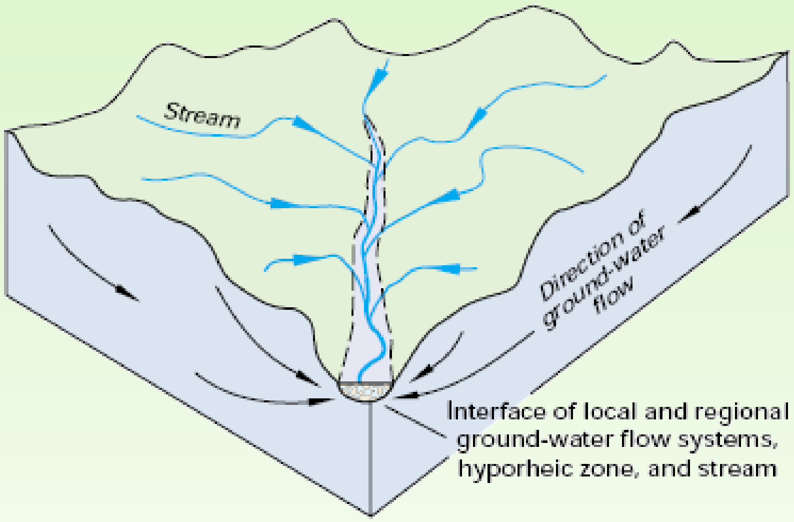
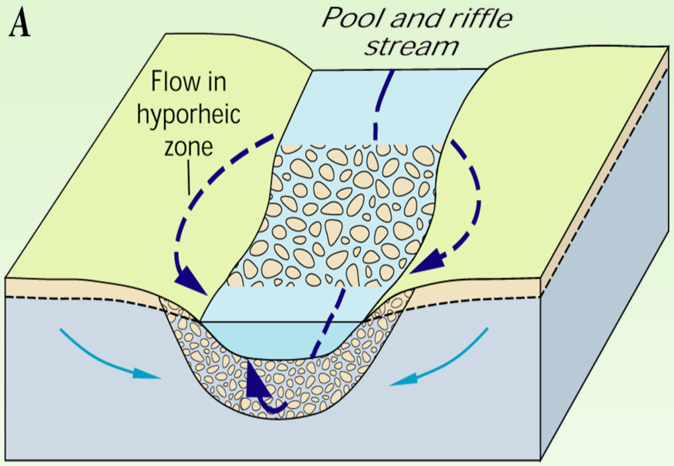
Surface-ground water interaction: From watershed processes to hyporheic exchange





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Scale – matching the study to the setting

- Geology, heterogeneity
- Flowpaths
- Time of travel

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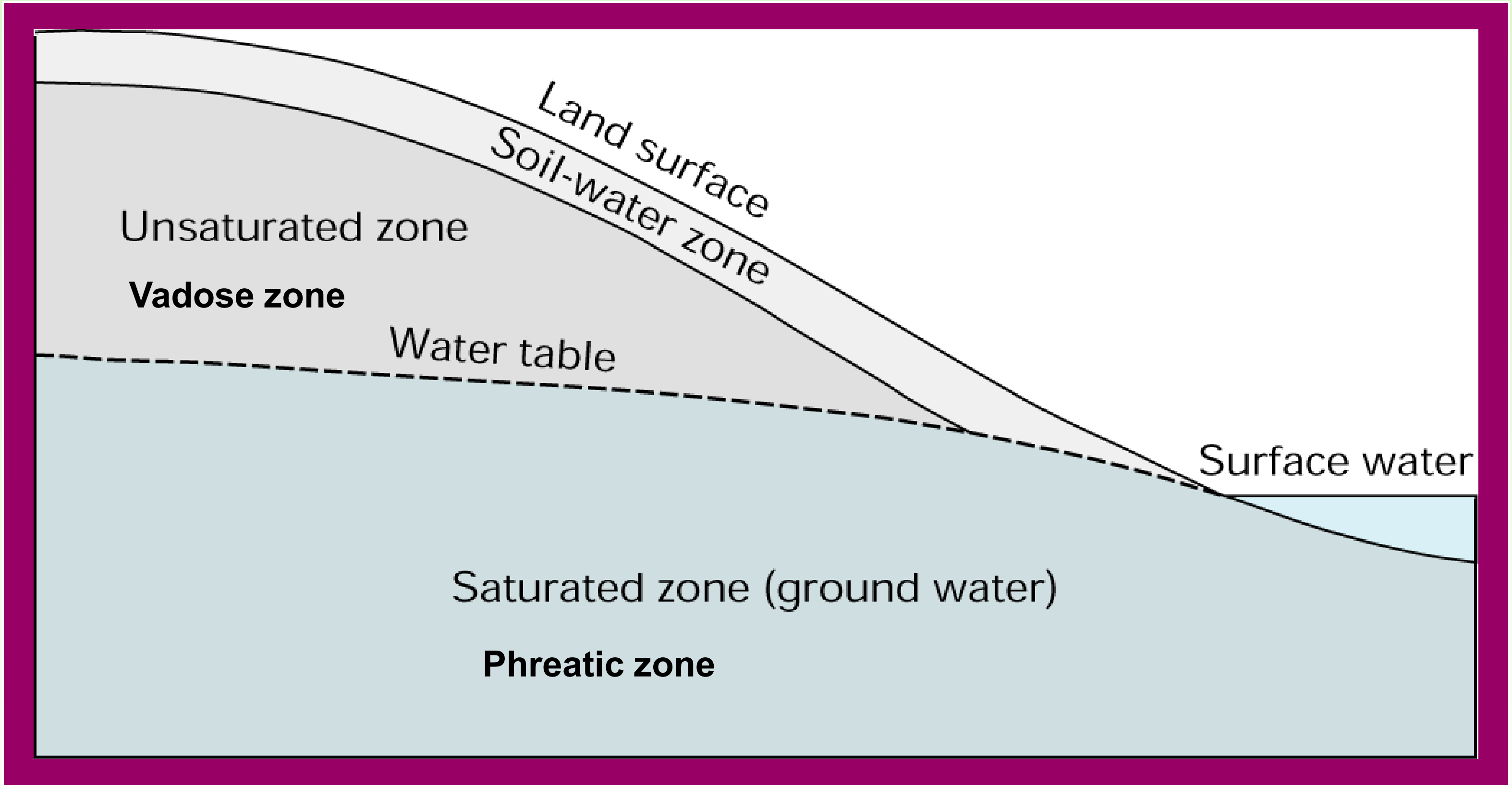
Typical physical setting – some general terms

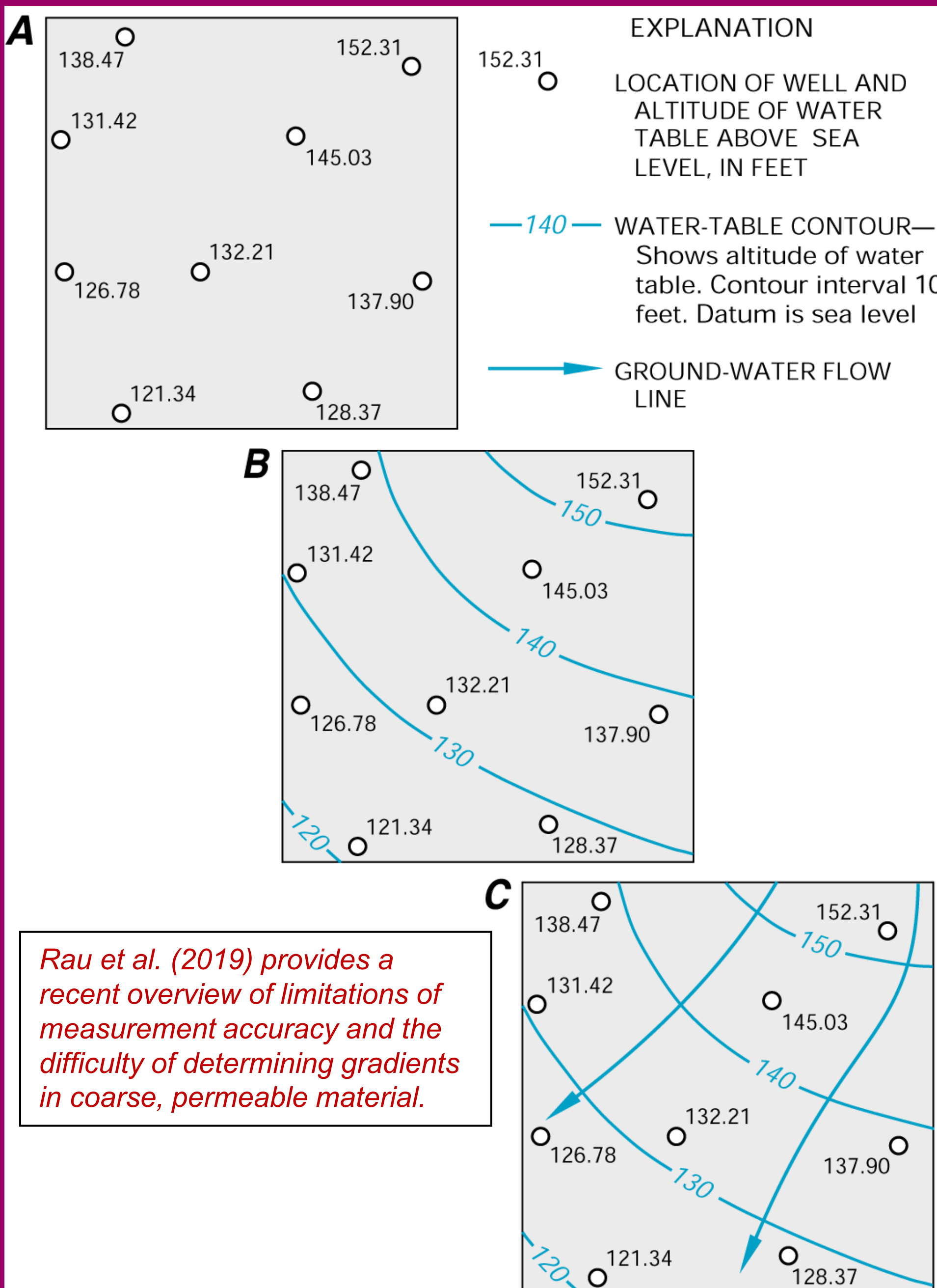


First, some general terms. The water table is the upper surface of the saturated zone. The water table meets surface-water bodies at or near the shoreline of surface water if the surface-water body is connected to the ground-water system.

Determining GW flow

A. Install wells and determine water-table elevation
B. Contour the data, creating "equipotential" lines
C. Draw perpendicular flowpath lines, creating approximately rectilinear squares

This is the beginning of a flow-net analysis for quantifying GW flow that will be discussed later

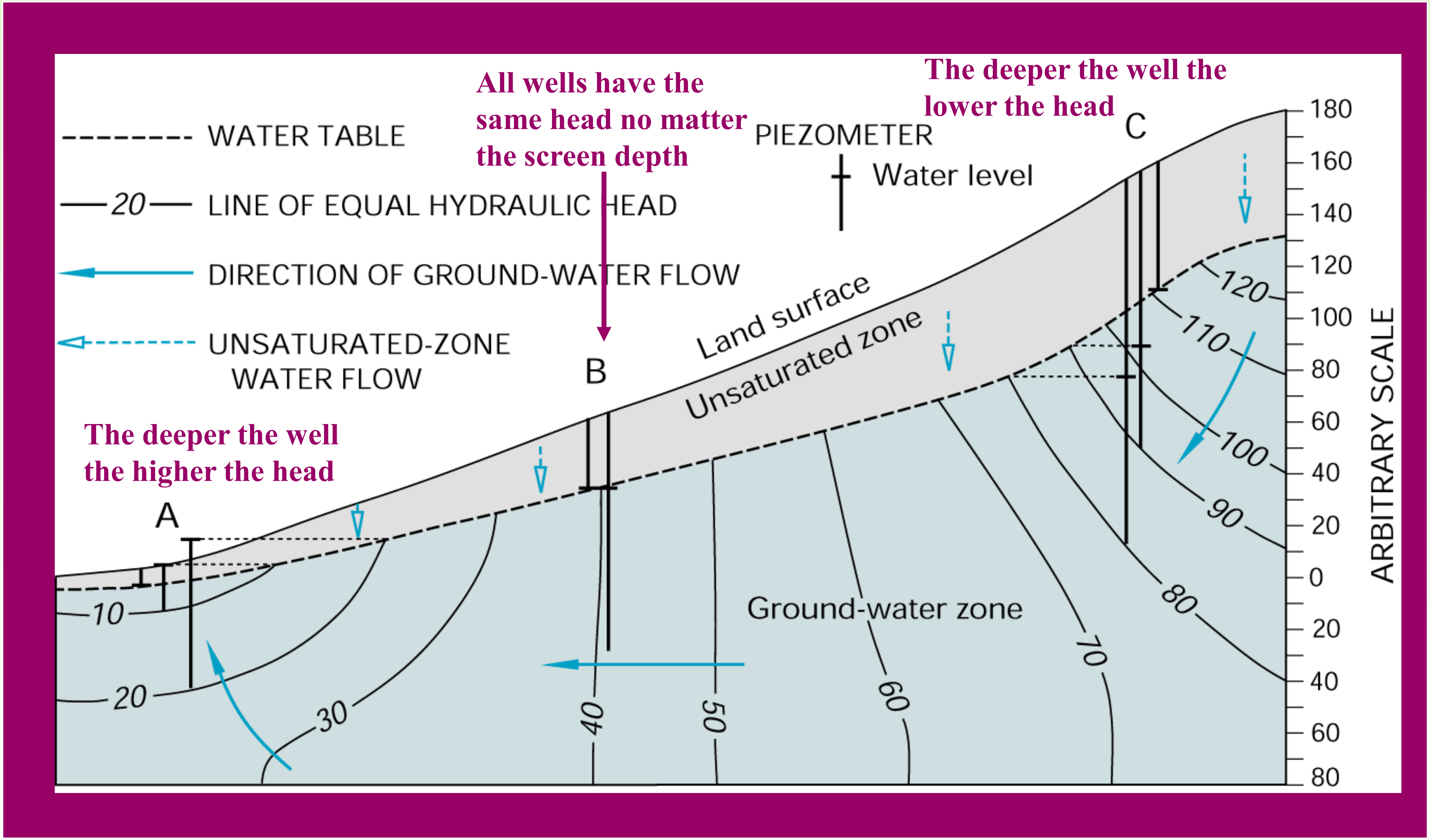


Rau et al. (2019) provides a recent overview of limitations of measurement accuracy and the difficulty of determining gradients in coarse, permeable material.

Using known altitudes of the water table at individual wells (A), contour maps of the water-table surface can be drawn (B), and directions of ground-water flow along the water table can be determined (C) because flow usually is approximately perpendicular to the contours.

Although this concept is pretty basic to any hydrogeologist, obtaining good data with sufficient accuracy is critical to this process. Because of accuracy limits wells may need to be substantially far apart to determine directions of flow and horizontal gradients in coarse sediments where gradients are smaller than about 0.0001.

