The interaction of ground water and surface water

From modeling to the field and back again

UNIVERSIDAD DE GRANADA
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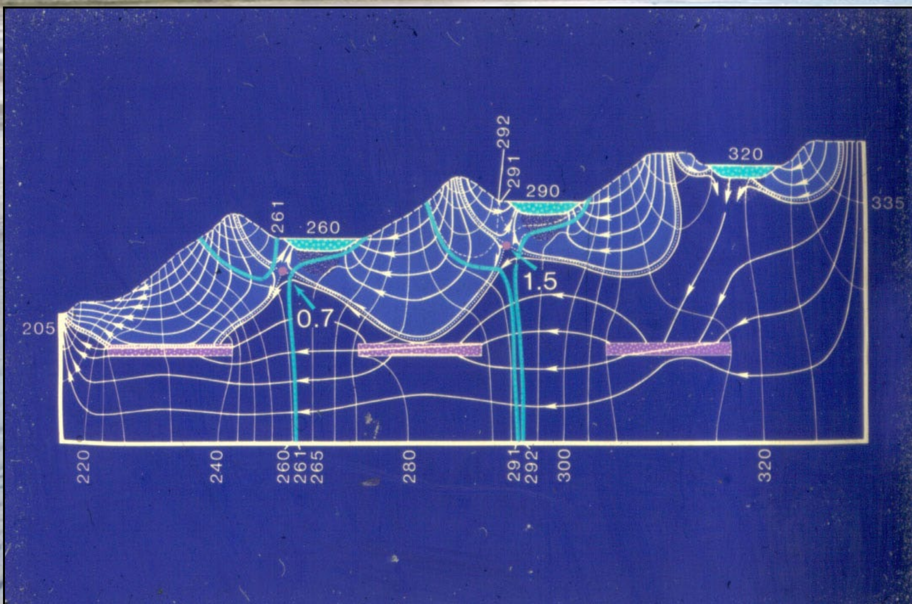
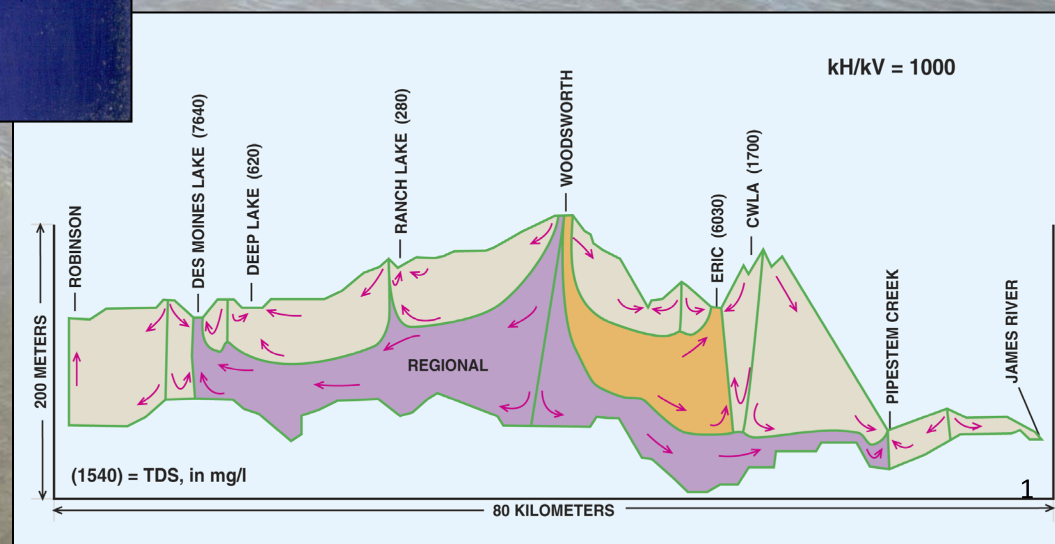


Physiography related to flowpath



Take-home message:
Iterate between modeling and field work

Ground-breaking research on exchange between groundwater and surface water

O.E. MEINZER AWARD

Presented to Thomas C. Winter

Tom Winter is not just another old guy whose name you have to memorize for a hydrogeology exam. Tom's ground-breaking research in the 1970s and 1980s greatly changed the way we view the connection between groundwater and surface water. We will look at some of his early modeling results of hypothetical settings and compare them with what we see in actual field settings.

VOL. 14, NO. 2 WATER RESOURCES RESEARCH APRIL 1978

Numerical Simulation of Steady State Three-Dimensional Groundwater Flow Near Lakes

THOMAS C. WINTER

U.S. Geological Survey, Denver, Colorado 80225

Limnol. Oceanogr., 26(5), 1981, 925–934

Effects of water-table configuration on seepage through lakebeds

Thomas C. Winter

U.S. Geological Survey, Mail Stop 413, Denver Federal Center, Denver, Colorado 80225

Numerical Simulation Analysis of the Interaction of Lakes and Ground Water

By THOMAS C. WINTER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1001

1976

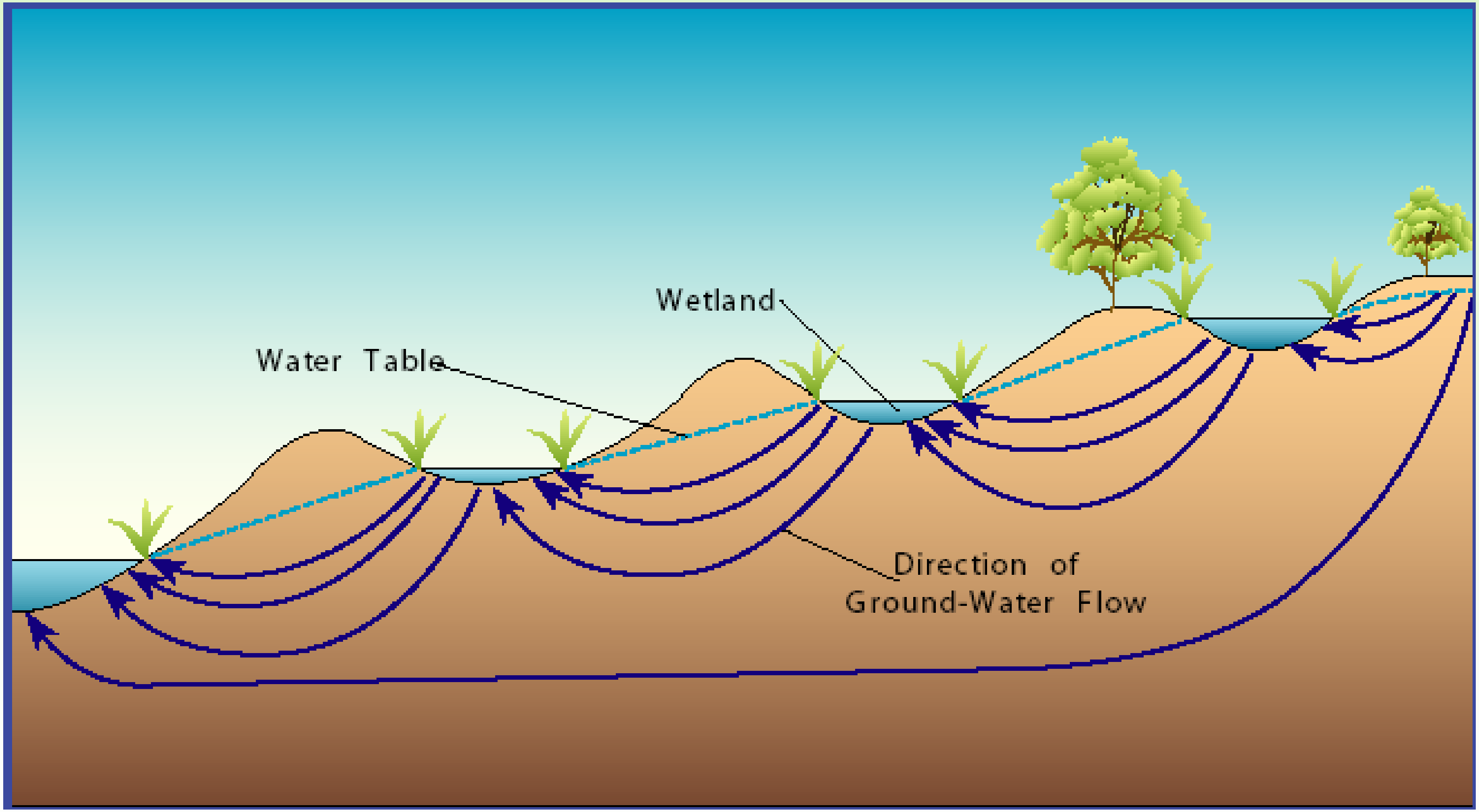
WATER RESOURCES RESEARCH, VOL. 19, NO. 5, PAGES 1203–1218, OCTOBER 1983

