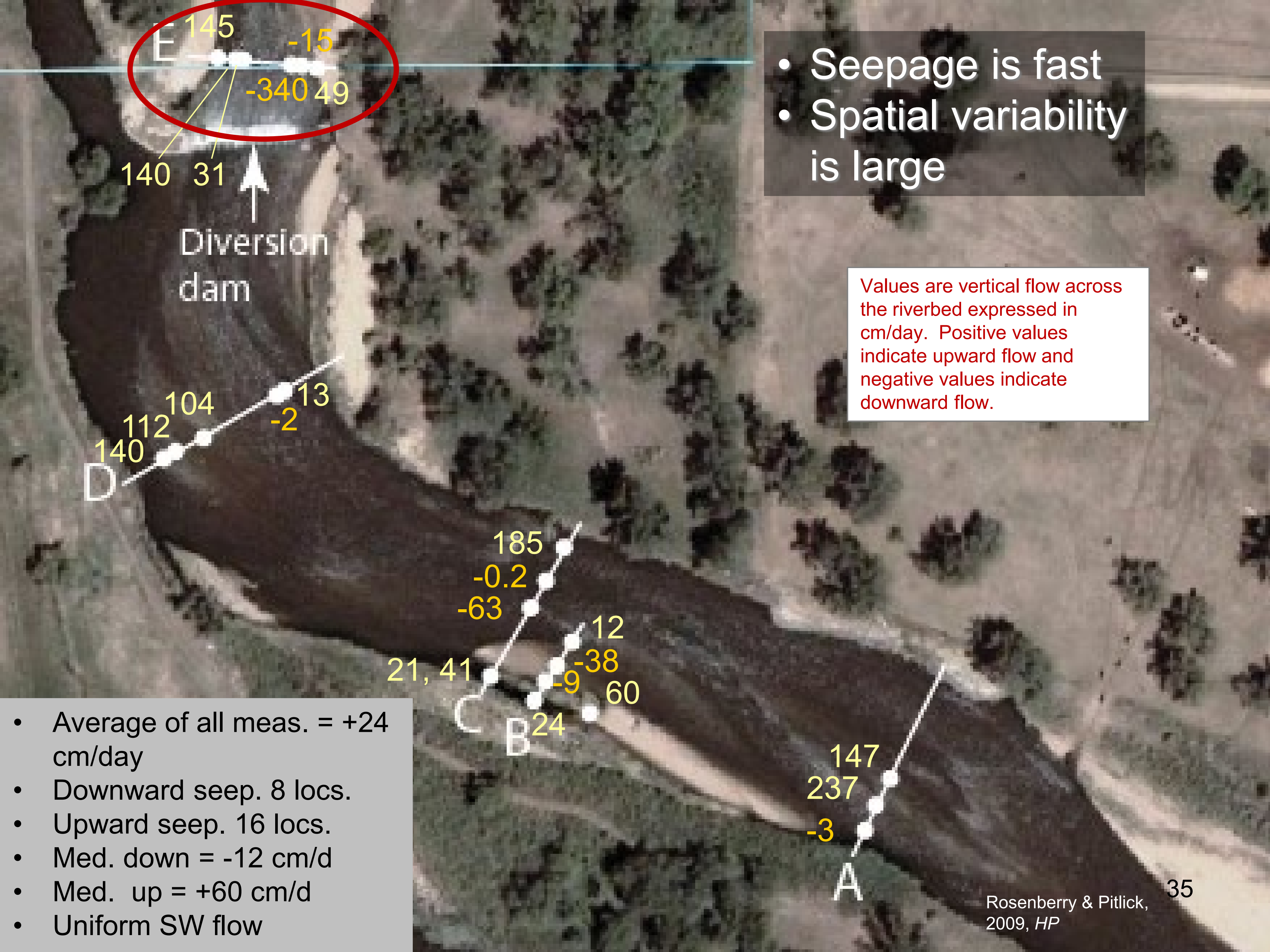
This study demonstrates the complexity of GW-SW exchange in coarse-grained fluvial settings.

First, we had to develop a seepage meter that could be used in flowing water. The cylinder is streamlined to reduce drag and a bag shelter removes hydraulic effects from the seepage bag. We will talk more about these modifications in another lecture.