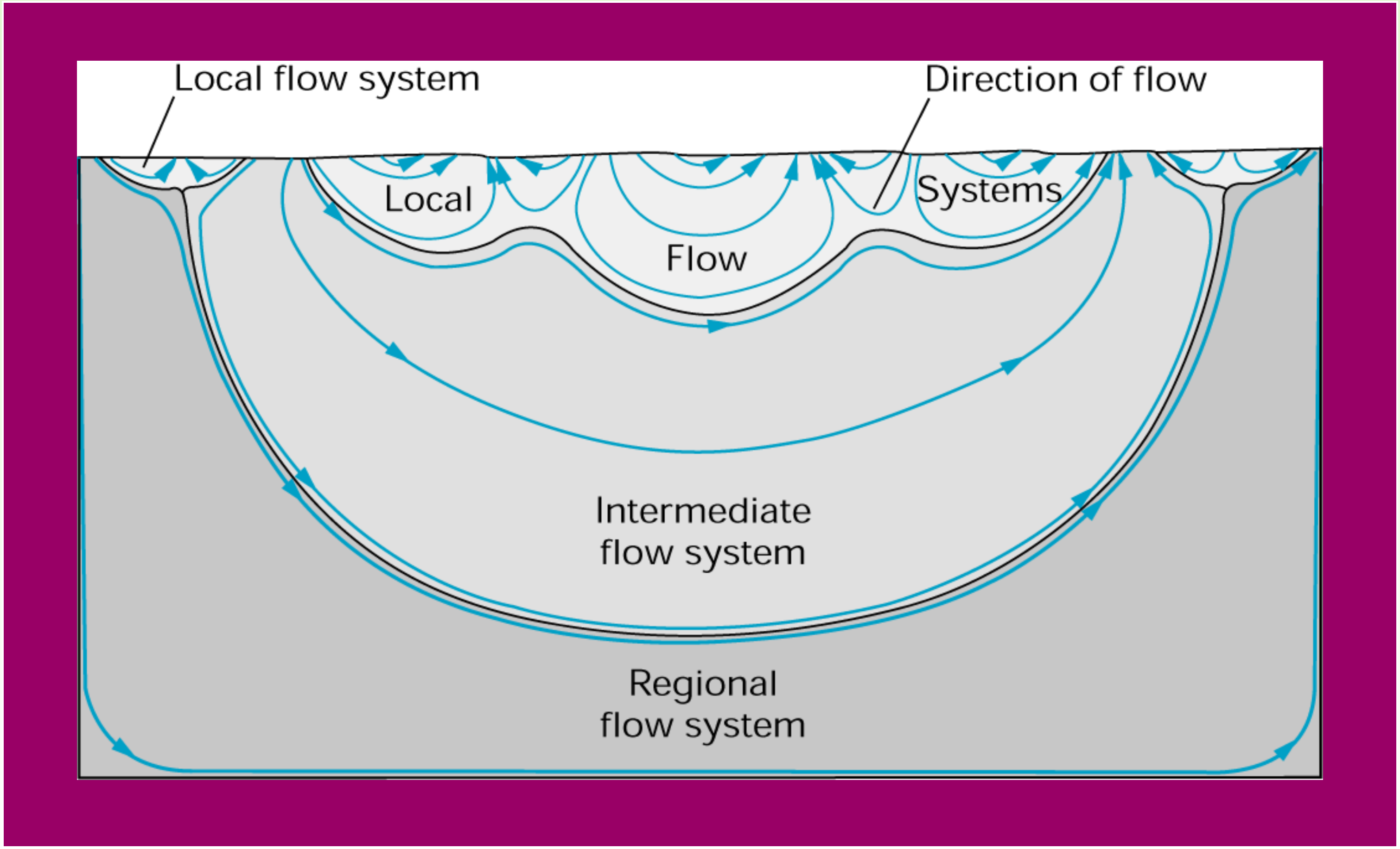
GW flow in cross section – piezometers indicate potential for flow



If the distribution of hydraulic head in vertical section is known from nested piezometer data, zones of downward, lateral, and upward components of ground-water flow can be determined. Although this also is fundamental knowledge to all hydrogeologists, we find that many have a difficult time grasping this concept and/or its implications.

Flow systems can be nested and much more complex

- The **scale** of the flow path or system and the **travel time** can be widely variable



You explored this earlier using Topodrive software.

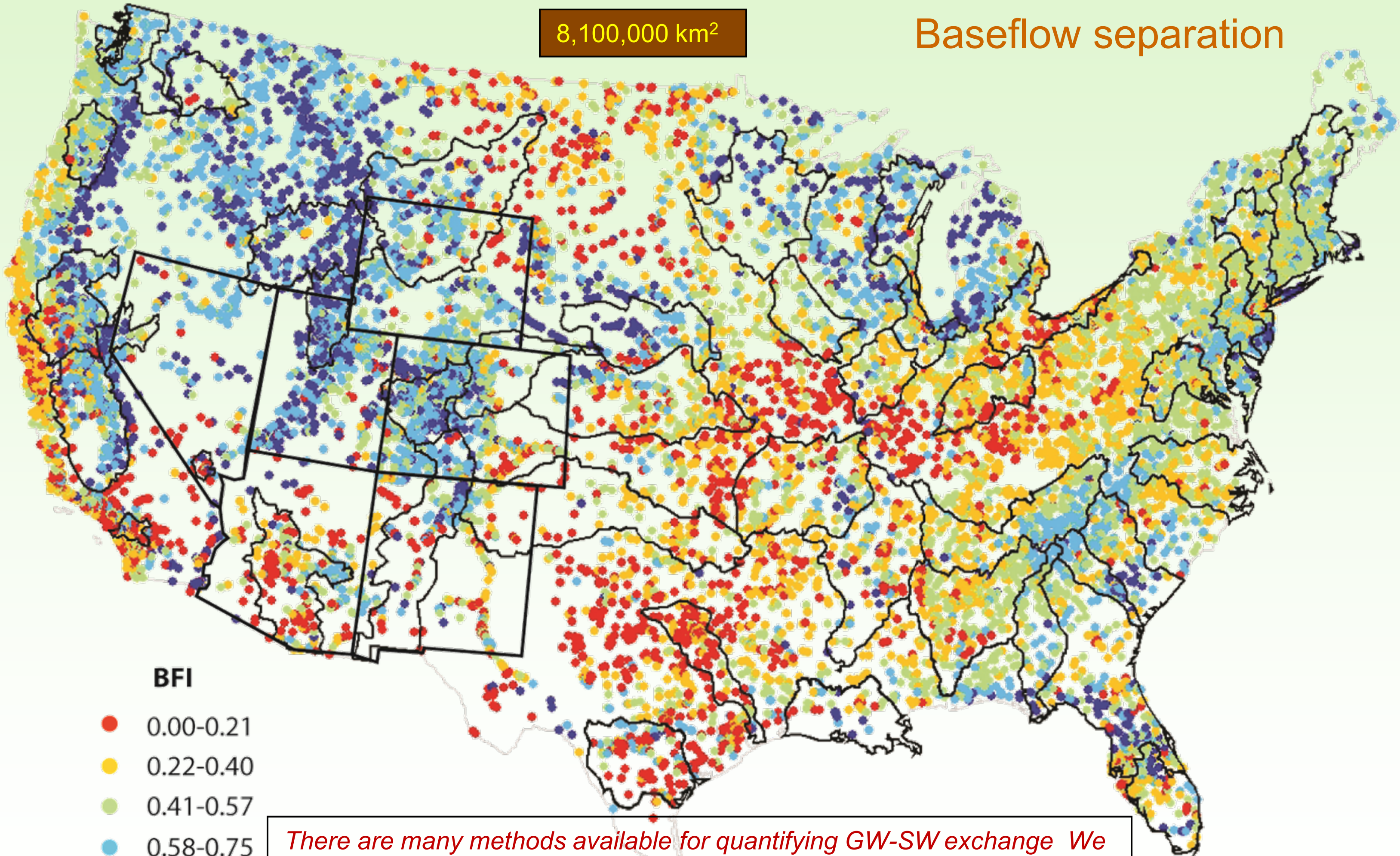
Toth, 1963, *J. Geophys. Res.*

Scales of interest

Nationwide scale (percent river flow as baseflow)

8,100,000 km²

Baseflow separation

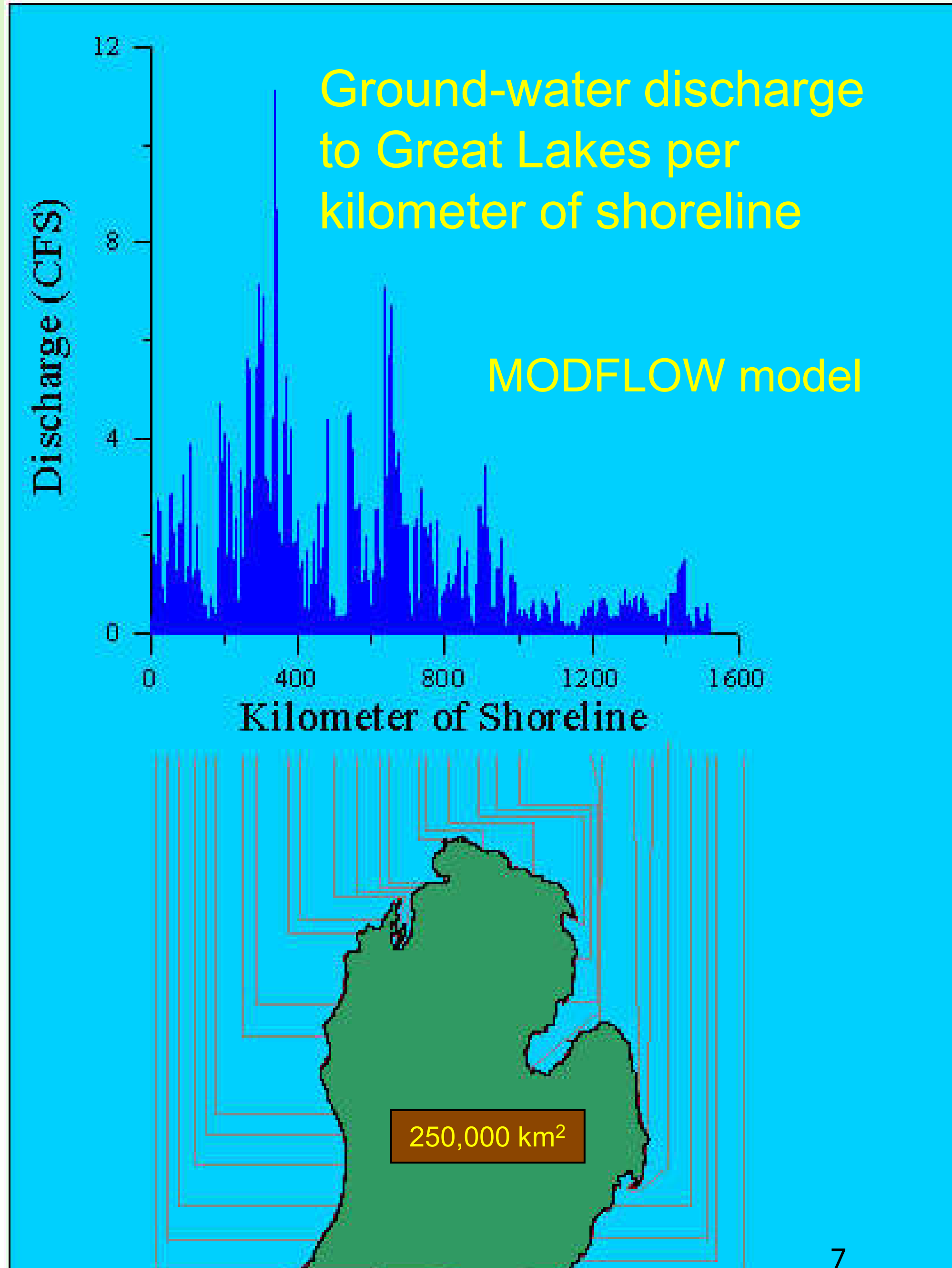


There are many methods available for quantifying GW-SW exchange We need to fit the method to the scale of the interest. Here, baseflow estimates provided values for GW contribution to streams across 8.1 million square kilometers.

Wolock, 2003, USGS OFR 03-146

Regional scale

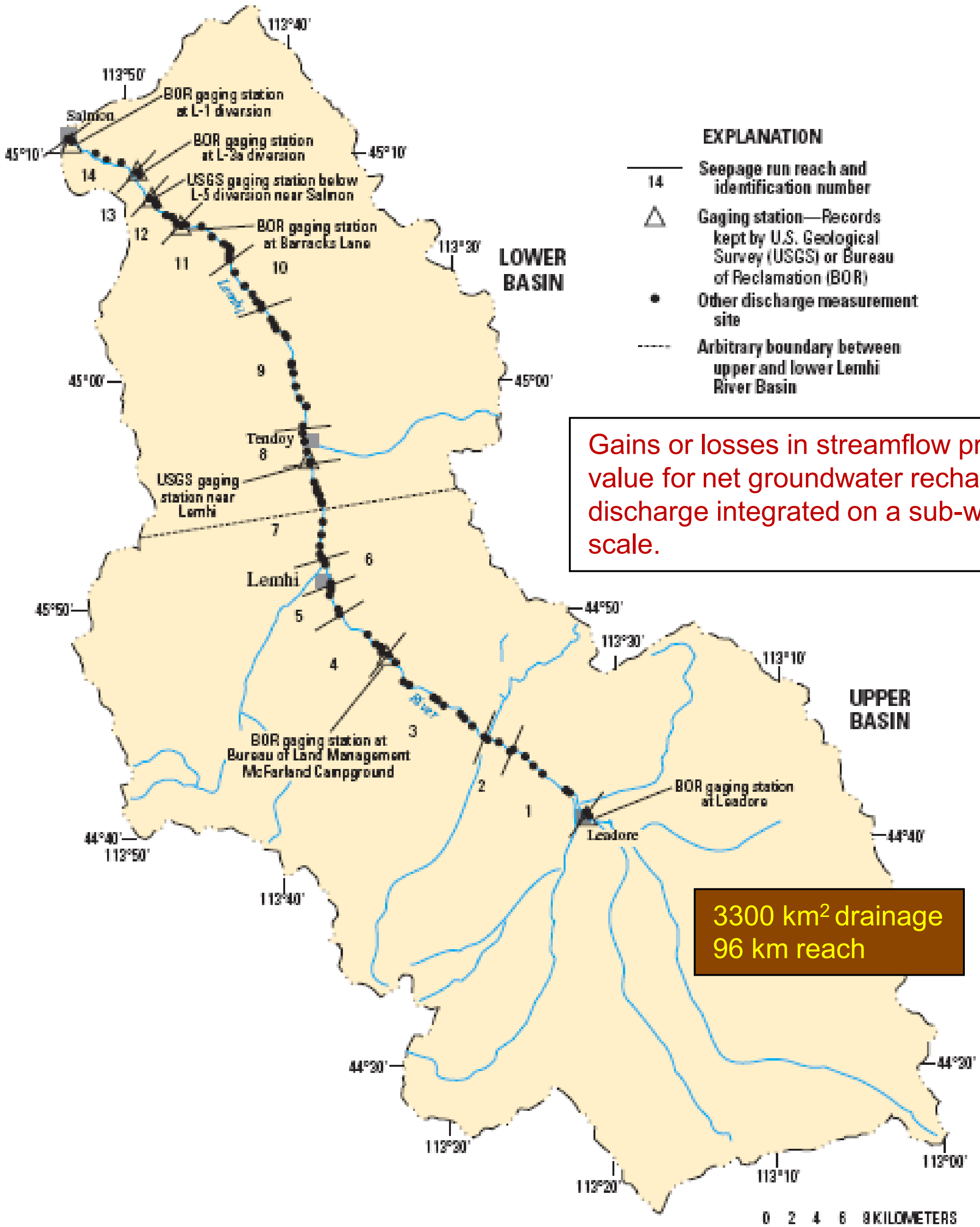
The groundwater-flow model MODFLOW was used to calculate distribution of discharge directly to the Great Lakes. The modeled area was 250,000 km².