The Interaction of Lakes With Variably Saturated Porous Media

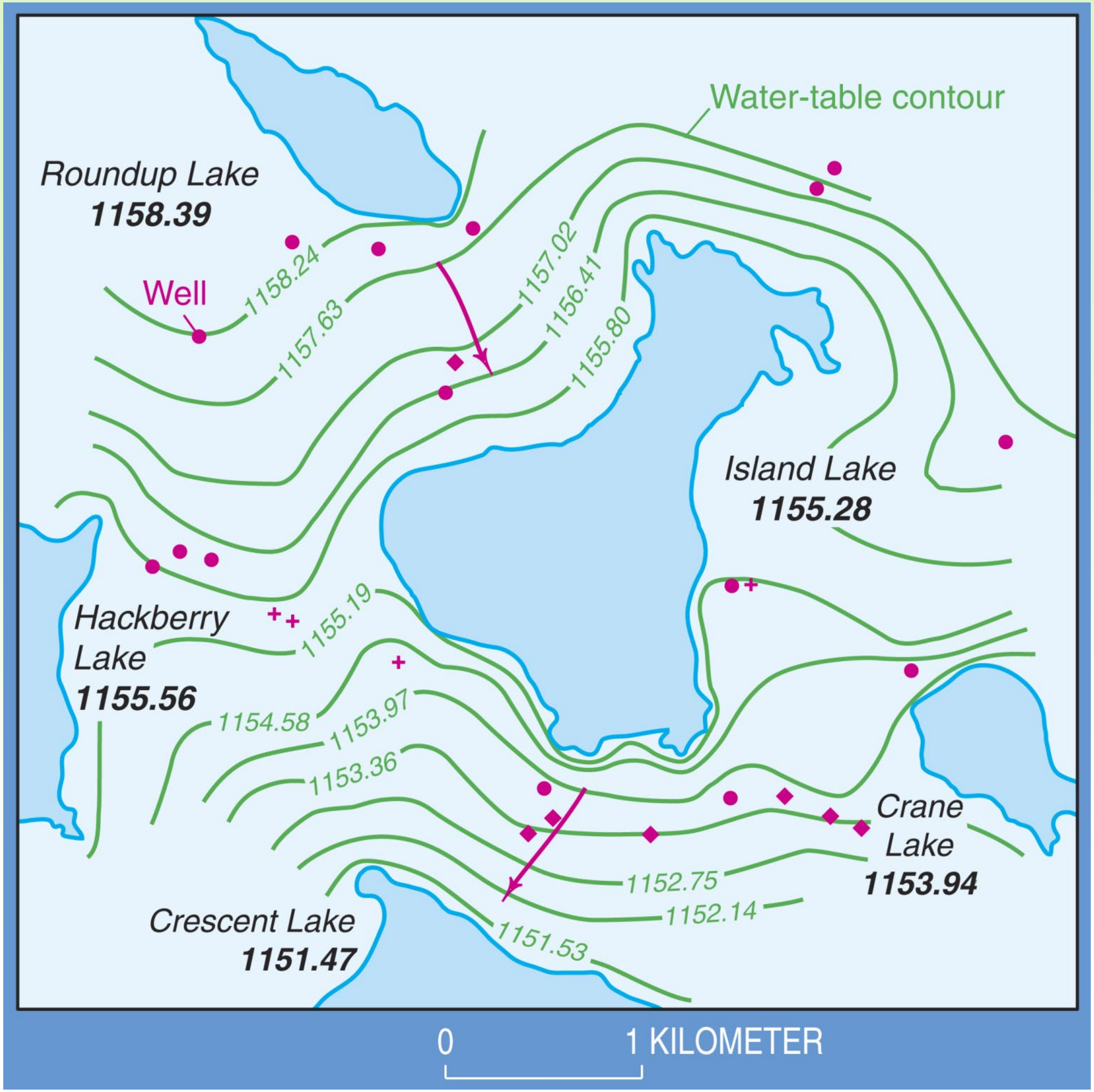
THOMAS C. WINTER

U.S. Geological Survey, Denver

Common concept: water flows from wetland to wetland to wetland



This is just common sense, right? As the next few slides will demonstrate, maybe not, and certainly not in some settings.