Rosenberry & Pitlick, 2009, *HP*

- Seepage is fast
- Spatial variability is large

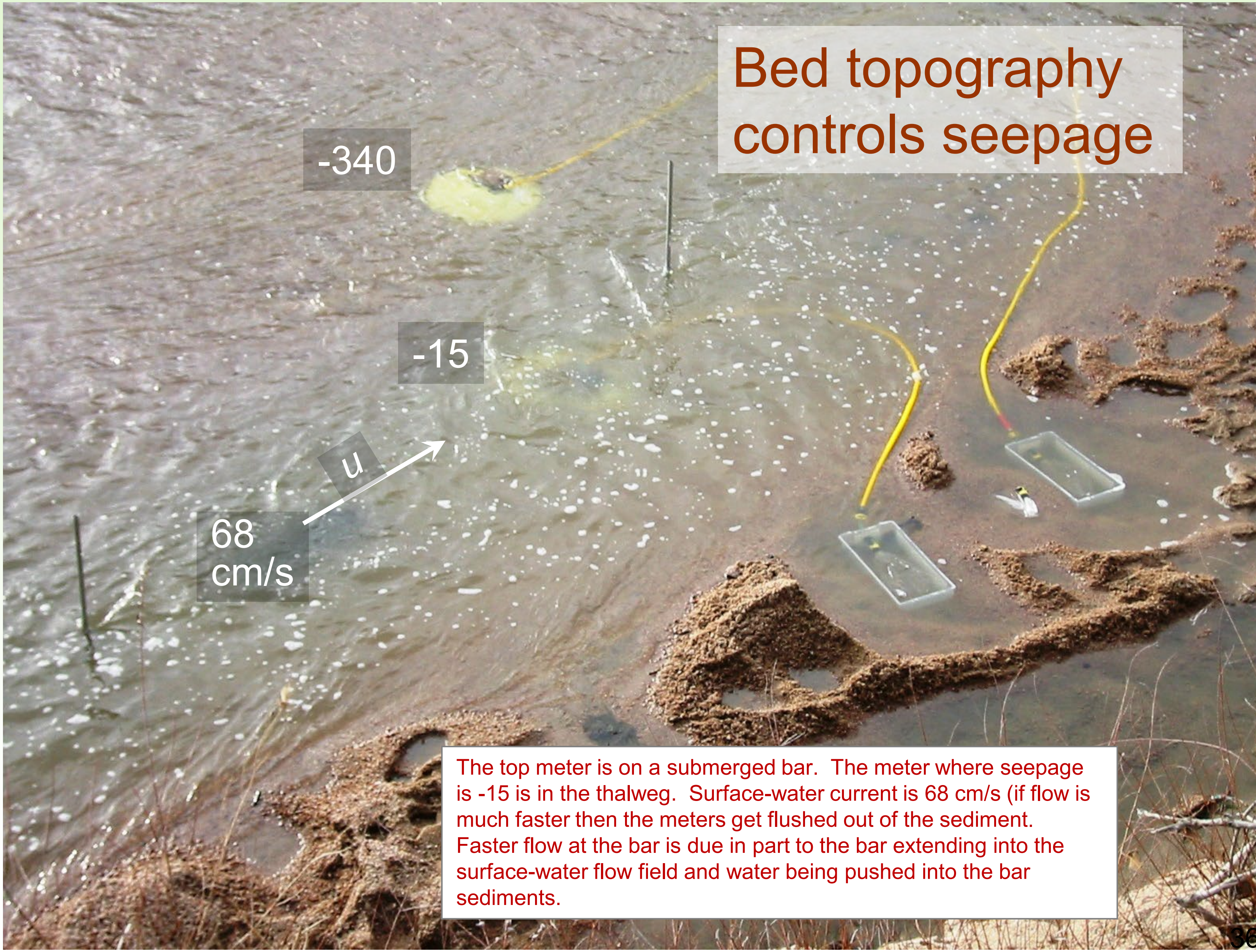


Values are vertical flow across the riverbed expressed in cm/day. Positive values indicate upward flow and negative values indicate downward flow.

- Average of all meas. = +24 cm/day
- Downward seep. 8 locs.
- Upward seep. 16 locs.
- Med. down = -12 cm/d
- Med. up = +60 cm/d
- Uniform SW flow