Hoaglund et al., 2002, *Ground Water*

Watershed scale

Seepage run



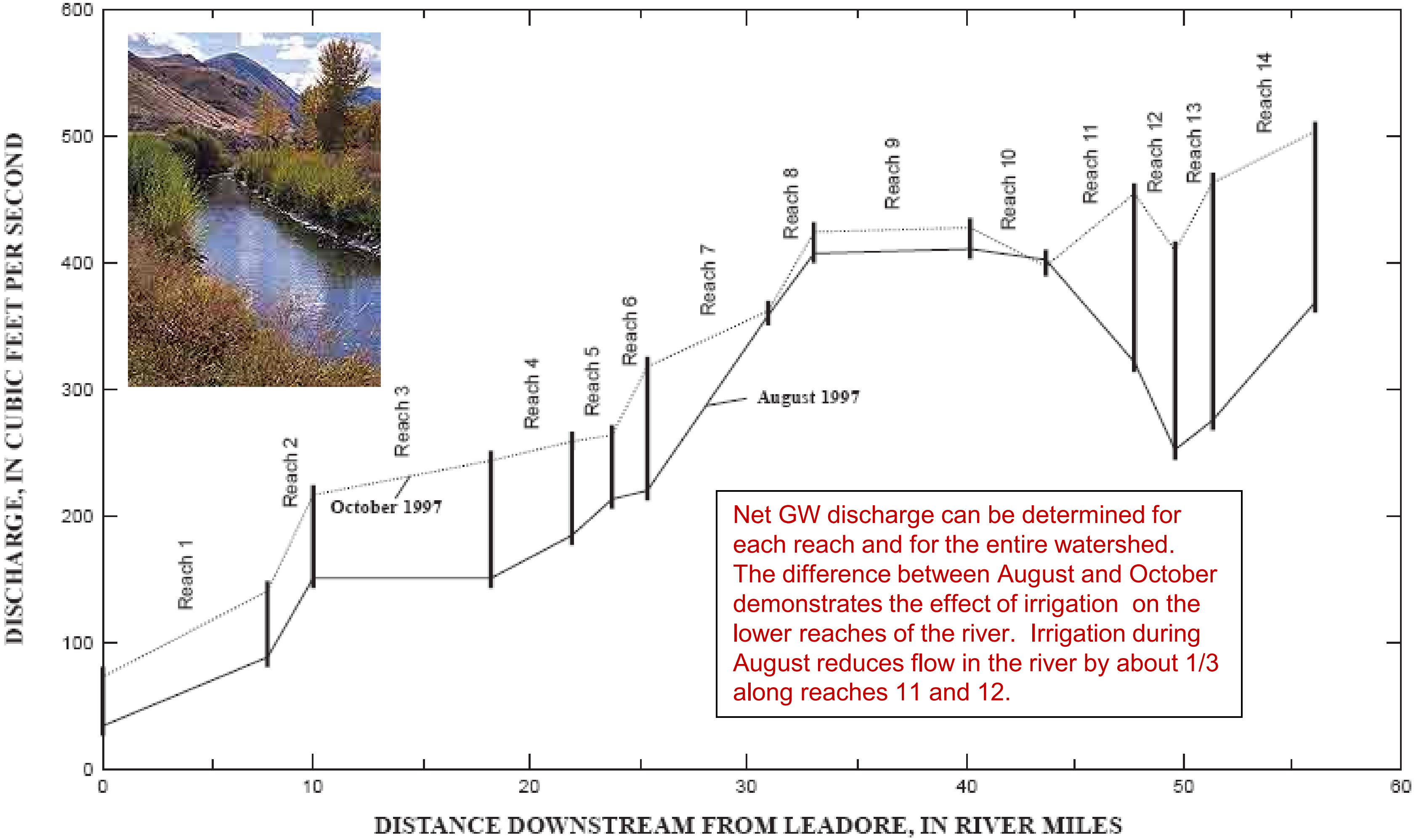
Gains or losses in streamflow provide a value for net groundwater recharge or discharge integrated on a sub-watershed scale.

3300 km^2 drainage
96 km reach

Donato, 1998, USGS WRIR 98–4185

Seepage run (“differential gaging”) to measure change in river discharge

More about this later when we discuss methods



Net GW discharge can be determined for each reach and for the entire watershed. The difference between August and October demonstrates the effect of irrigation on the lower reaches of the river. Irrigation during August reduces flow in the river by about 1/3 along reaches 11 and 12.

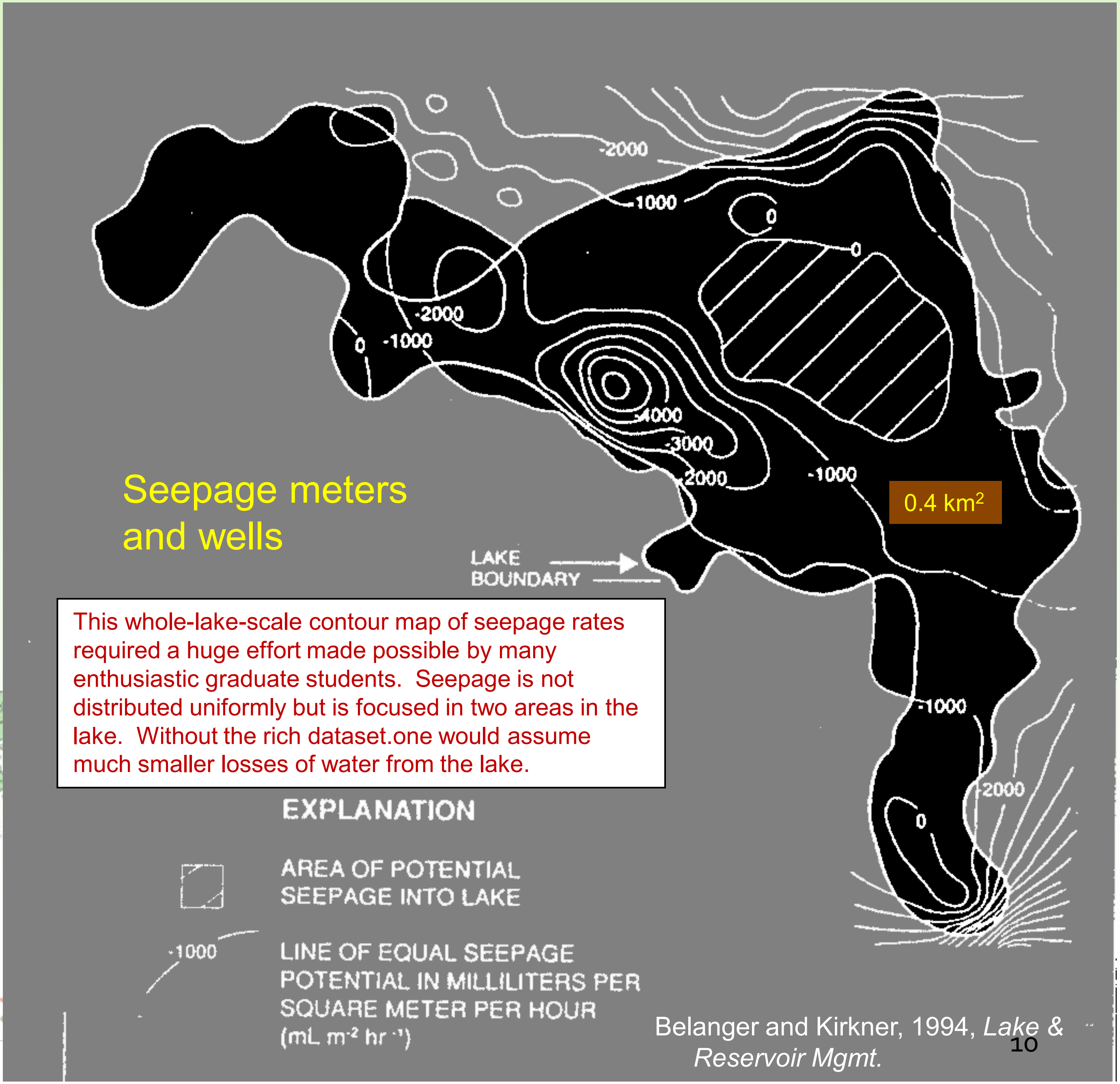
Lakebed scale

Karst

Mountain Lake, FL

Belanger and Kirkner 1994

very labor intensive



This whole-lake-scale contour map of seepage rates required a huge effort made possible by many enthusiastic graduate students. Seepage is not distributed uniformly but is focused in two areas in the lake. Without the rich dataset.one would assume much smaller losses of water from the lake.

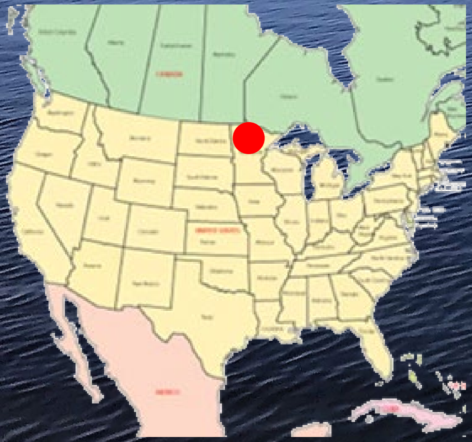
Belanger and Kirkner, 1994, *Lake & Reservoir Mgmt.*

Large-lake scale

$$G_i \pm \varepsilon = \frac{V\frac{\Delta C_w}{\Delta t} + (C_W - C_P)P + (C_W - C_{Si})S_i + (C_W - C_{Of})O_f + (C_{ET} - C_W)ET}{C_{Gi} - C_W} \quad (3.41)$$

From Rosenberry & Hayashi, 2013

1170 km^2



For large lakes, such as Red Lake in northern Minnesota, a water-budget or combined water and chemistry budget is a good option.

We are using a water-budget approach for the largest lake completely in Minnesota. Lake of the Woods, at 4350 km^2, is larger yet, but that lake is shared with Canada and a water budget would be much more complex.

Lakes can be challenging

Lake O'Hara, Alberta, Canada

Masaki gets to work in some ridiculously beautiful areas. His students and he used a water-budget approach to show that groundwater provided even more input to the lake than did snowmelt and streamflow.

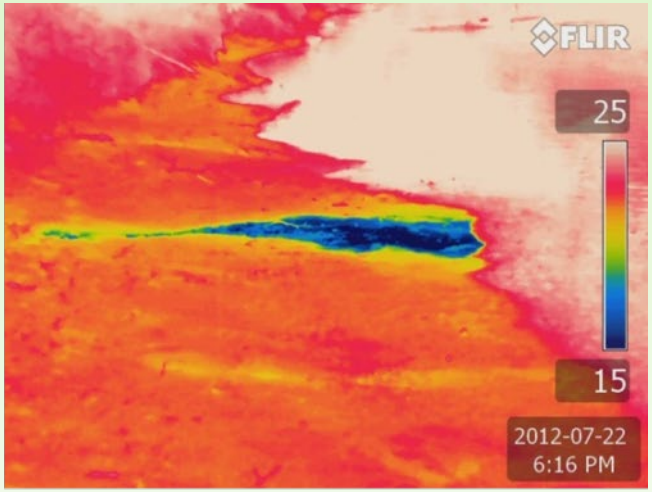
Hood et al., 2006, *Geophys. Res. Let.*

BWCA-Quetico, northern MN, southwestern Ontario

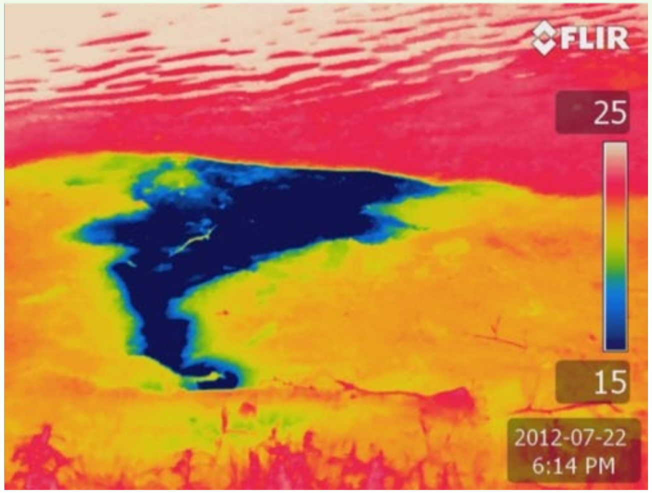
In fractured-rock settings, groundwater discharge often is distributed based on the distribution of networks of inter-connected fractures. But which fractures transmit water? Thermal infra-red often can be used to determine where to focus efforts. More on this on Day 4 in the measurement-method section.

FLIR thermal camera – a great reconnaissance tool

Upper Delaware River



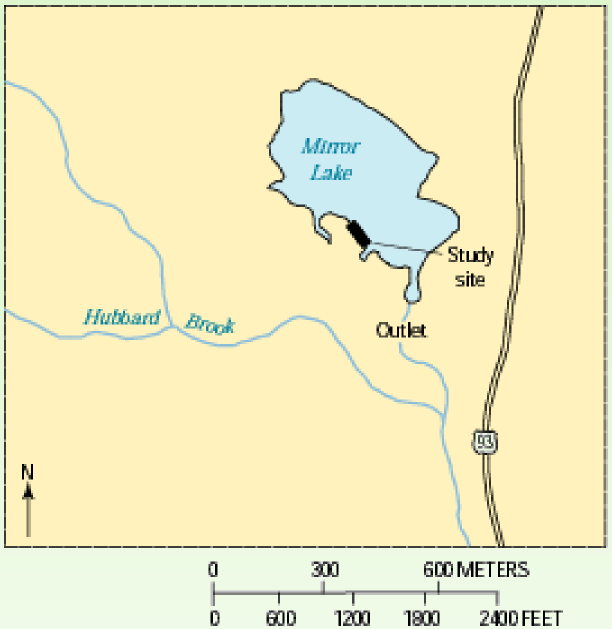
Here is a tool that helps us find areas of focused GW discharge on a local scale. We will talk more about this method when we cover methods of measurement.