Sometimes this actually happens

Crescent Lake National Wildlife Refuge, Nebraska sand hills

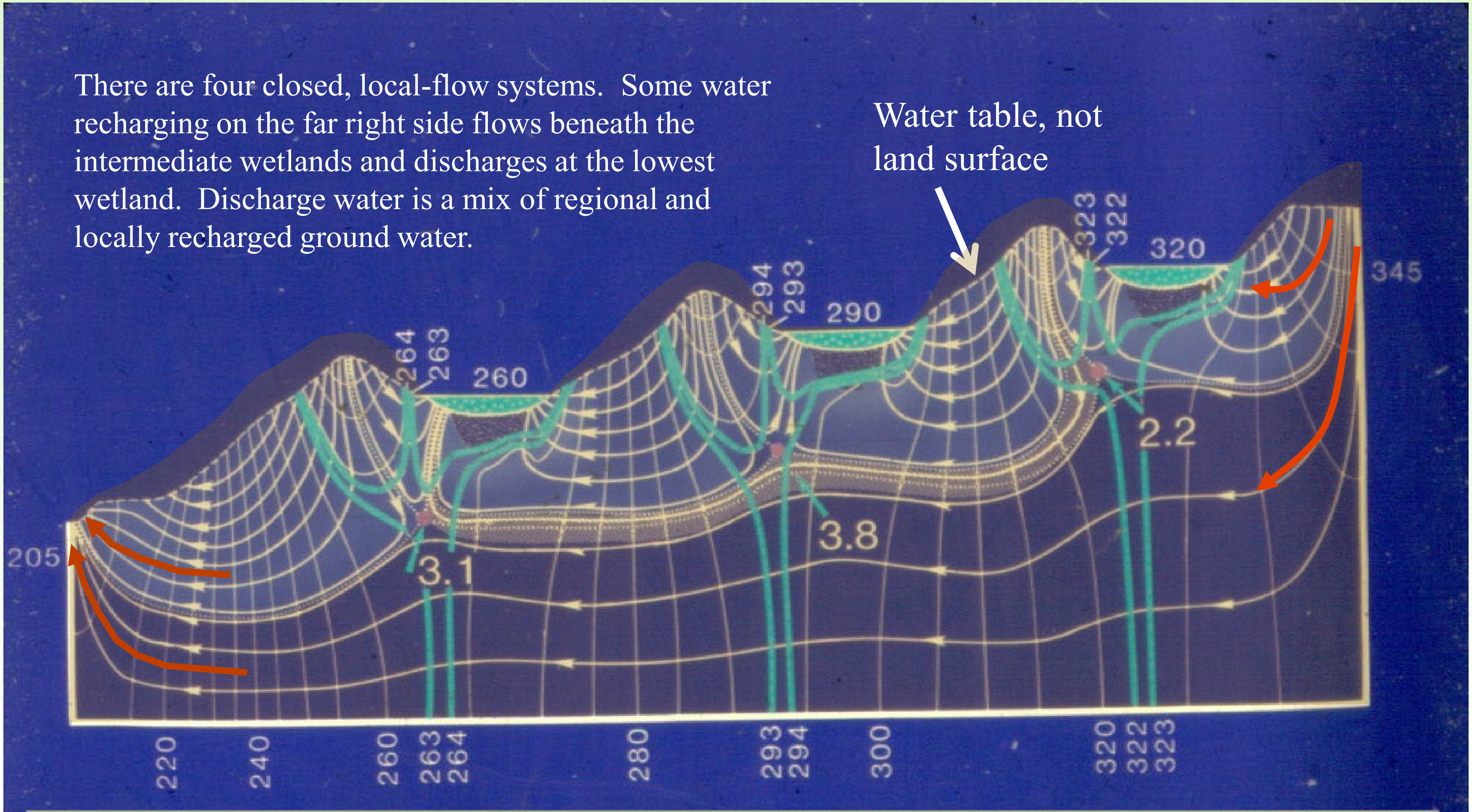
Island Lake wells and piezometers showed a simple system – perhaps because of the simple geology? It's all dune sand.

Here finally may be a setting where we might have homogeneity.

Winter, 1986, *JHydrol.*

But not if *K* is decreased

Water in lowest wetland can be a mix of local and regional flow but it can not contain any water from upgradient wetlands

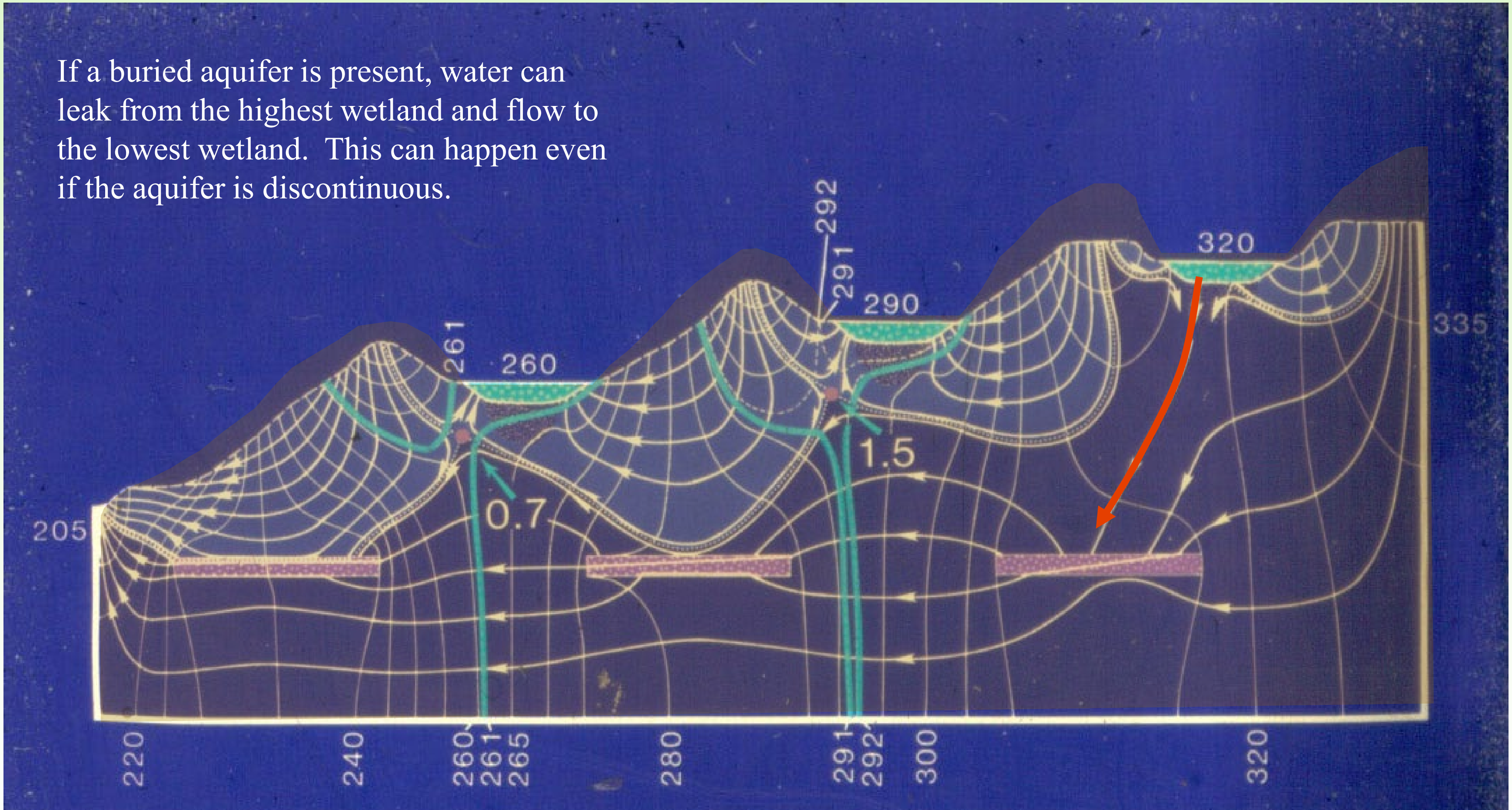


With lower *K*, water basically can't move through the flow field fast enough and with sufficient recharge it piles up above the wetlands. We still have uniform geology, but now we have flow-separation lines that represent the boundary between local and inter-basin flow. These boundaries distinguish water that remains within a single topographic basin and water that is recharged in one basin and discharges to another downgradient basin. The downgradient basin could be considered as a regional drain for the flow domain. Discharge at the drain to the left is a mix of older and younger waters.

But if we have buried aquifers. . .