Rosenberry & Pitlick, 2009, *HP*

Bed topography controls seepage

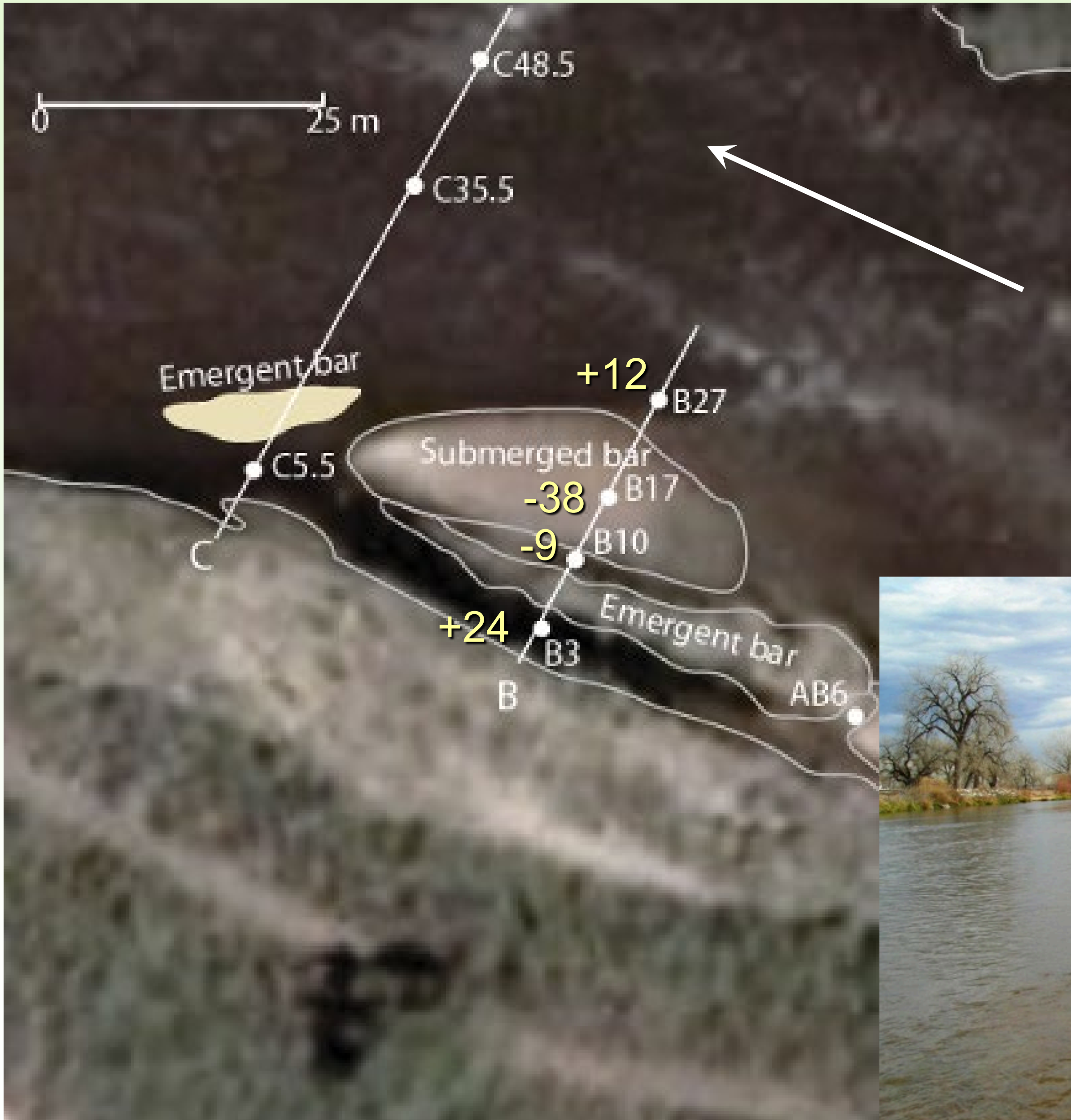


The top meter is on a submerged bar. The meter where seepage is -15 is in the thalweg. Surface-water current is 68 cm/s (if flow is much faster then the meters get flushed out of the sediment. Faster flow at the bar is due in part to the bar extending into the surface-water flow field and water being pushed into the bar sediments.

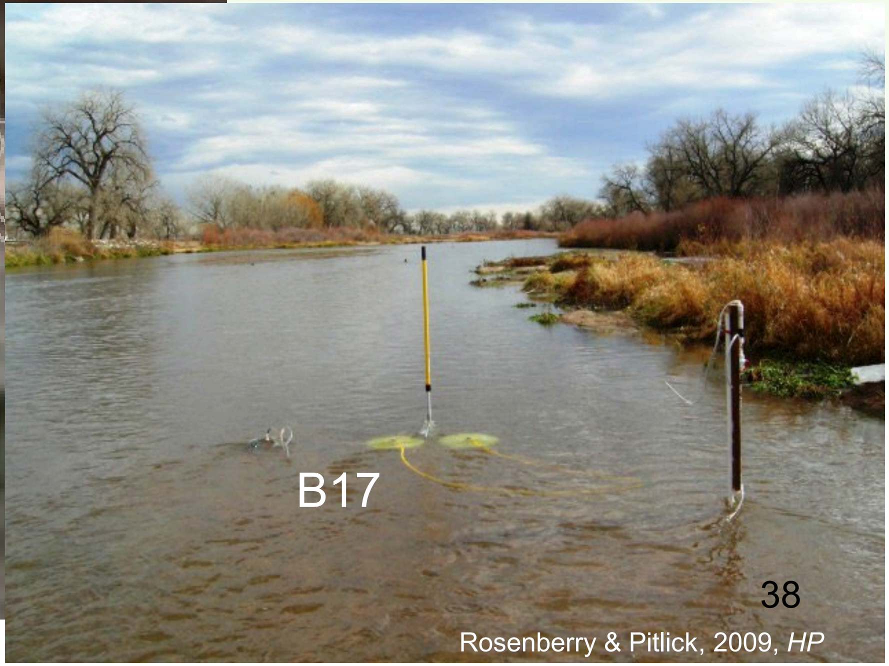
Rosenberry & Pitlick, 2009, *HP*

But downward seepage (at both locations) also is due to larger-scale exchange caused by two braids of the river being at different elevations. Water is seeping downward through the bed in the channel to the left and flowing toward the channel just visible at the right edge of the photograph.