Briggs et al., 2013, *ES&T*

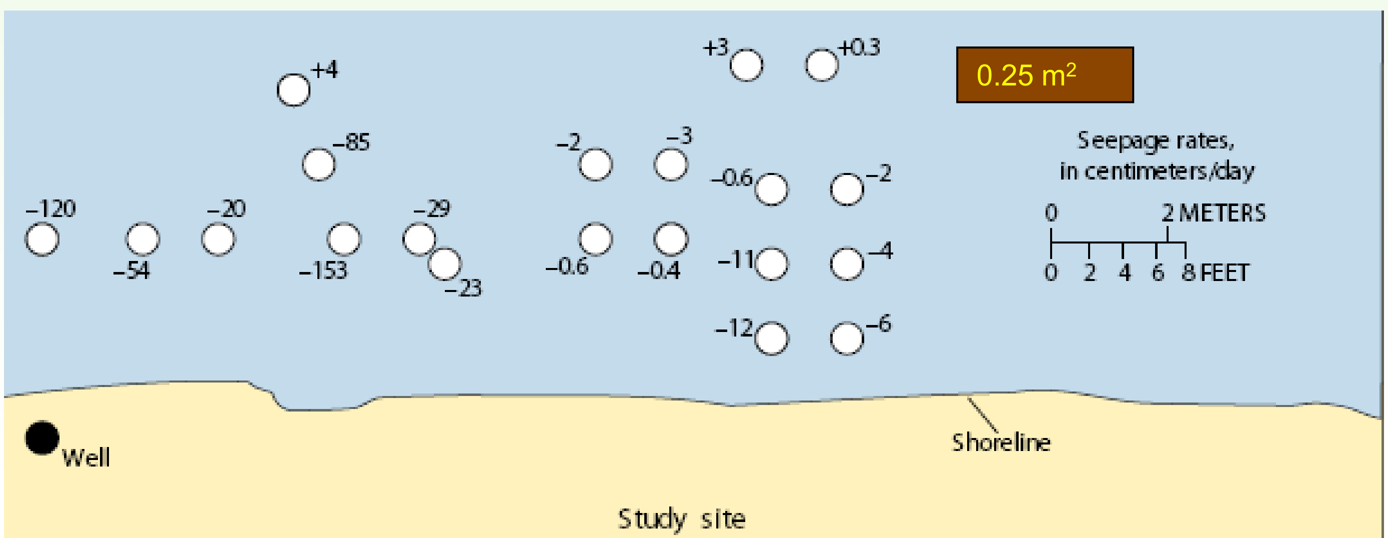
Local scale

Seepage meters



Flow on a one to several meters scale can be obtained with a dense network of seepage meters. Each seepage-meter measurement integrates seepage flow over about 0.25 m of the sediment-water interface.

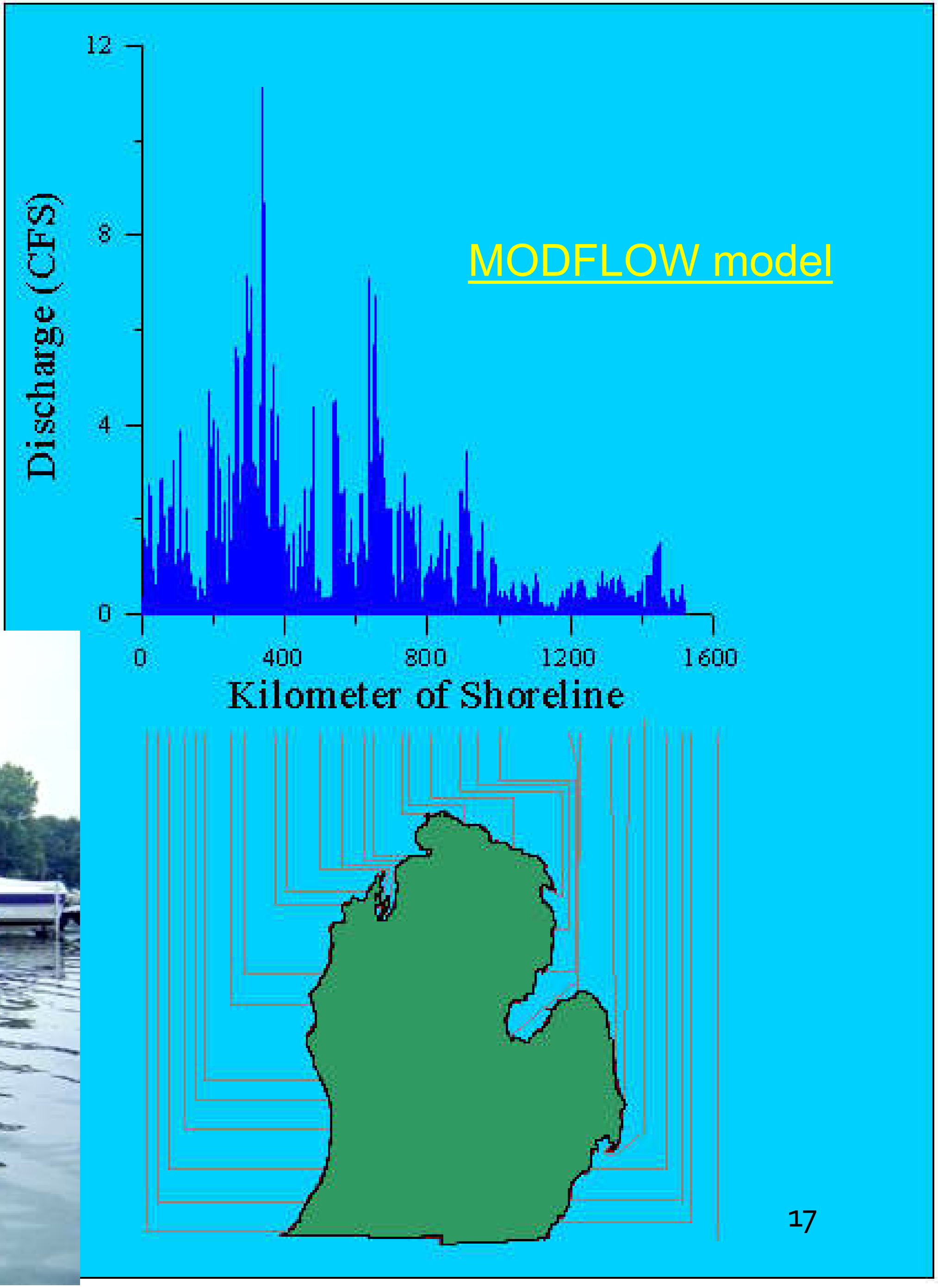
Mirror Lake, NH



Rosenberry, 2005, *L&O-Methods*

Need to scale measurements and methods to match the scale of concern

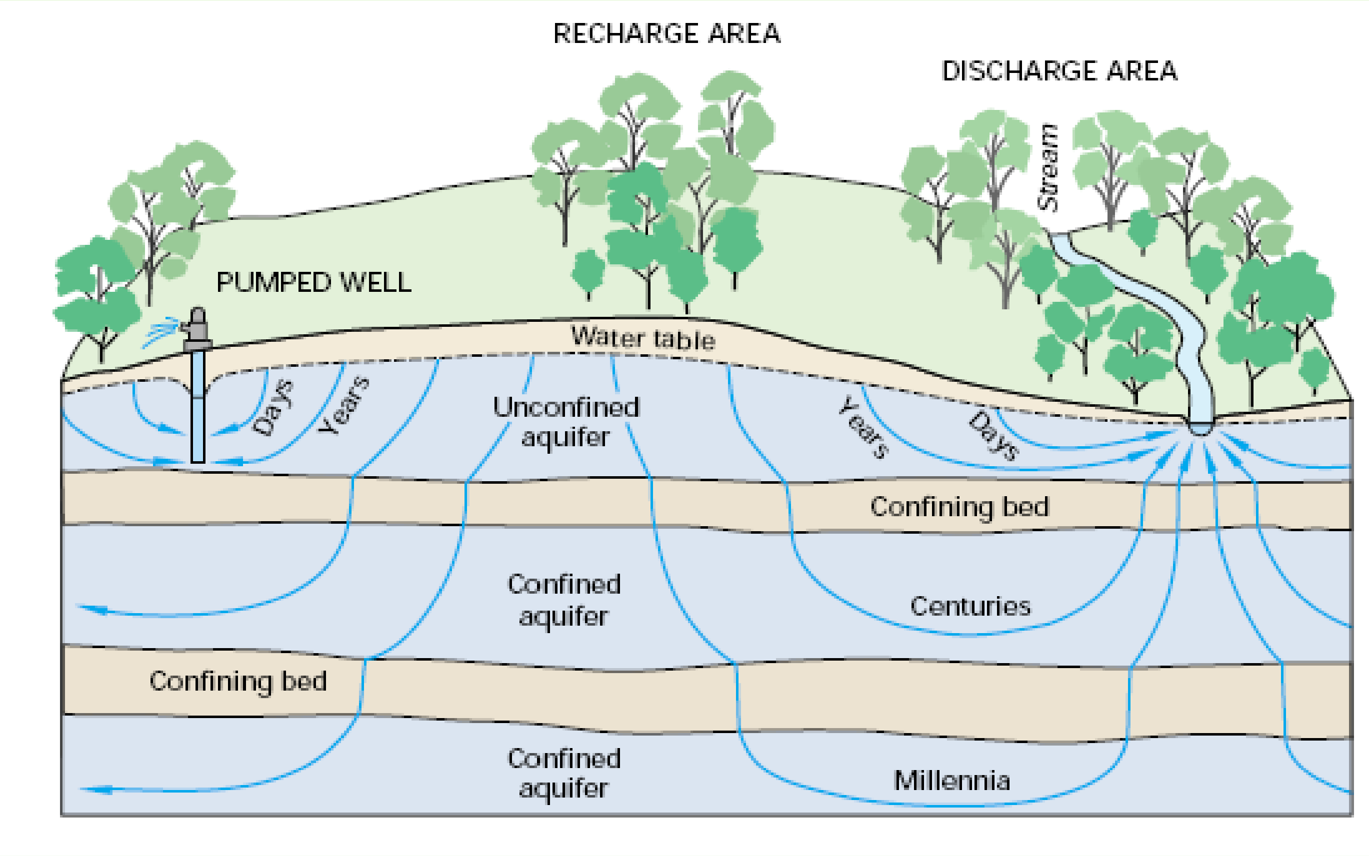
You would not want to use seepage meters, for example, to quantify groundwater discharge to the Great Lakes surrounding Michigan.



Scale and residence time

Variability of flowpath length and age of GW discharge

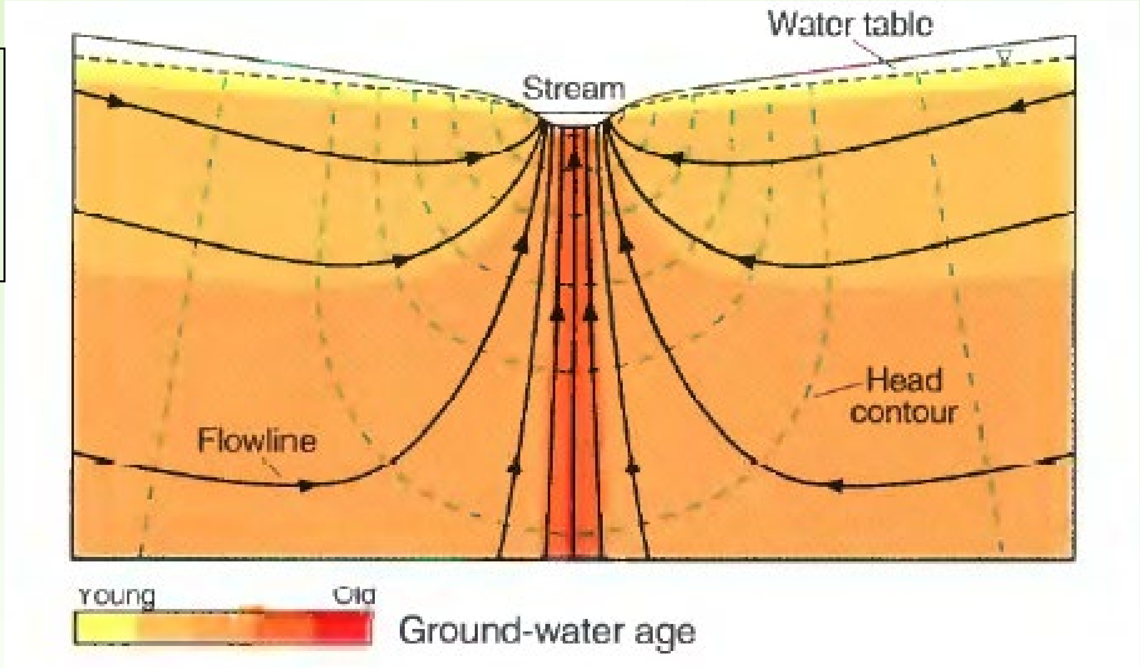
This drawing, from Figure 4 in Winter et al., 1998, is one often shown in talks. It nicely displays the scales and range of residence time (the time required for water to flow from where it first becomes groundwater to where it dischages to surface water). Residence time is not the same as the age of the water. It is simply the total distance of a groundwater flow path divided by the average velocity of flow along that flow path. However, as Masaki pointed out earlier, water in any given volume of groundwater is a mixture and the average age could be substantially younger or older.



Ground-water flowpaths vary in length, depth, and travel time from points of recharge to points of discharge

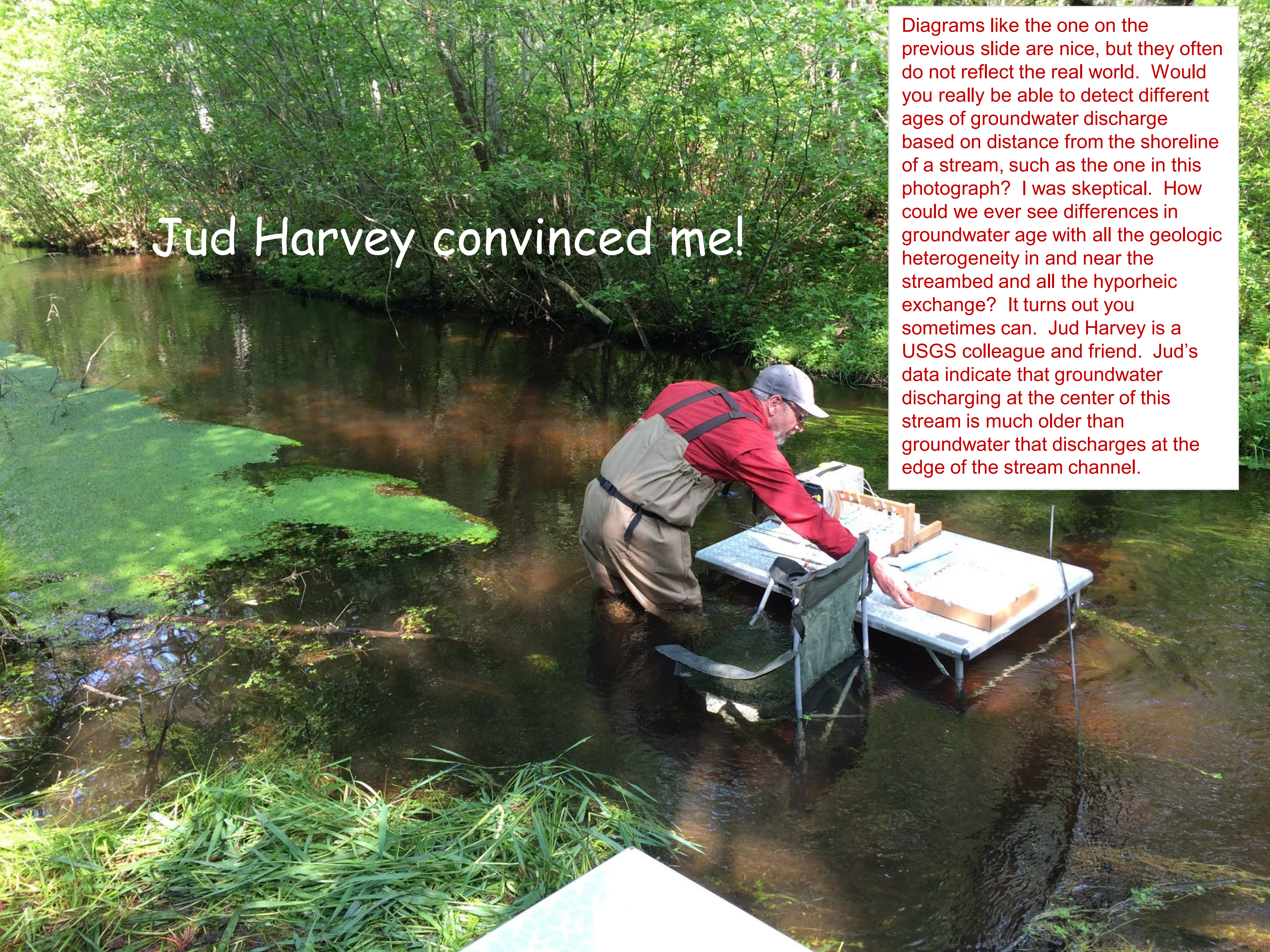
The Age of Ground-Water Discharge to a Stream Channel Can Vary Widely

These are nice drawings but, given all the heterogeneity in the world, could this actually be measurable?