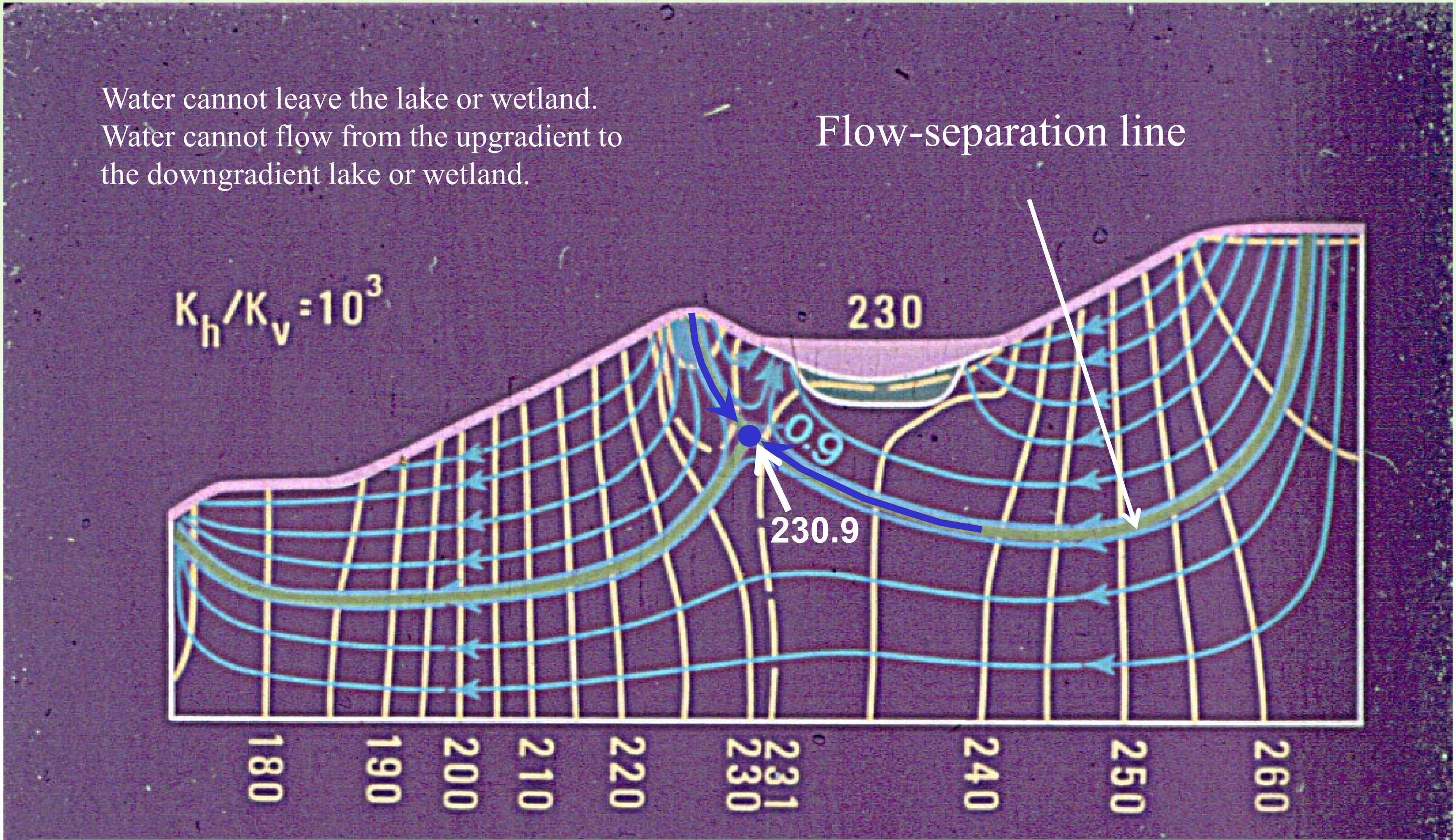
Middle two wetlands still are closed flow systems, but water from upper wetland now can flow to lowest wetland

If a buried aquifer is present, water can leak from the highest wetland and flow to the lowest wetland. This can happen even if the aquifer is discontinuous.



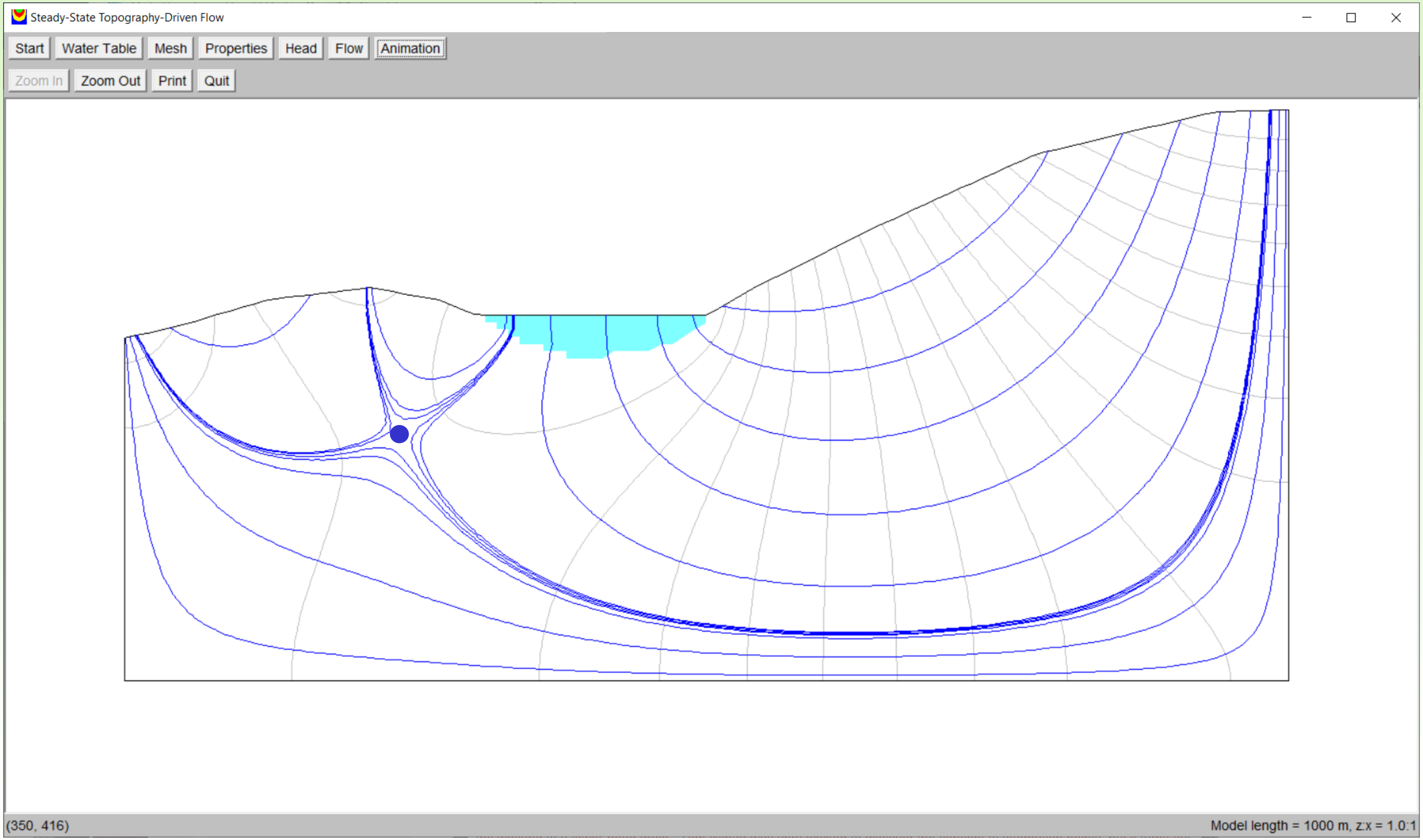
A buried aquifer, or zone of sediment that transmits water more rapidly, basically creates a short circuit in the flow system that draws water from the upper wetland. Now the upper wetland has changed from a closed, local flow system to become a recharge wetland that supplies water to the aquifer and eventually to the drain at the left end of the flow field.