Bed topography controls seepage

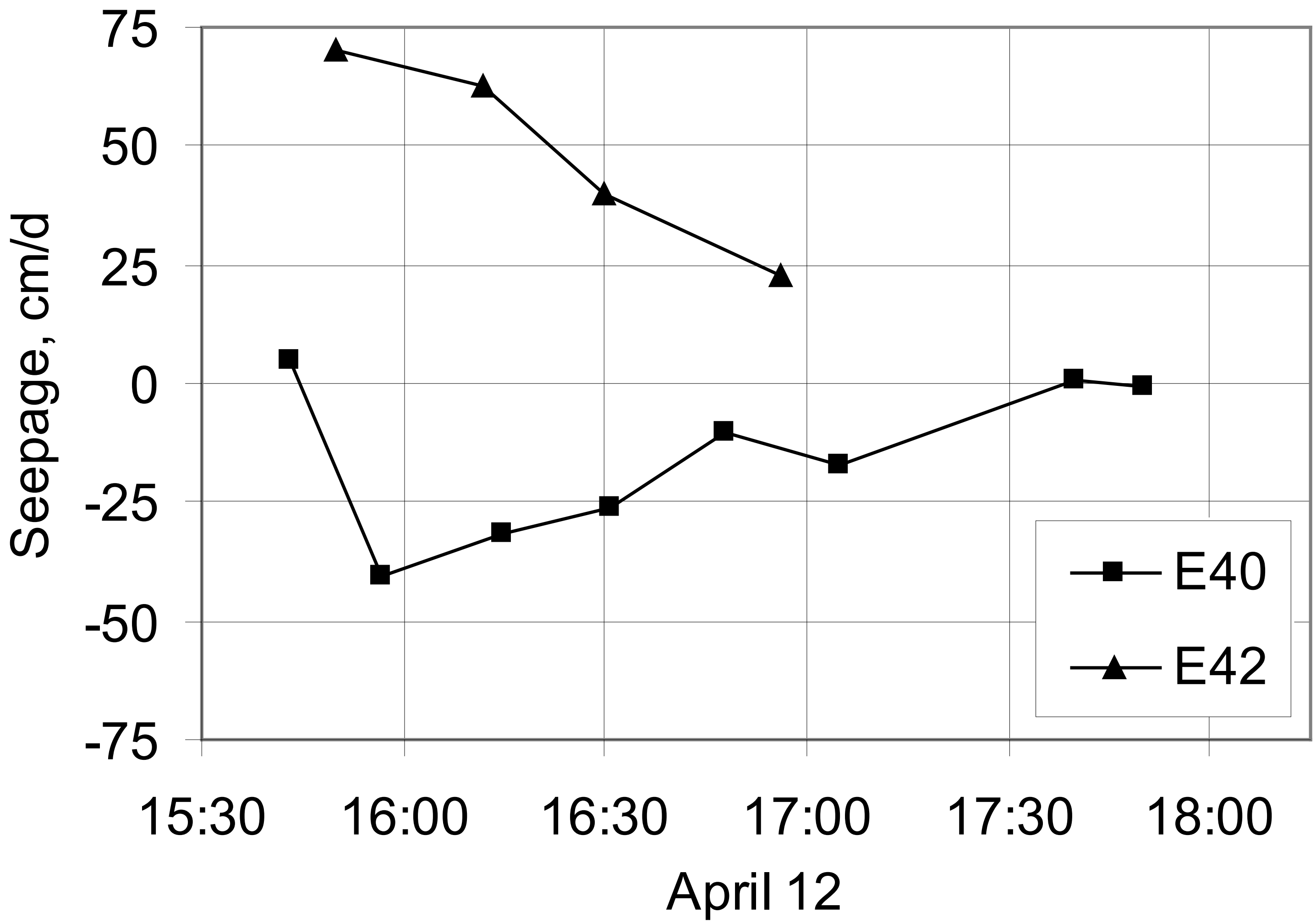


Here is another example of bed topography controlling distribution of seepage. Seepage is downward where water is shoaling over a submerged bar, but seepage is upward in slightly deeper water at location B27 (and also at B3 and C5.5) The inset photo shows measurements of seepage (two yellow cylinders), sediment transport (meter placed on the bed just upstream of the seepage meters), hydraulic gradient (manometer near the right side of the photo), and use of a piezoseep that will be discussed later.