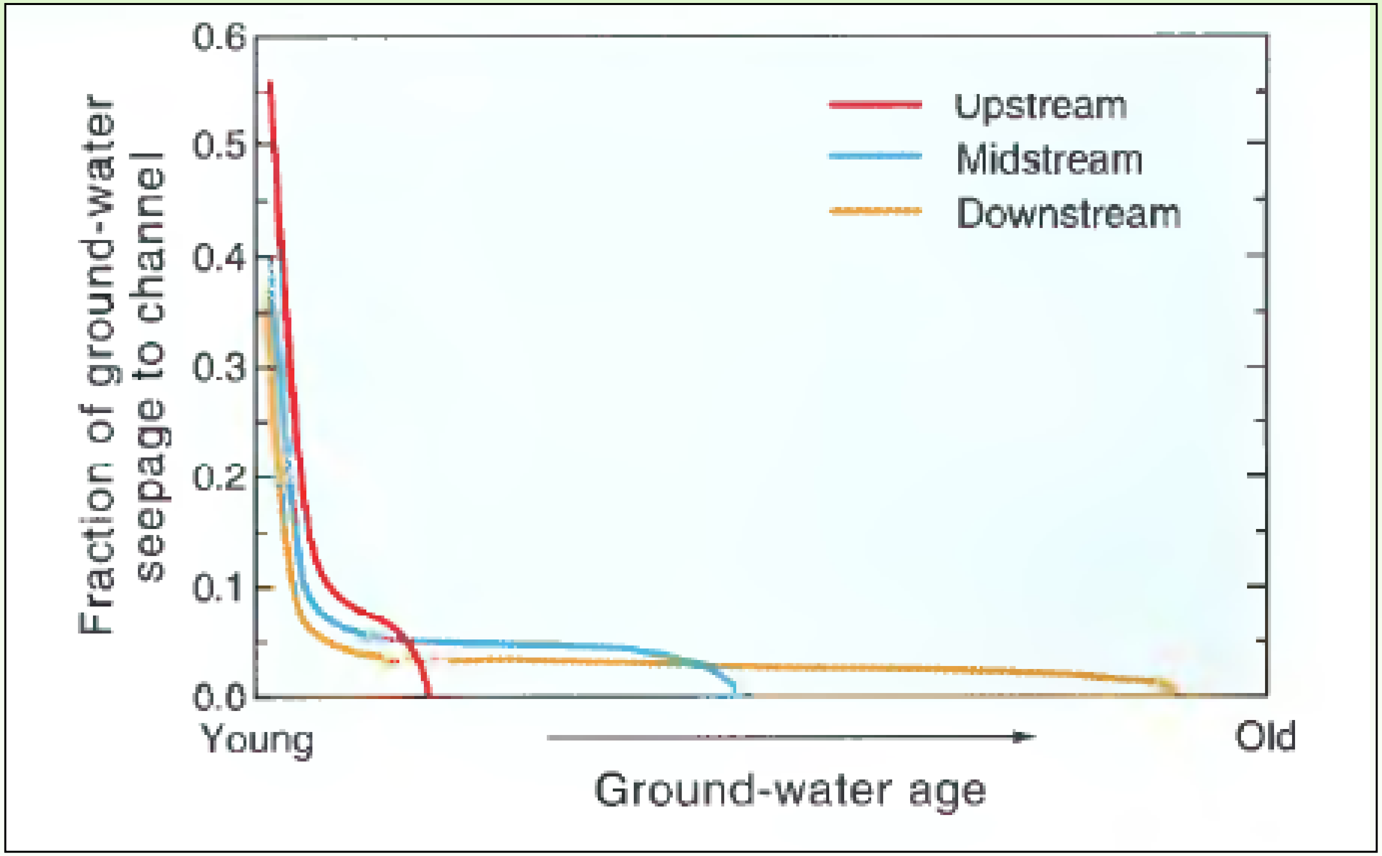
Local sources of ground water discharge near streambanks and are relatively young; regional sources of ground water discharge to the center of the stream channel and are relatively old.

Modica, 1999, *USGS Fact Sheet*



Diagrams like the one on the previous slide are nice, but they often do not reflect the real world. Would you really be able to detect different ages of groundwater discharge based on distance from the shoreline of a stream, such as the one in this photograph? I was skeptical. How could we ever see differences in groundwater age with all the geologic heterogeneity in and near the streambed and all the hyporheic exchange? It turns out you sometimes can. Jud Harvey is a USGS colleague and friend. Jud's data indicate that groundwater discharging at the center of this stream is much older than groundwater that discharges at the edge of the stream channel.

Ground-Water Discharge Becomes Increasingly Older with Distance Downstream



Groundwater that discharges farther downstream commonly is older (but not always) because the contributing area is getting larger with distance downstream, providing the opportunity for longer flowpaths and longer travel times.

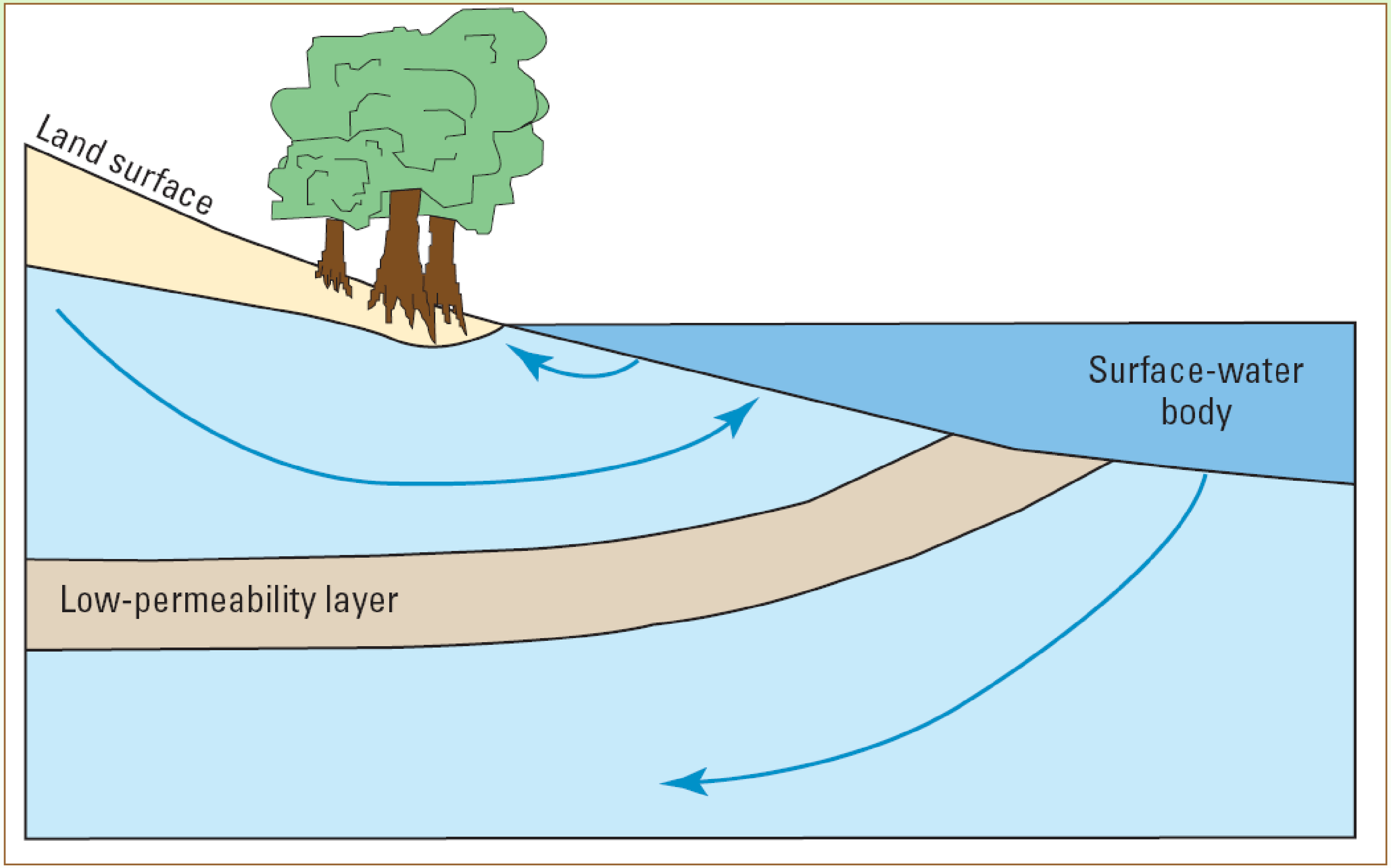
Modica, 1999, *USGS Fact Sheet, Modica et. al, 1997*

Heterogeneity

- Interlayering of sand and organics
- Logs and rocks
- Trapped gas
- Vegetation zones
- Stage changes – shoreline movements
- Anthropogenic effects (veg. removal, beaches, prop wash)
- Stream meanders

Heterogeneity is one of the largest problems for measurement and interpretation of flows between ground water and surface water. Because of the numerous processes that occur in these areas, heterogeneity often is even larger at the interface between groundwater and surface water than in other aquifer environments. Sometimes you can actually see it.

Near-shore processes + geological variability



Here we show heterogeneity due to multiple influences. There certainly is not an exponential decrease in seepage with distance from shore here! Surface water is flowing to groundwater near the shoreline because water removal caused by evapotranspiration (ET) has pulled down the water table. Groundwater is discharging to surface water beyond the local influence of ET. Farther from shore, beyond a low-permeability layer that isolates different portions of presumably higher-K sediments, a drain somewhere beyond the view shown here is resulting in surface water flowing into the aquifer.

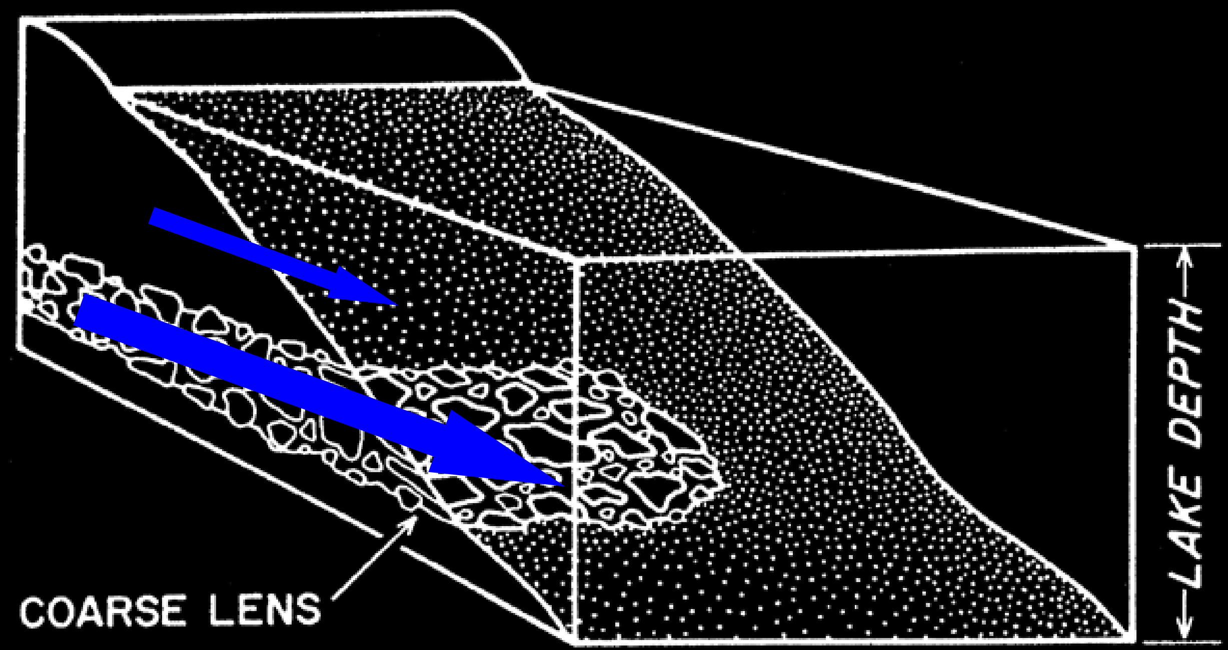


Fig. 5. Three-dimensional schematic drawing of the hypothesized situation at Trout Lake showing a coarse lens intersecting the lakebed.