A stagnation point (blue dot) forms at the point where head along a flow-separation line is lowest. A stagnation point is a point in a flow field of zero velocity. Ground water is not moving at a stagnation point. (Water could be very old near a stagnation point and interesting chemistry could result.)



If a stagnation point is present, a closed, local flow system exists. Water cannot leave the wetland; water cannot flow from the wetland to a lower-head drain. Tom Winter was very excited to discover the concept of stagnation points, but it turns out petroleum engineers had known about this years earlier. But no one had thought about this from a groundwater-surface-water perspective. Luckily, Tom's advisor was well versed in the petroleum-engineering literature.

A stagnation point shown with Topodrive

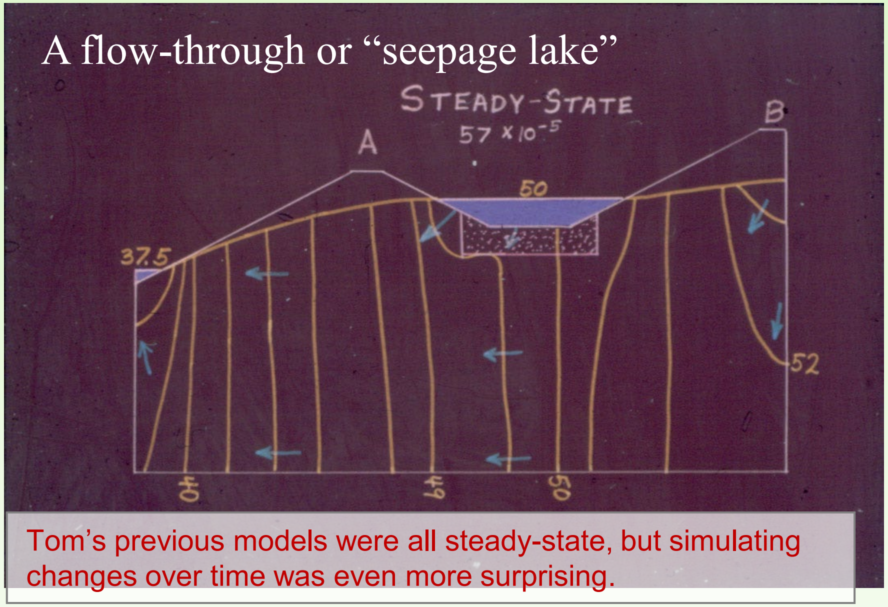


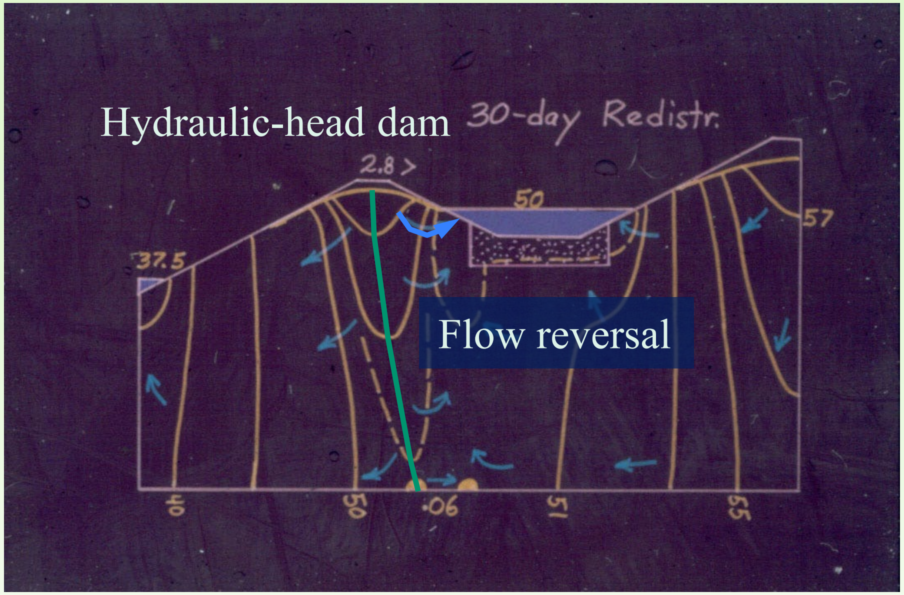
You can also clearly see the flow separation lines by creating new flowlines that become increasingly closer to the stagnation point.