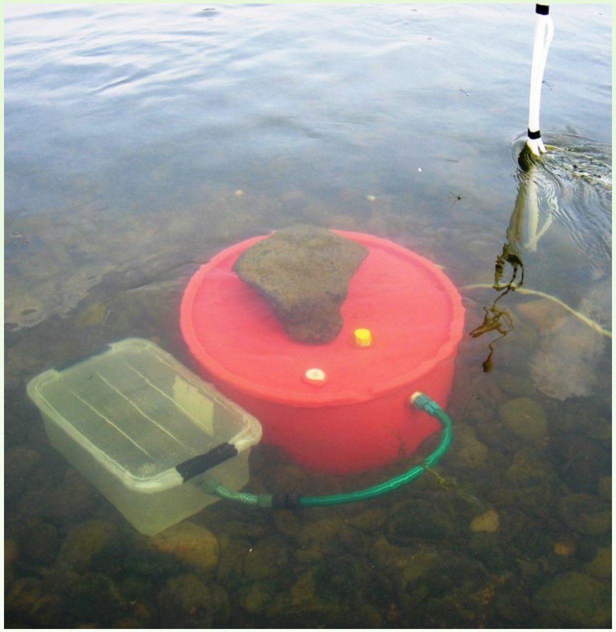
Rosenberry & Pitlick, 2009, *HP*

And exchange can vary substantially over time

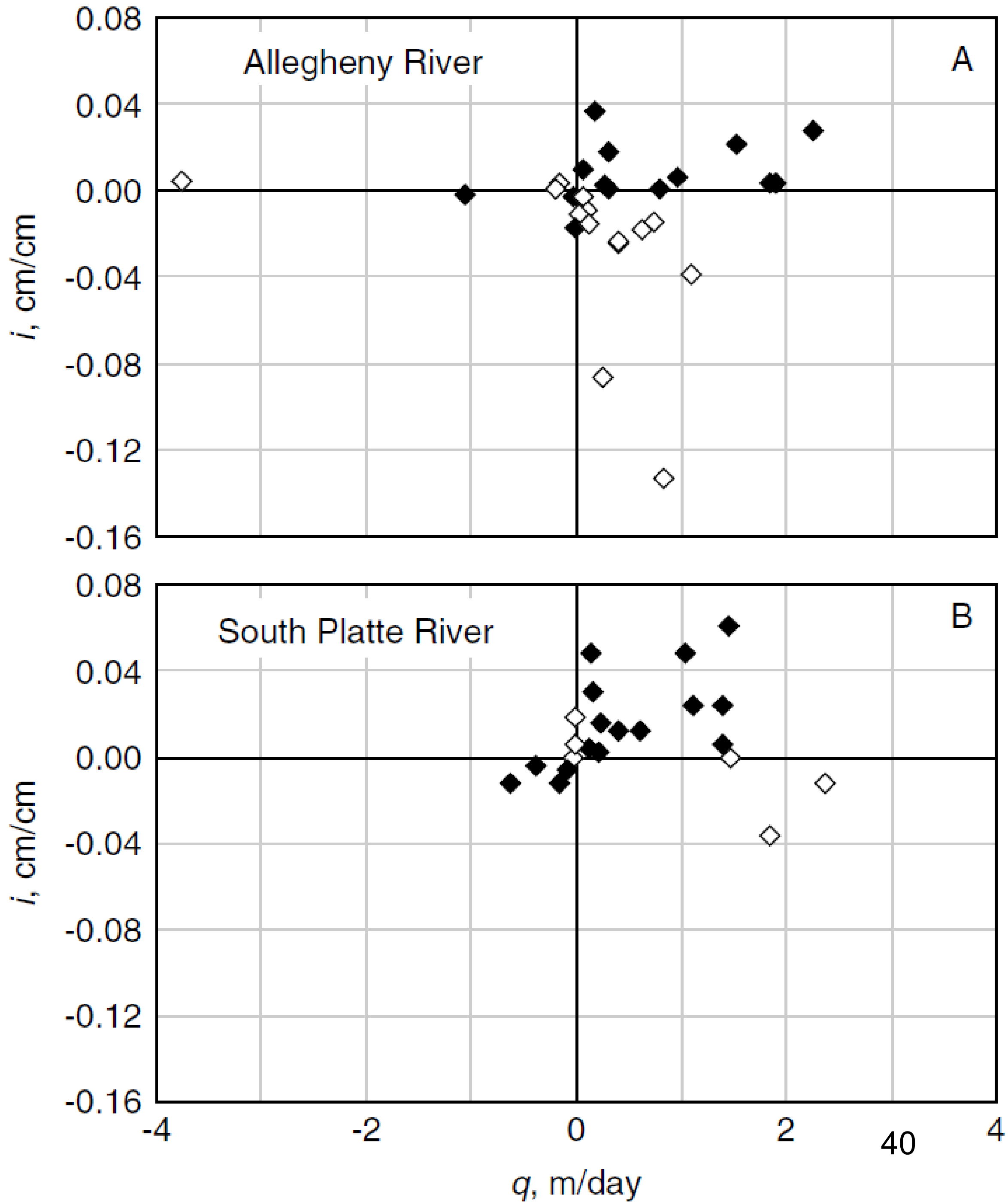


Rosenberry & Pitlick, 2009, *HP*

q and *i* might not correlate very well in hyporheic settings

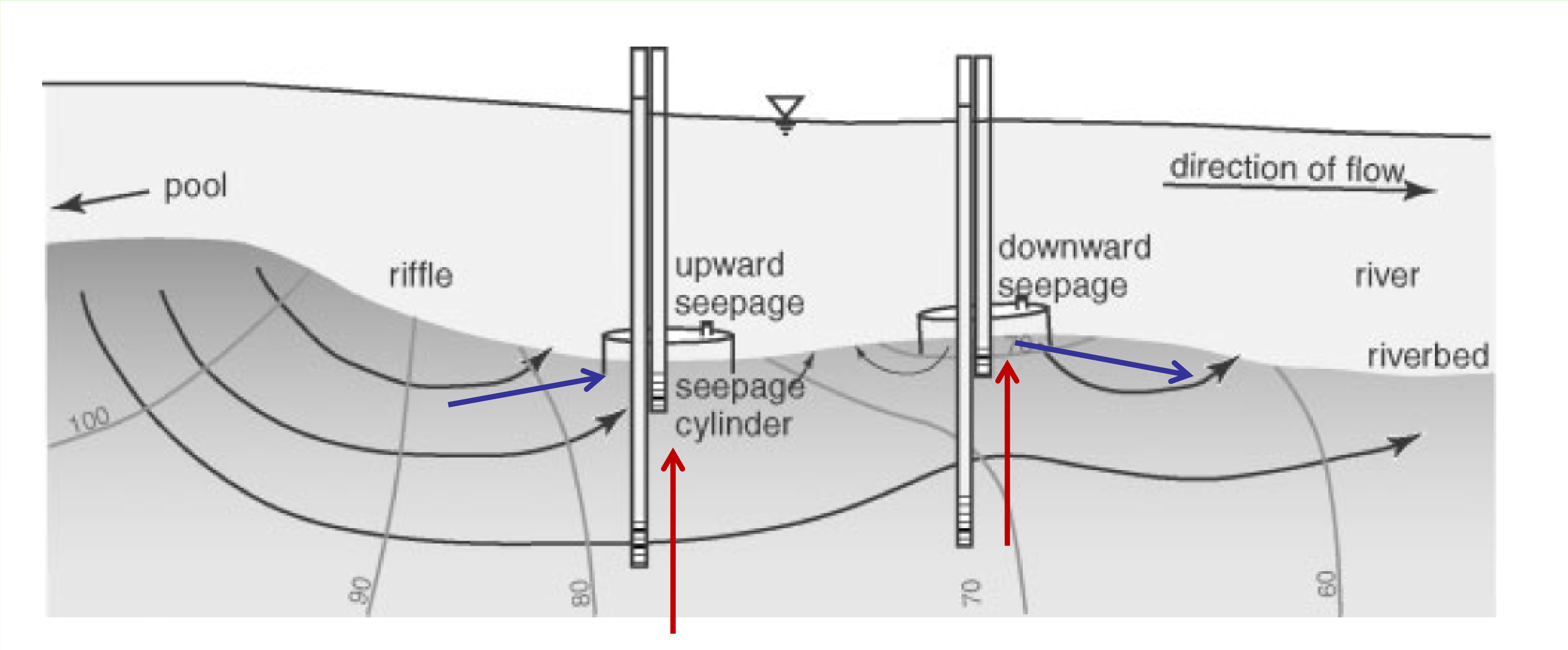


The open diamonds are locations where the seepage meter indicated flow in one direction and the adjacent piezometer indicated the potential for flow in the opposite direction. Why?