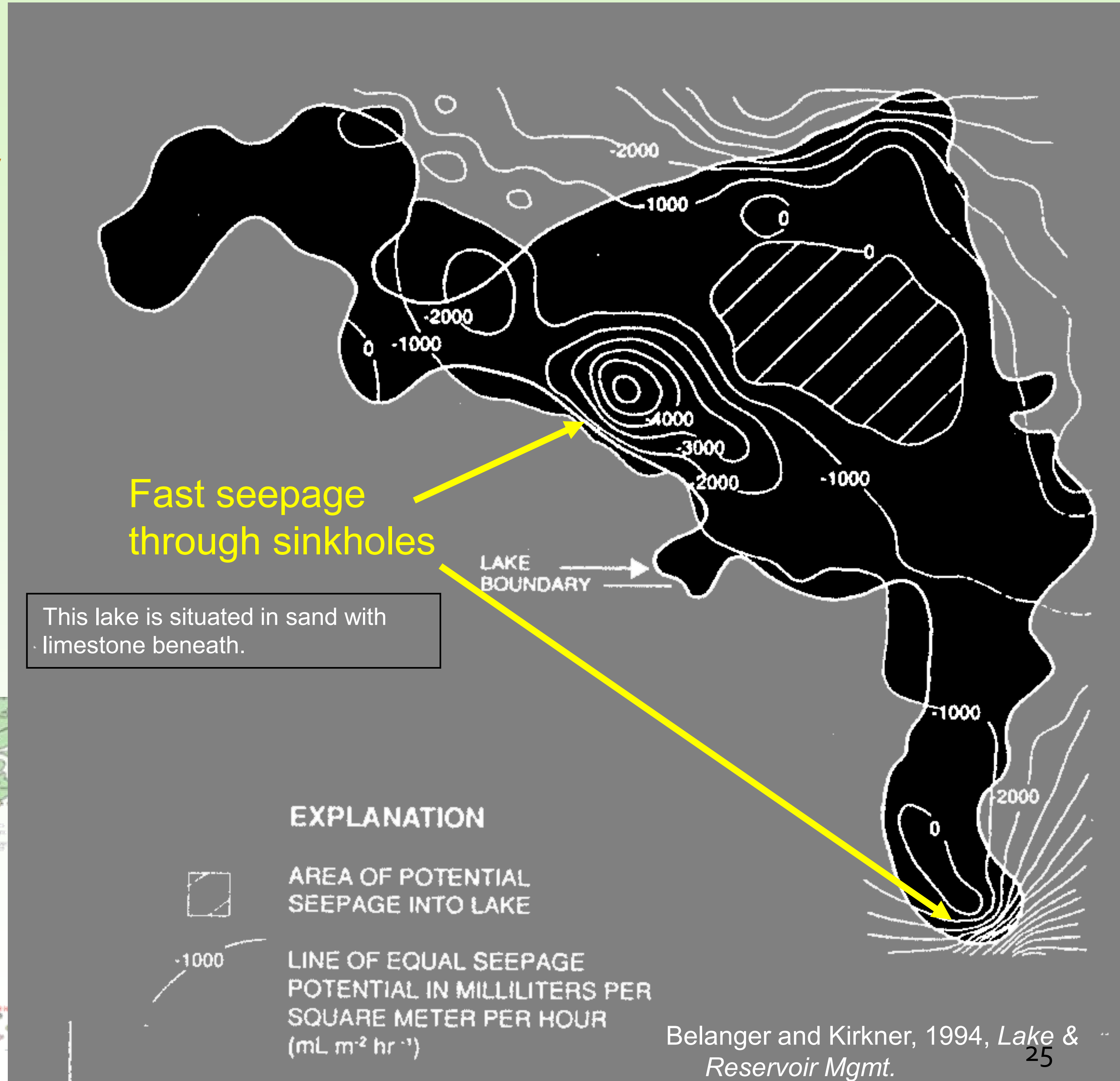
This was a nice example from the literature that indicated a gravel lens was transmitting a much larger volume of seepage to the lake than were the surrounding sandy sediments.

Krabbenhoft and Anderson, 1986, *Ground Water*

Geologic controls on heterogeneity

Mountain Lake, FL

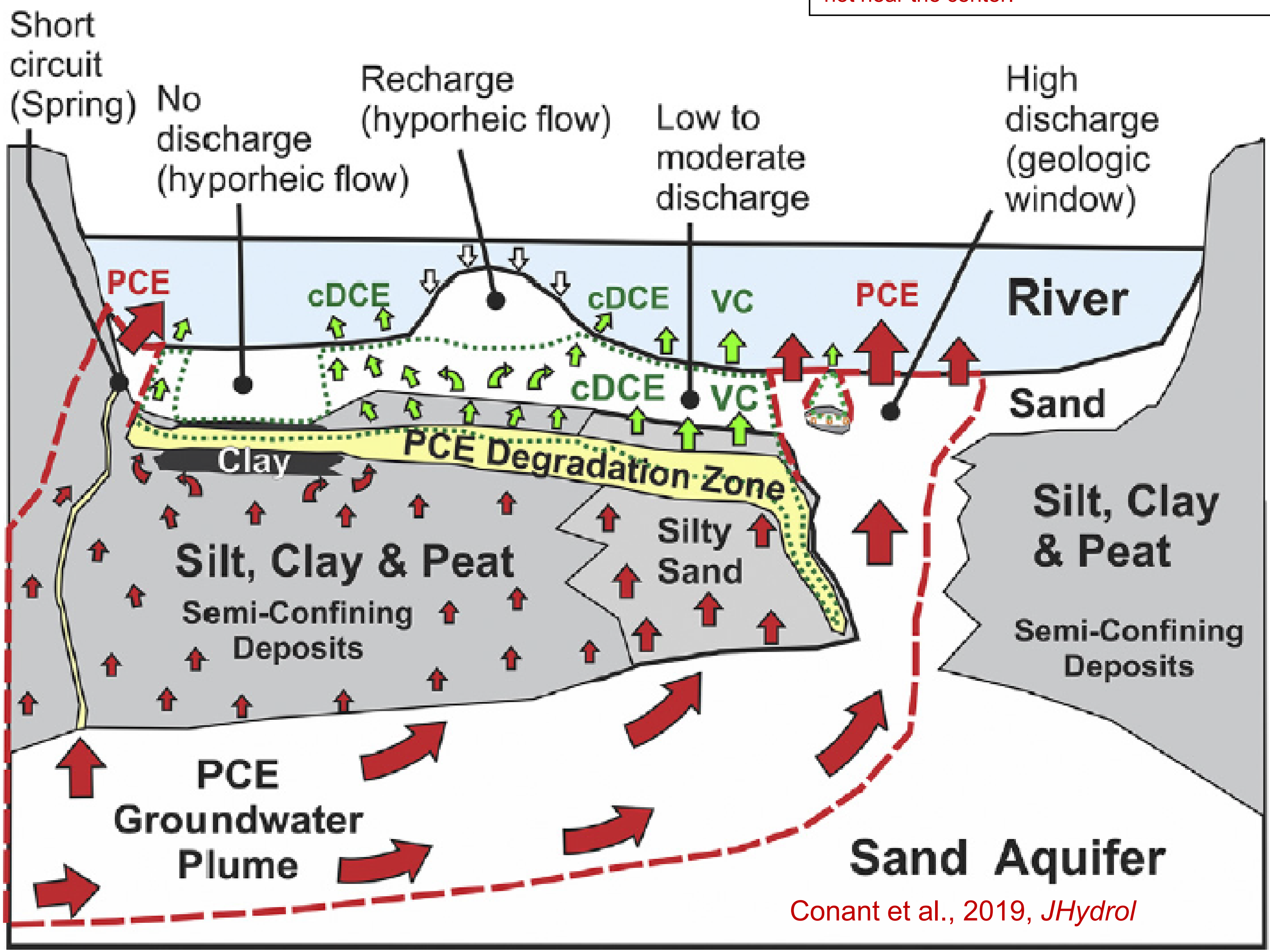
They used seepage meters to show this heterogeneity. This represented a large amount of work. Was that scale-appropriate?



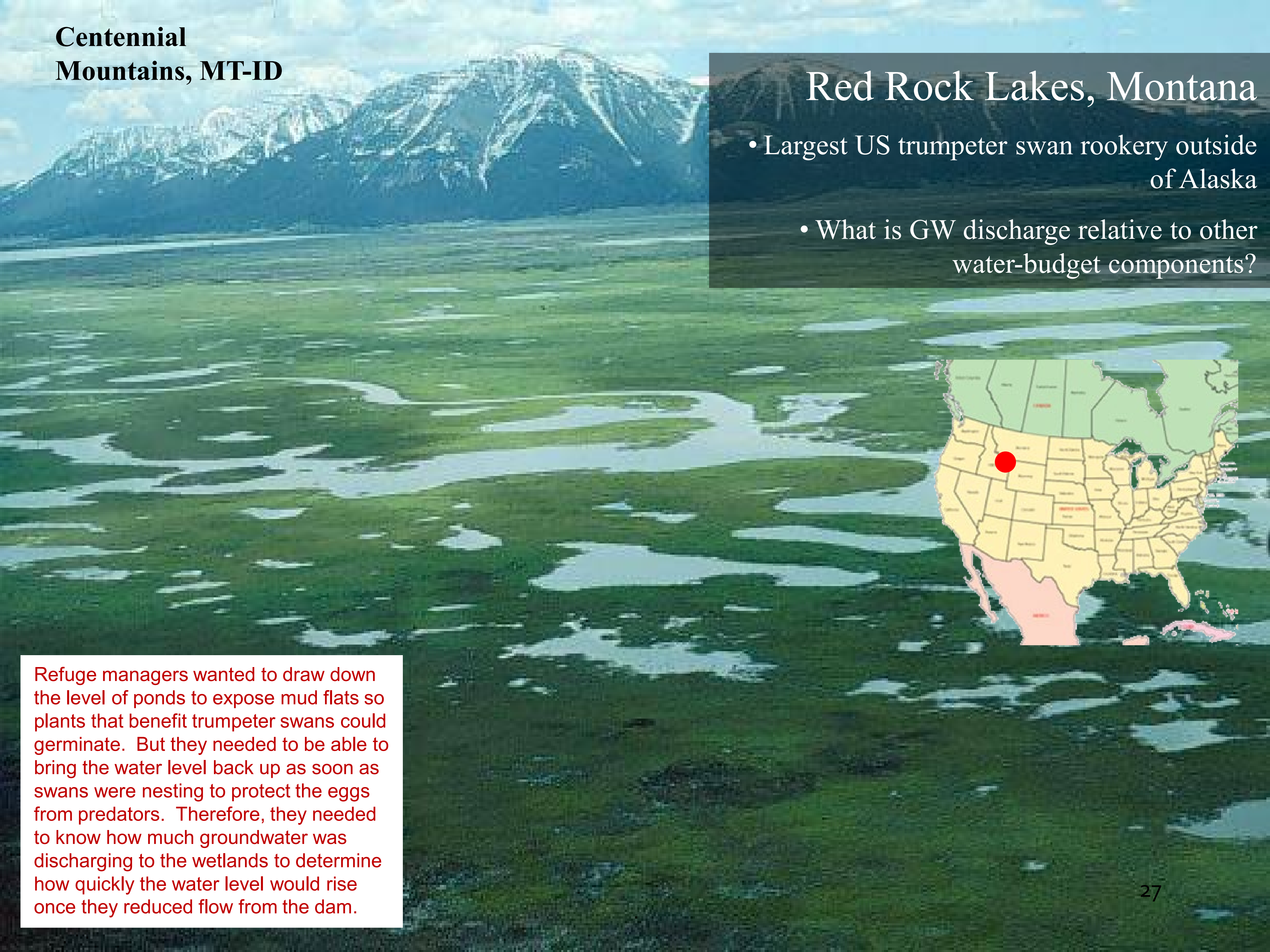
Belanger and Kirkner, 1994, *Lake & Reservoir Mgmt.*

"Geology trumps topography"

If we didn't know the geology we would think most of the GW discharge would be at the edges of the river, not near the center.



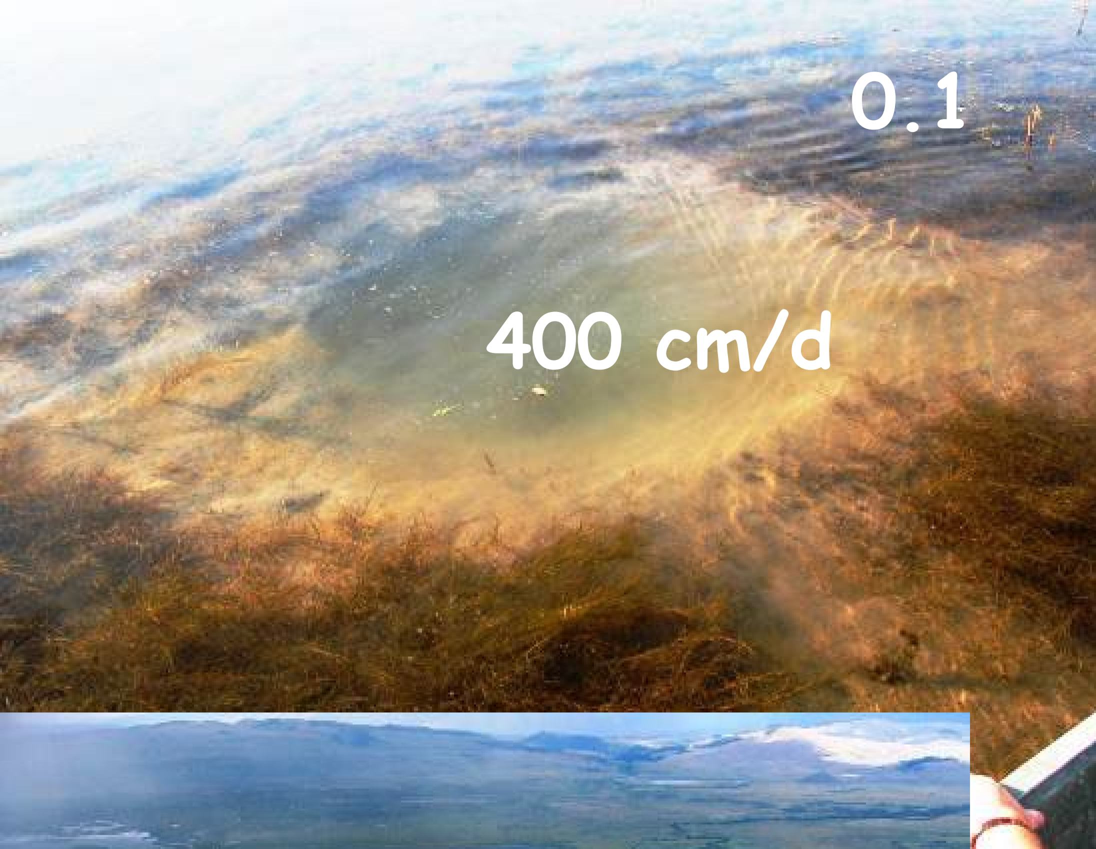
Conant et al., 2019, *JHydrol*

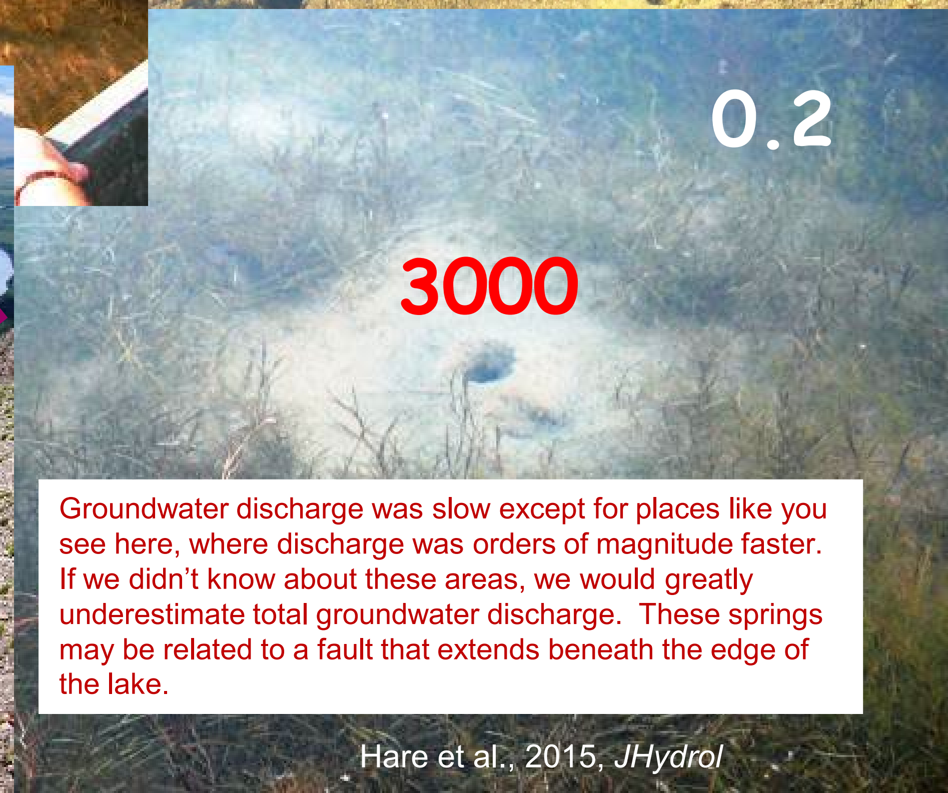


Red Rock Lakes, Montana

- Largest US trumpeter swan rookery outside of Alaska
- What is GW discharge relative to other water-budget components?