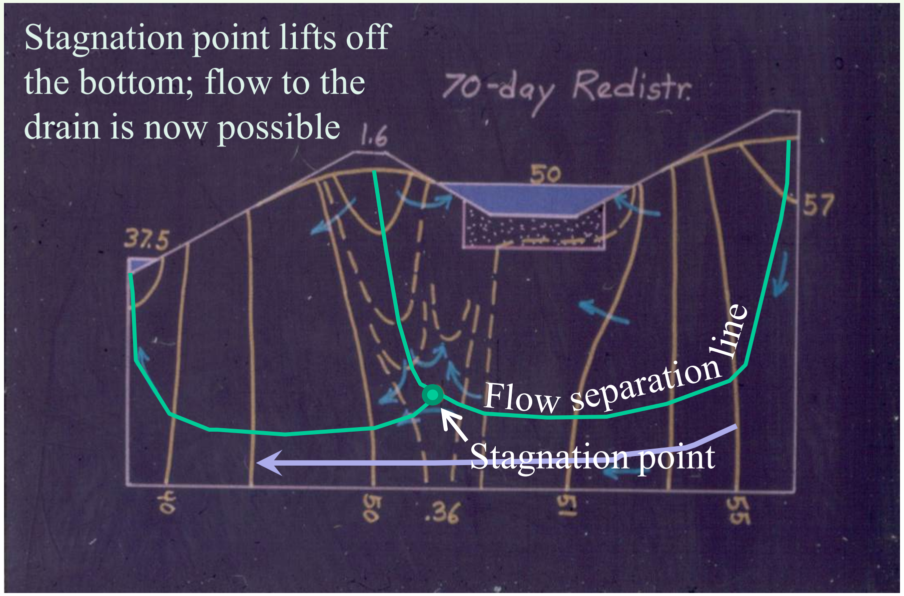
Transient flow reversals

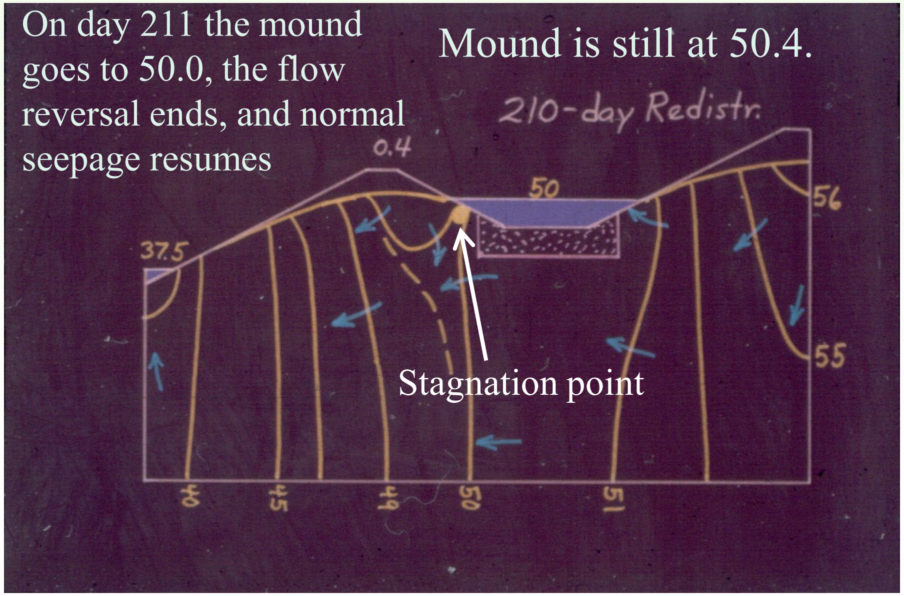
Winter, 1983, *WRR*

Tom simulated the response to a snowmelt recharge event





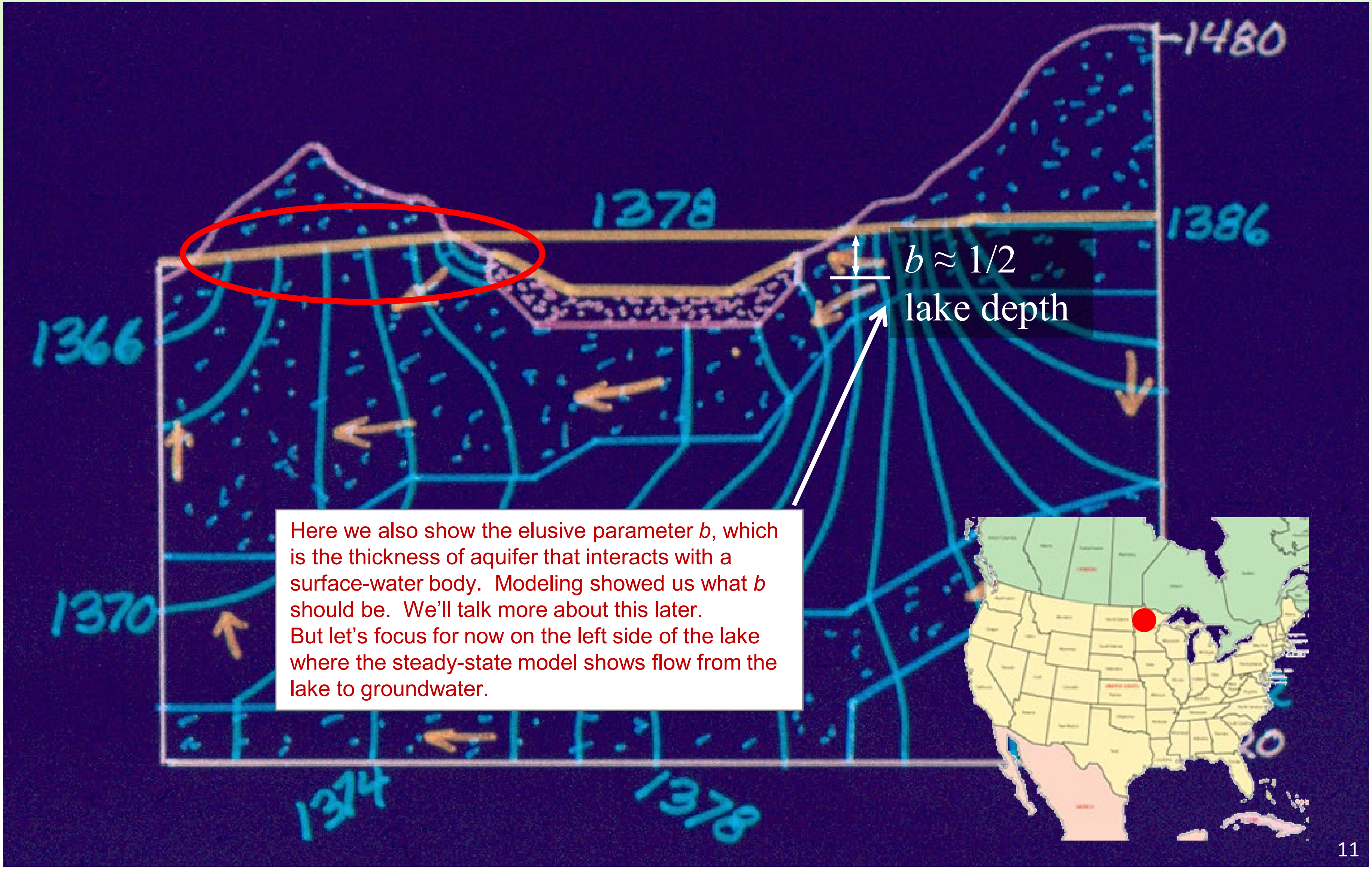




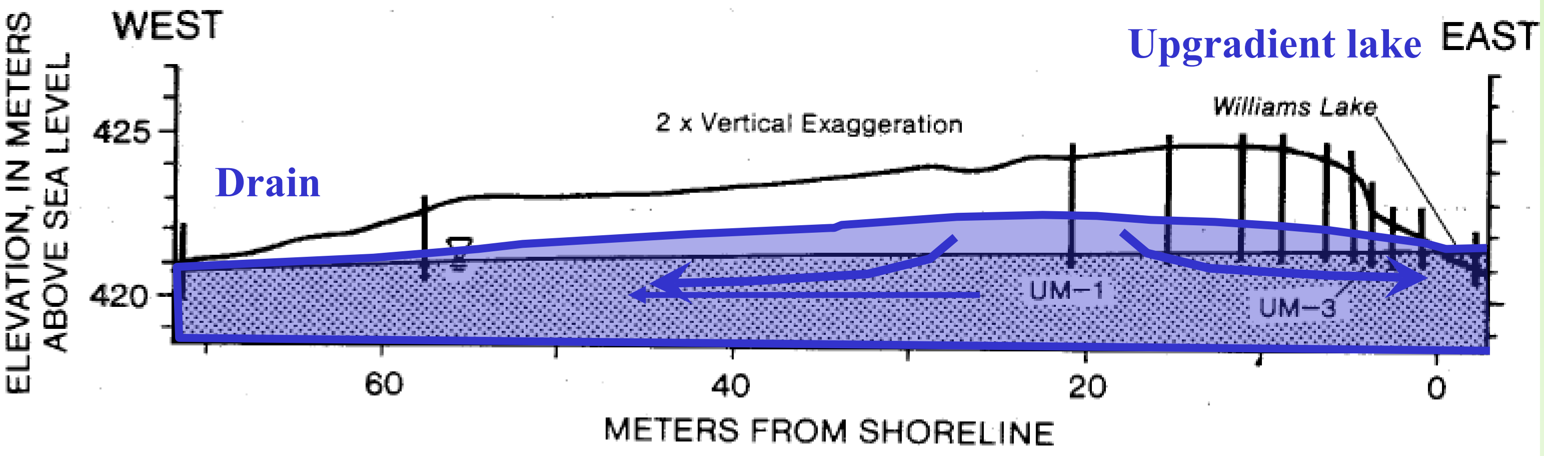

But have you ever seen this in the real world?