Rosenberry et al., 2012, *Hydrological Processes*.

Riverbed heterogeneity may result in different instruments measuring processes at different scales



Seepage is primarily horizontal

Gradient (*i*) measured along a vertical axis

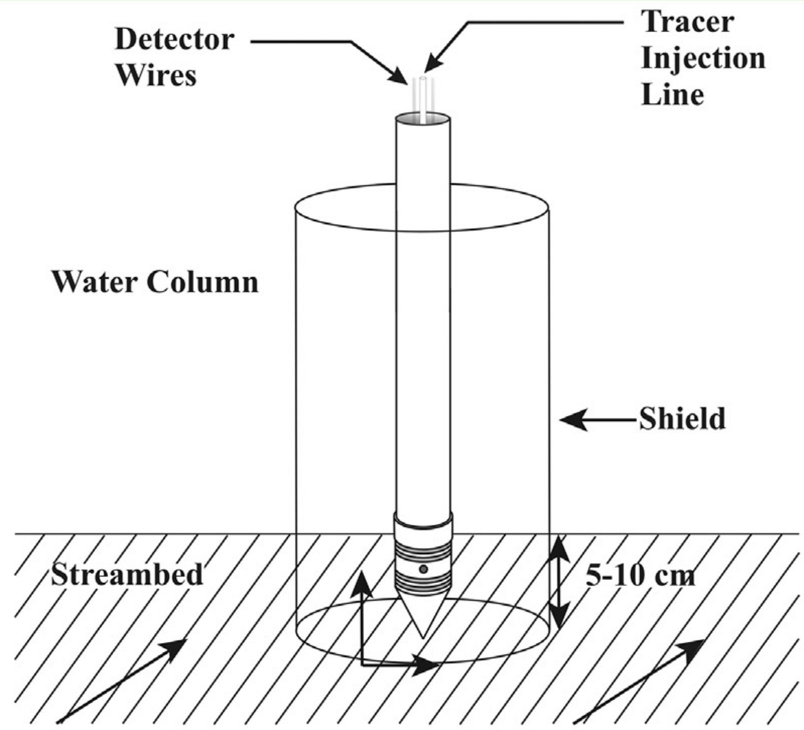
When we measure a hydraulic gradient with a piezometer installed in a streambed, the gradient is measured along a vertical axis (unless the piezometer is installed at an angle). However, seepage measured with a seepage meter is often in response to flowpaths that are not vertical. In some settings, interpretations of seepage based on these two methods can be quite different, including settings where hydraulic gradients and seepage meters can indicate flows in opposite directions. Such is the case in the seepage meter and piezometer shown on the right.

Rosenberry et al., 2012, *Hydrological Processes*.

Streambed point-velocity probe

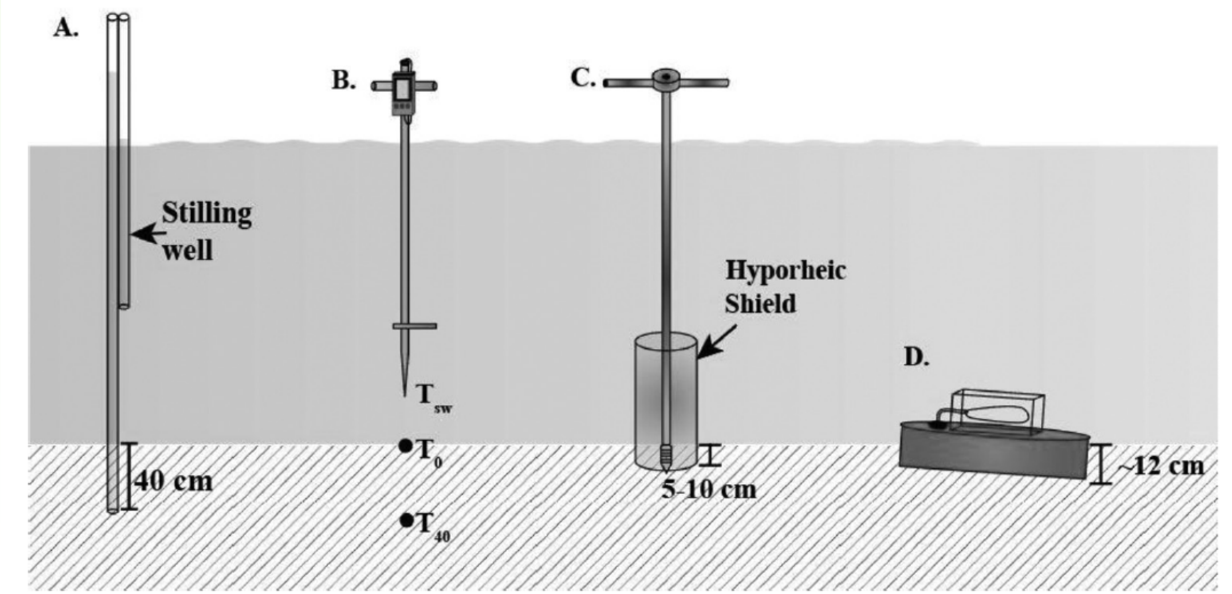
Modified to measure only vertical component of flux

They deployed a point-velocity probe that measures velocity based on timed tracer injections, a device typically used to measure flow either in boreholes or screened invervals of wells. They placed a metal cylinder, open on both ends, to block horizontal flow and allow measurement of only the vertical component of flow. They went on to compare this tool with other methods presented in a paper published in 2020. Those results are presented in a later lecture on methods for quantifying GW-SW exchange.