Refuge managers wanted to draw down the level of ponds to expose mud flats so plants that benefit trumpeter swans could germinate. But they needed to be able to bring the water level back up as soon as swans were nesting to protect the eggs from predators. Therefore, they needed to know how much groundwater was discharging to the wetlands to determine how quickly the water level would rise once they reduced flow from the dam.





Groundwater discharge was slow except for places like you see here, where discharge was orders of magnitude faster. If we didn't know about these areas, we would greatly underestimate total groundwater discharge. These springs may be related to a fault that extends beneath the edge of the lake.

Hare et al., 2015, *JHydrol*

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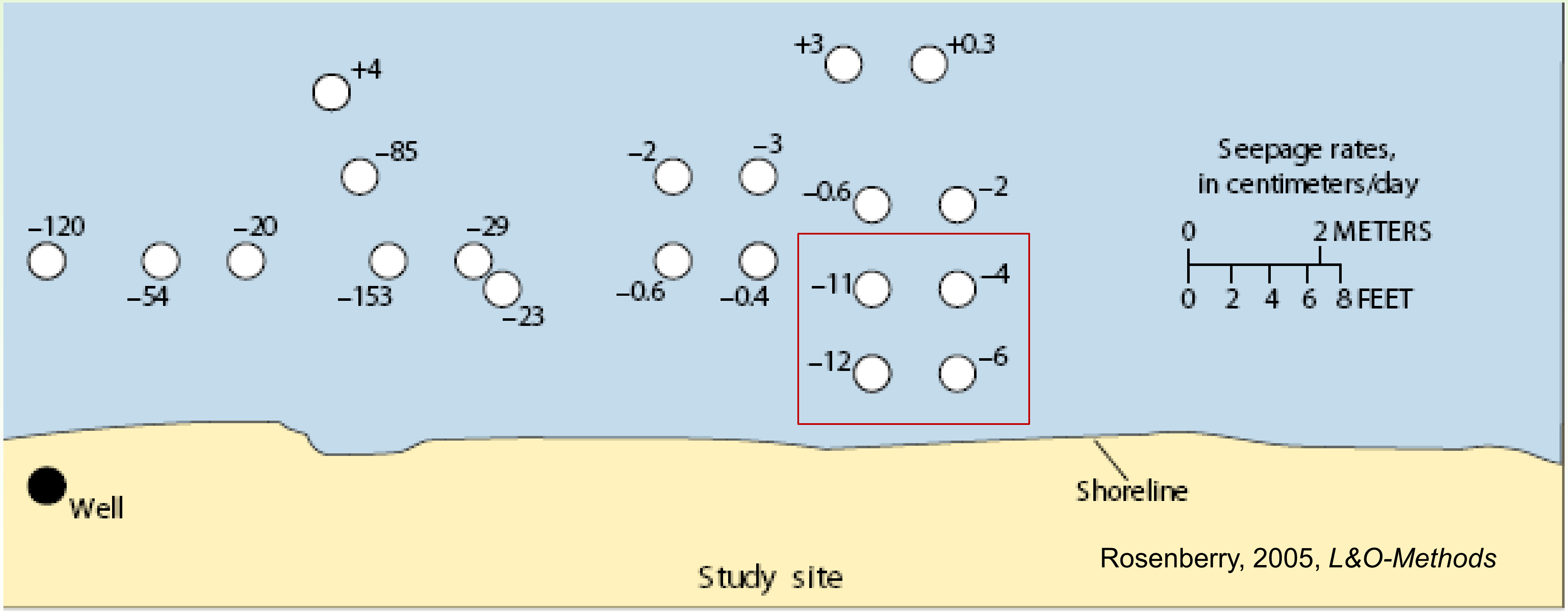
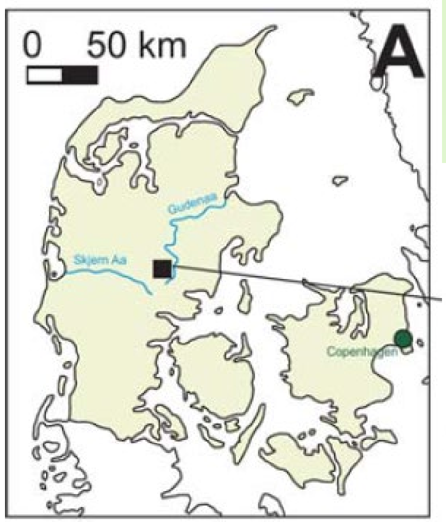
Mirror Lake, NH, USA – GW seepage distribution varies greatly on a local scale



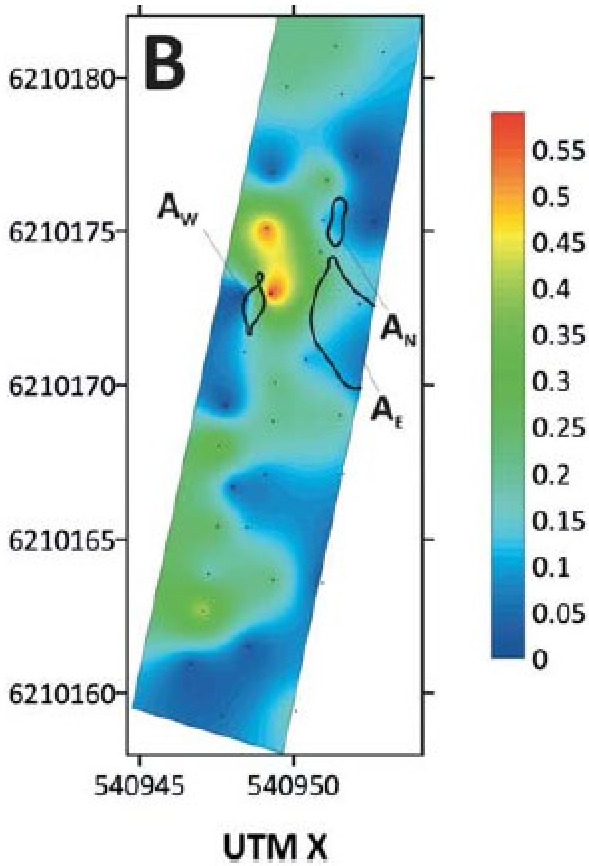
Rosenberry, 2005, *L&O-Methods*

The four meters to the southeast indicate seepage ranges from -4 to -12 cm/day (negative means flow from the lake to groundwater). But if you walk 15 meters along the shoreline to the northwest, seepage is much faster, up to -153 cm/day. And look at the positive values farther from shore. This complexity will be explained in greater detail in a subsequent lecture.

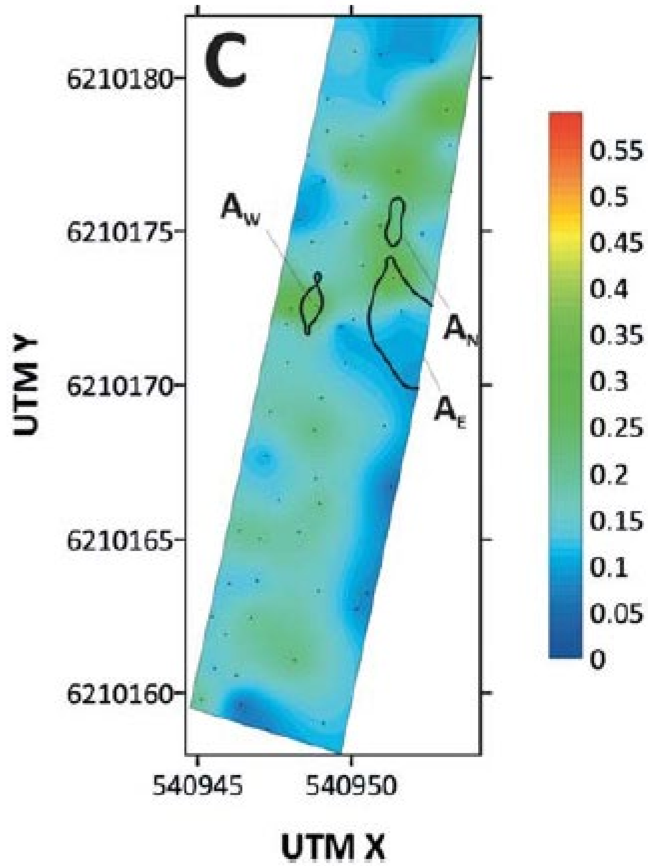
LAKE VÆNG



Heterogeneity in GW-SW exchange is very common in lakebeds and streambeds. Here is another example, this one from a lake in Denmark, where the degree of heterogeneity is revealed differently depending on the measurement method. Seepage meters indicate discharge is focused in the yellow to orange areas. Based on bed-surface temperature means and standard deviations, Aw and An are likely to be GW discharge zones, but Ae is inconclusive based on temperature at the bed surface.



Seepage meters



Vertical temperature profiles

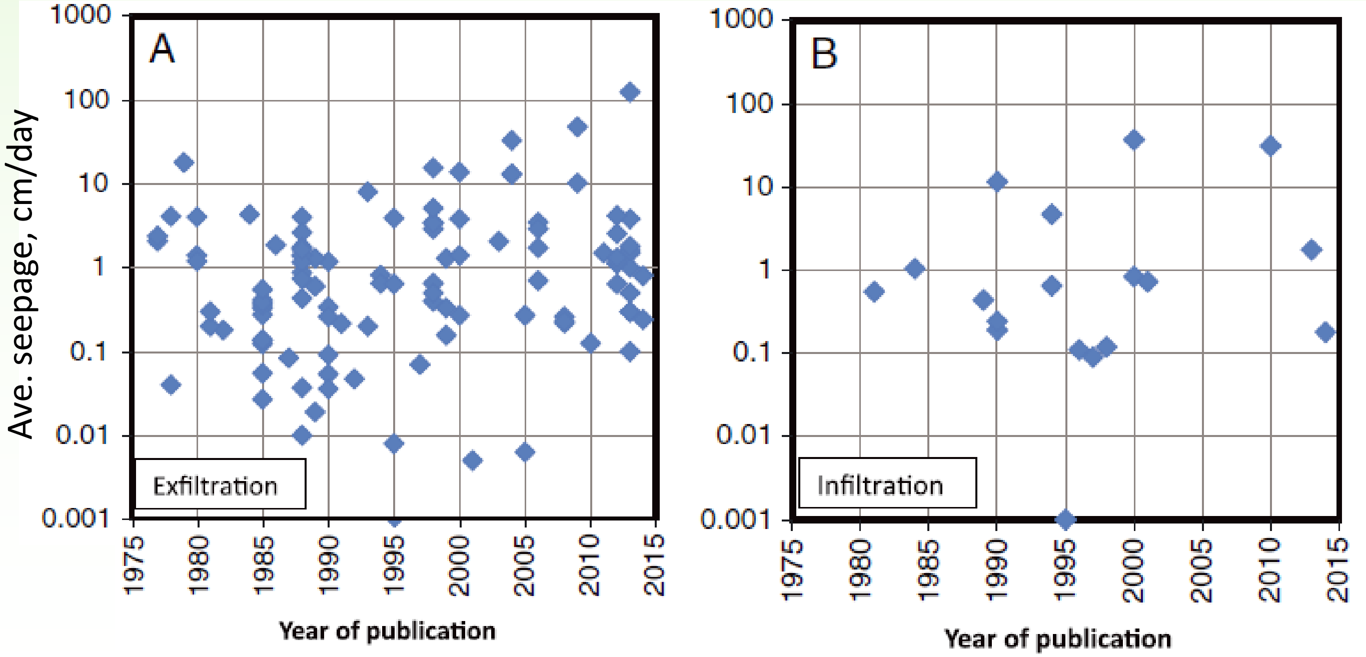
Sebok et al., 2013, *WRR*

What rates of exchange are common?

Table II. Seepage rates for upward seepage (exfiltration) and downward seepage (infiltration) at 108 lakes across the world

	Exfiltration average	Exfiltration maximum	Infiltration average	Infiltration maximum
Count	109	59	18	18
Minimum	0.005	0.019	0.001	0.15
25th percentile	0.23	0.76	0.18	0.92
Median	0.74	5.10	0.60	1.64
75th percentile	2.09	13.30	1.58	30.5
Maximum	124.1	745.0	37.0	263.0

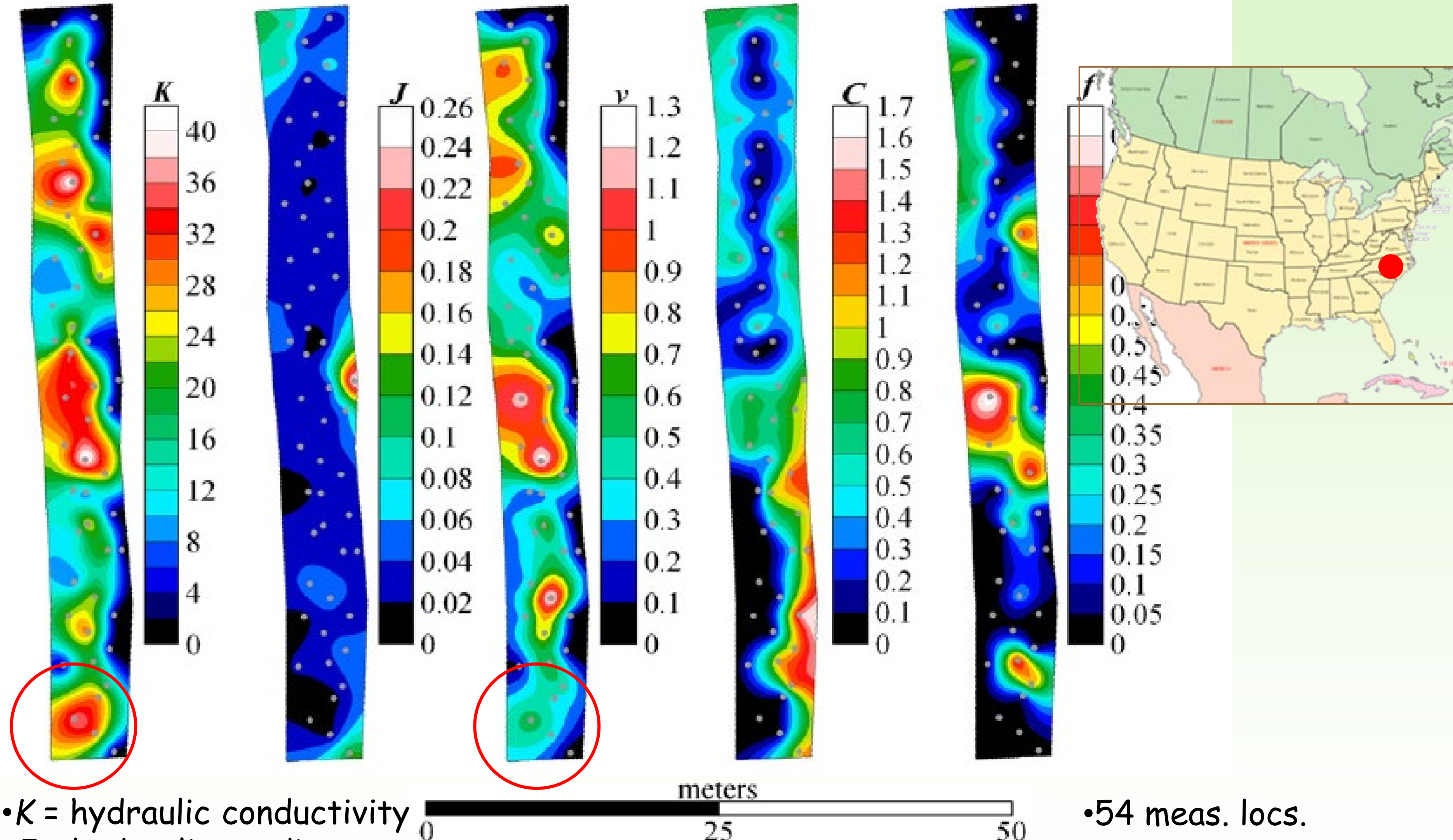
Data culled from the literature are average and maximum values reported for particular lakes. Values are in centimetres per day.