Off to Williams Lake

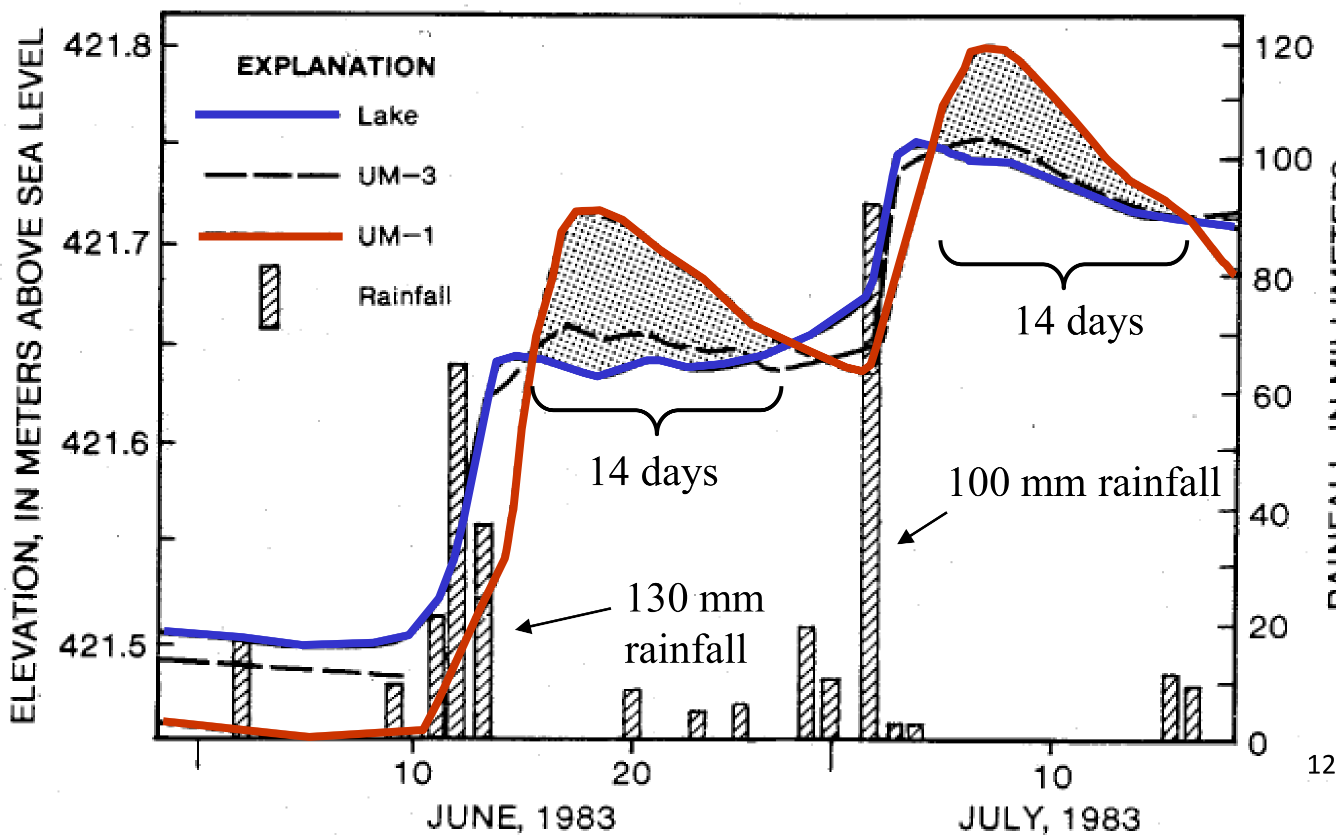
Where we already had a good idea of what was going on



Here we also show the elusive parameter *b*, which is the thickness of aquifer that interacts with a surface-water body. Modeling showed us what *b* should be. We'll talk more about this later.
But let's focus for now on the left side of the lake where the steady-state model shows flow from the lake to groundwater.



Transient mounds did form in response to recharge, but not during snowmelt



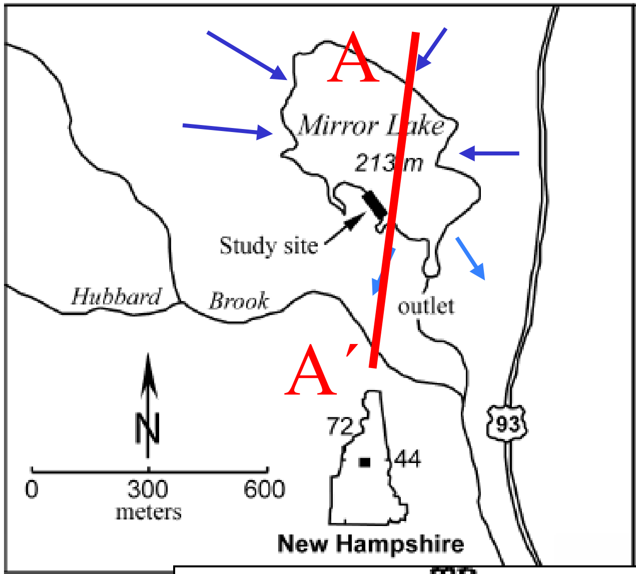
Field studies confirmed the occurrence of flow reversals on the downgradient sides of lakes. However, in these sandy sediments, reversals lasted for weeks, not months.