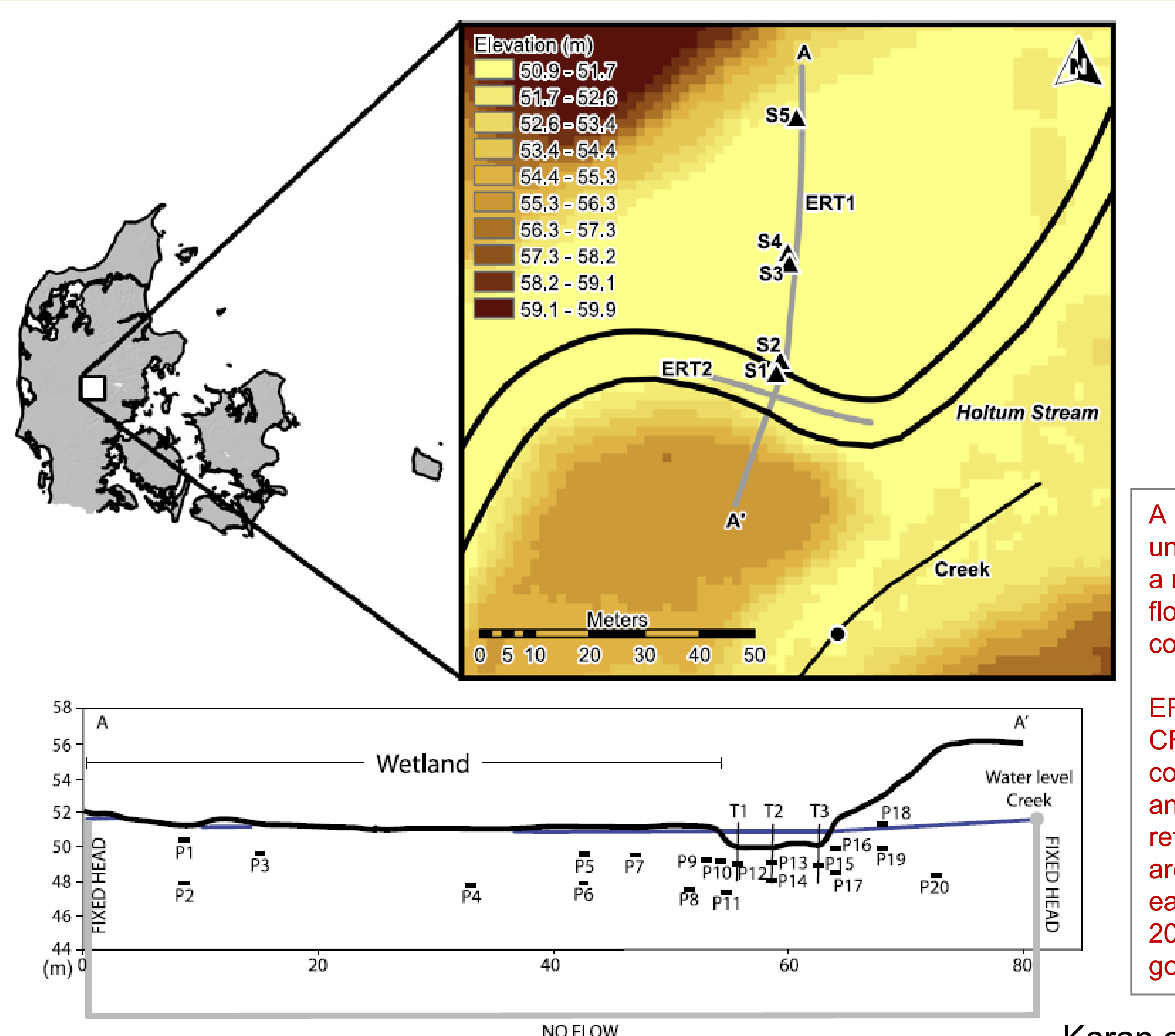


Cremeans and Devlin, 2017, *J. Contam. Hydrol*.

Methods comparison (published in 2020)



Field example: A reminder that broader-scale heterogeneity is still important to hyporheic exchange, in this case to nutrient transport to the stream



Combined ERT and slug tests from wells to map *K*, measured seepage in-situ.