This study summarized seepage for lakes. Our best estimate is that values for hyporheic settings will be 1 to 2 orders of magnitude larger.

Rosenberry et al., 2015, *Hydrological Processes*

➢West Bear Creek, North Carolina

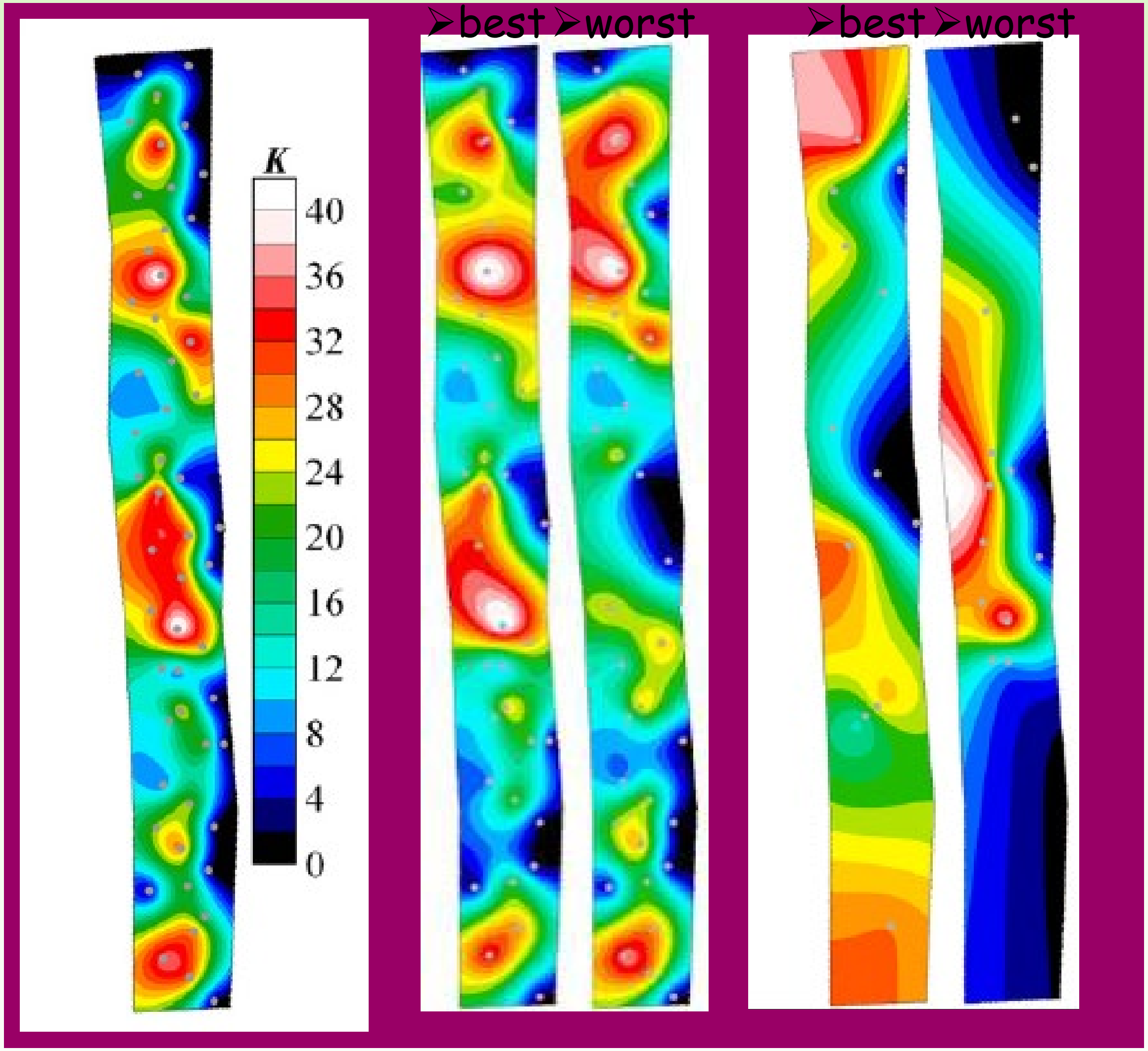


- *K* = hydraulic conductivity
- *J* = hydraulic gradient
- *v* = seepage velocity
- *C* = nitrate concentration
- *f* = nitrate seepage flux

A nice study showing complexity. Note that areas of large *K* do not always result in faster seepage or greater nutrient flux.

- 54 meas. locs.

Kennedy et al., 2008, *JHydrol.*
Genereux et al., 2008, *JHydrol.*



54 meas points
“true” meas.

36 meas points

12 meas points

Best and worst of 120 alternate maps based on random sub-sampling distrubutions

Our interpretation also is greatly influenced by the density of our measurements. If we made measurements at “only” 12 locations, we would not have enough information to indicate true conditions.

Kennedy et al., 2008, *Journal of Hydrology*

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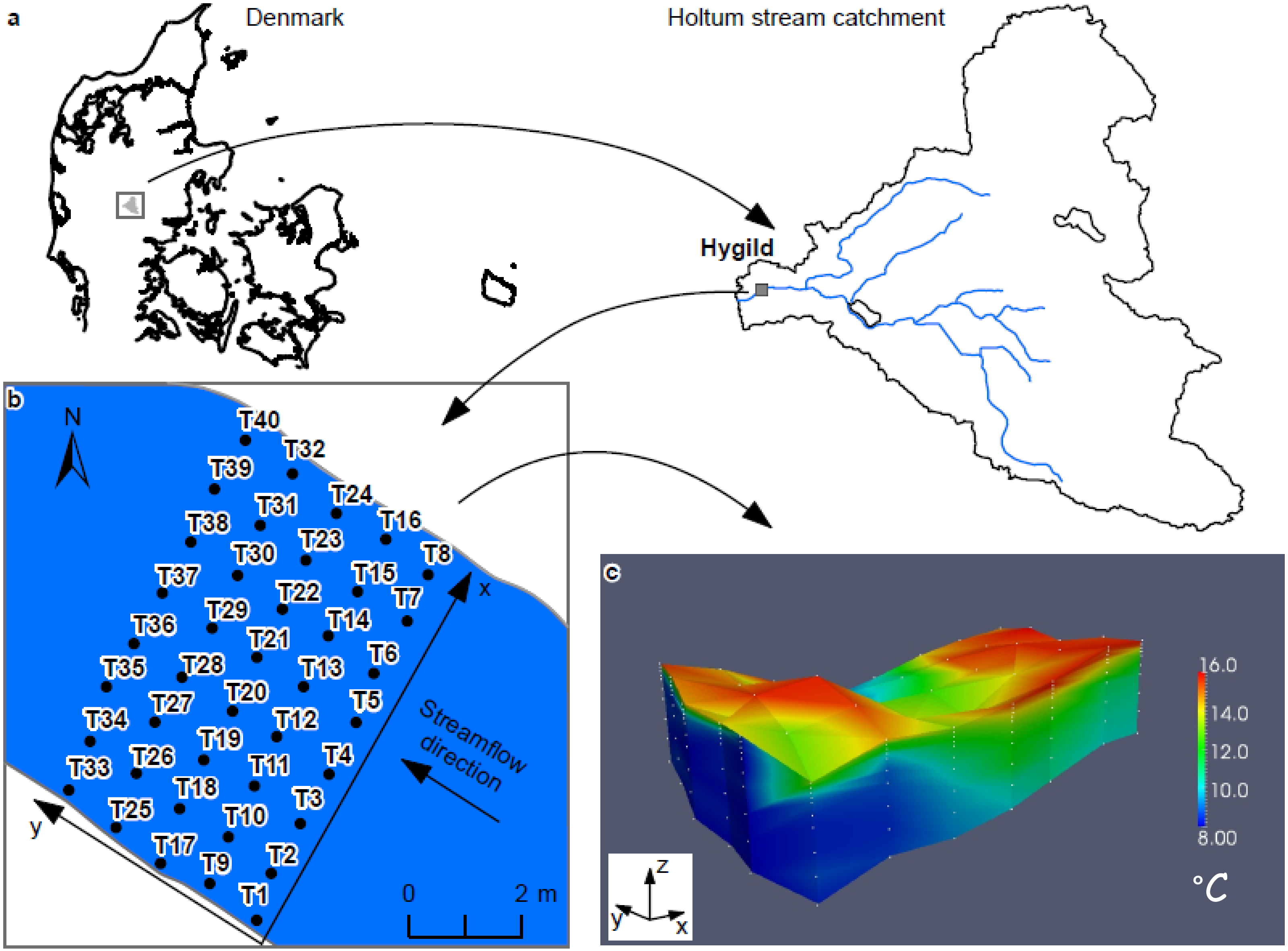
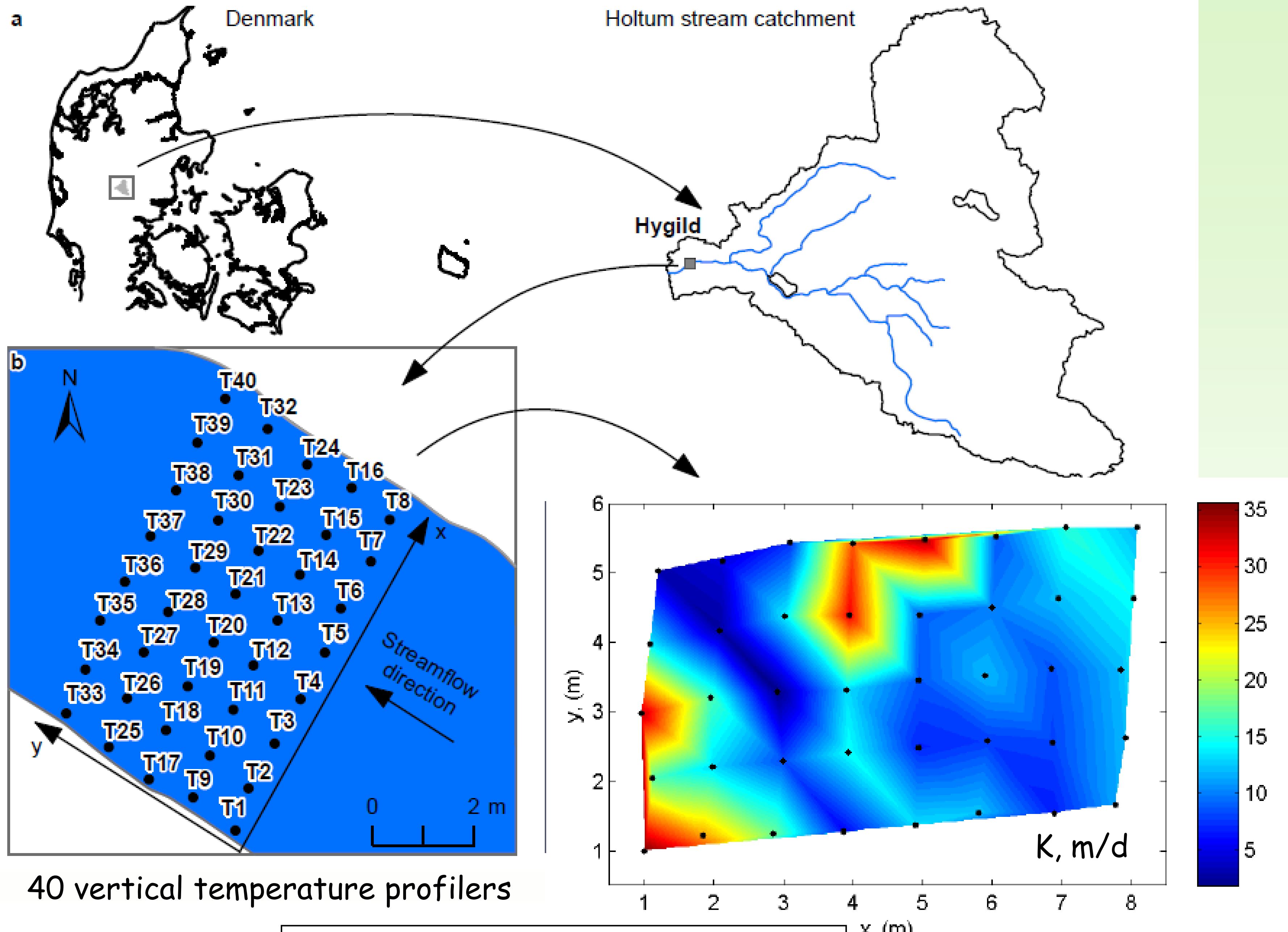


40 vertical temperature profilers

Sachin Karan, 2014, *WRR*

Here is a nice study that had a high density of data across a stream. These data show 3-d distribution of temperature beneath the streambed. We can use these data to calculate seepage.



40 vertical temperature profilers

119 slug tests

Sachin Karan, 2014, *WRR*

And here are the data from more than 100 slug tests!

Method	Spatial scale	Temporal scale
Techniques used in our field study		
Conservative tracer tests (chemical)	10^1–10^5 m	min–mo
Reactive Raz–Rru tracer system	10^{-1}–10^3 m	min–d
Mini drive-point (USGS MINIPOINT)	10^{-1}–10^0 m	min–h
Piezometer (head)	10^0–10^2 m	h–mo
Streambed temperature (FO-DTS)	10^0–10^4 m	s–mo
Streambed temperature (vertical drivepoint)	10^{-1}–10^0 m	s–mo
Electrical resistivity imaging	10^{-1}–10^2 m	min–h
Seepage meter	10^0–10^1 m	h–wk
Differential discharge gauging (manual or automated)	10^0–10^4 m	min–y

Table 4 – Review of techniques commonly used for estimating groundwater-surface-water interactions

Gonzalez-Pinzon et al., 2015
Freshwater Science

Here are a few methods that can be used to quantify exchange between groundwater and surface water.

"Take-home" message: We need to match the scale of the method with the scale of the process or setting that we are interested in quantifying.

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