Modeled flow to determine flowpaths and travel times

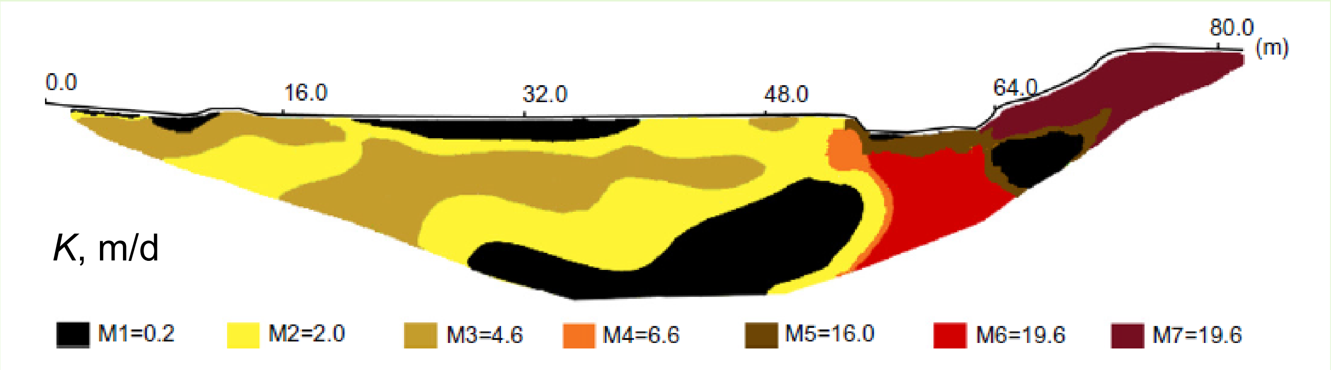
Used CFC and chemistry to confirm the model

A nice example of iteration; field data to understand the local system and constrain a model, then modeling to understand flowpaths and travel times, then data to confirm the modeling.

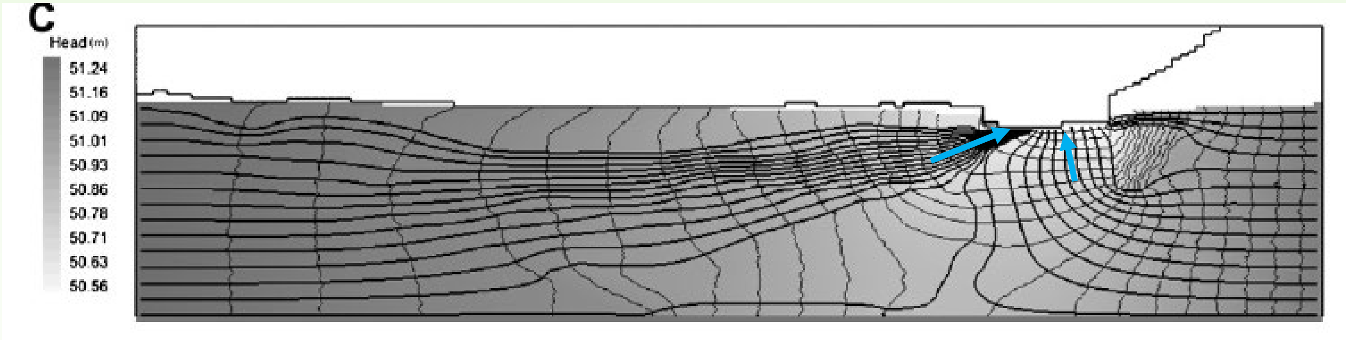
ERT is electrical resistivity tomography. CFC is chlorofluorocarbon, a class of compounds of carbon, hydrogen, chlorine, and fluorine, gases typically used in refrigerants and aerosol propellants. They are harmful to the ozone layer in the earth's atmosphere and were banned in 2000. In some settings, they serve as a good tracer.

Karan et al., 2013, *JHydrol*

Once again, "geology trumps topography"



Results based on field data



Results based on numerical model

K distribution changes the distribution of GW discharge to the stream, which affects flowpath length, degree of oxygenation of groundwater, and nitrogen loading to the stream

Instead of oxic GW discharging on the right side, most discharge was old, nutrient-laden, and was coming from the left side.

Knowing distribution of *K* was very important to this study. A homogeneous model would not have predicted the distribution of flow and the mix of oxic versus anoxic groundwater discharge to the stream. This affects the proportions of discharging groundwater subject to denitrification. Also, hydraulic head alone was not able to constrain the model during model calibration. Seepage measurements and geochemistry (including CFC age-dating) provided additional information that helped with model calibration.

Karan et al., 2013, *JHydrol*

Here are a few examples of hyporheic processes research priorities (according to UK Environmental Agency)

Hyporheic exchange continues to be a very active area of research

- Develop conceptual models of lowland hyporheic zones
- Develop methods for rapid 3-D in-situ monitoring of ground-water flow
- Determine the main controls on hyporheic exchange (in particular, for lowland rivers)
- Do more research on colmation processes
- Determine if GW and hyporheic water actually mix or if the interface simply shifts
- Does geochemical attenuation capacity vary with sediment deposition?
- What is the nature of immature organic carbon in hyporheic sediments and how does OC affect sorption?
- Is there a hyporheic zone in regulated lowland rivers or do the clay-rich sediment prevent hyporheic exchange?
- What is the potential for attenuation of agricultural nutrients (N and P), industrial pollutants, or heavy metals in hyporheic zones?
- What are the controls on phosphorus cycling in hyporheic zones?
- Review and contrast headwaters hyporheos with assemblages found in lowland rivers
- What is the effect of bioturbation on hydraulic conductivity in hyporheic sediments?
- How does hyporheic-zone hydrology relate to microbial processes and biodiversity?
- How do hyporheic-zone sediments relate to microbial processes and biodiversity?
- Do measures of ecological quality based solely on benthic fauna adequately describe the health of lotic systems?
- Up-scale hyporheic studies from reach scale to catchment scale

Smith, 2005, *UK Env. Agency Science Report*

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