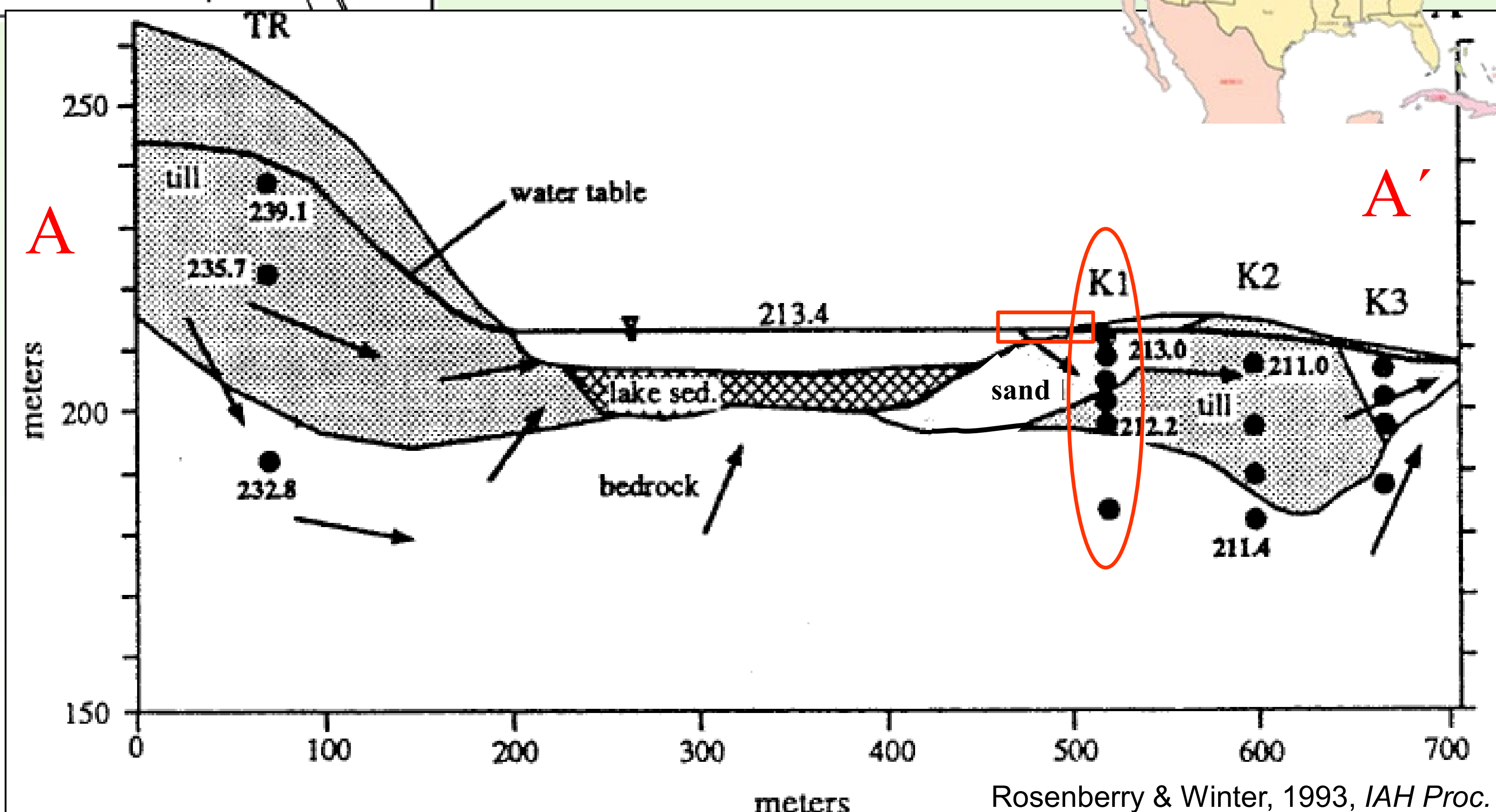
Rosenberry, 1990, *NALMS*

Mirror Lake, New Hampshire

- Lake situated in glacial drift and crystalline bedrock
- Modeling plus wells indicates a simple flow-through lake
- On first glance, this looks like a classic seepage lake

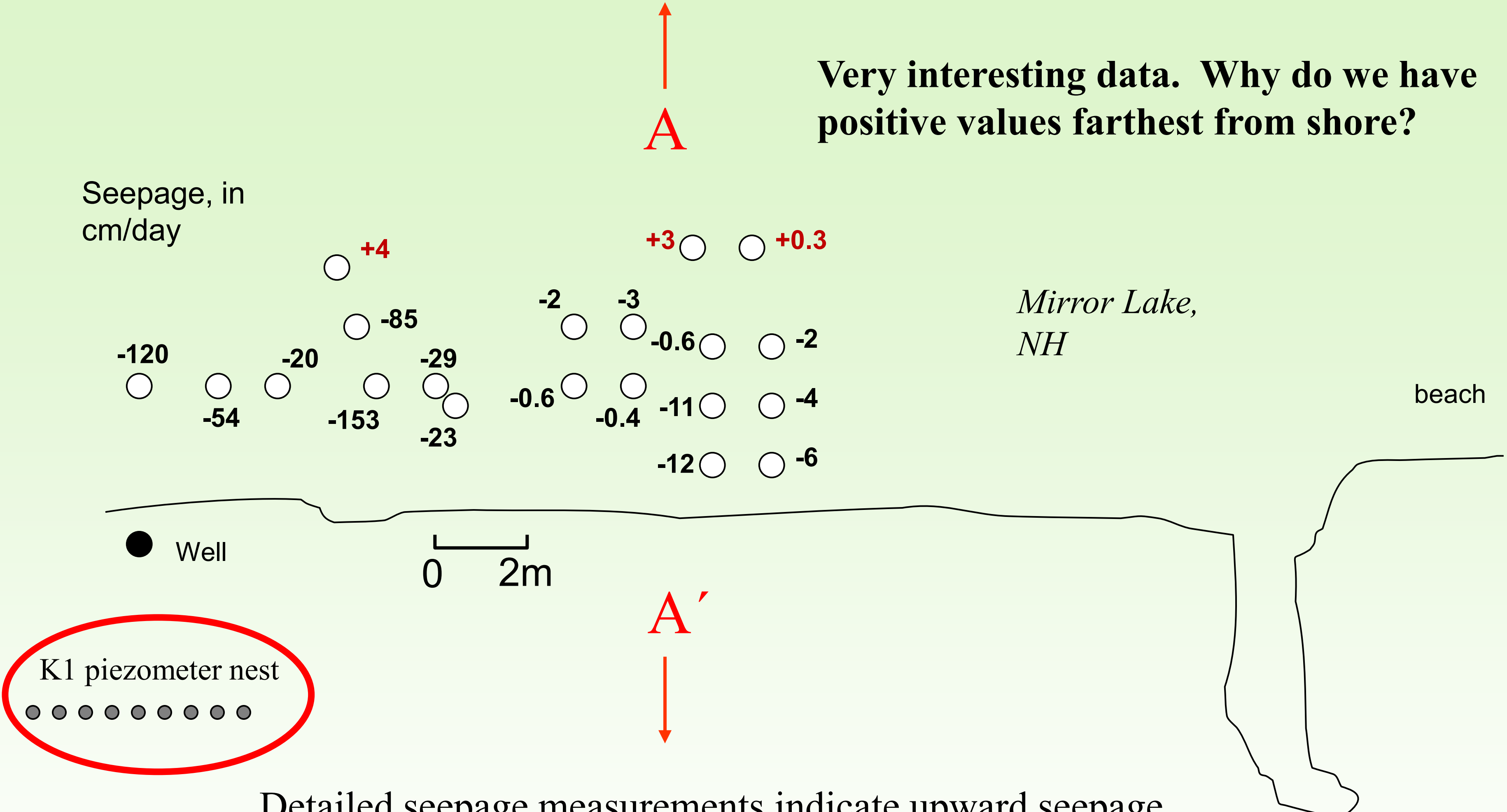
Without data at the K1 piezometer nest, we would assume GW flows into the lake on the north and lake water flows to GW on the south side of the lake.





Rosenberry & Winter, 1993, *IAH Proc.*

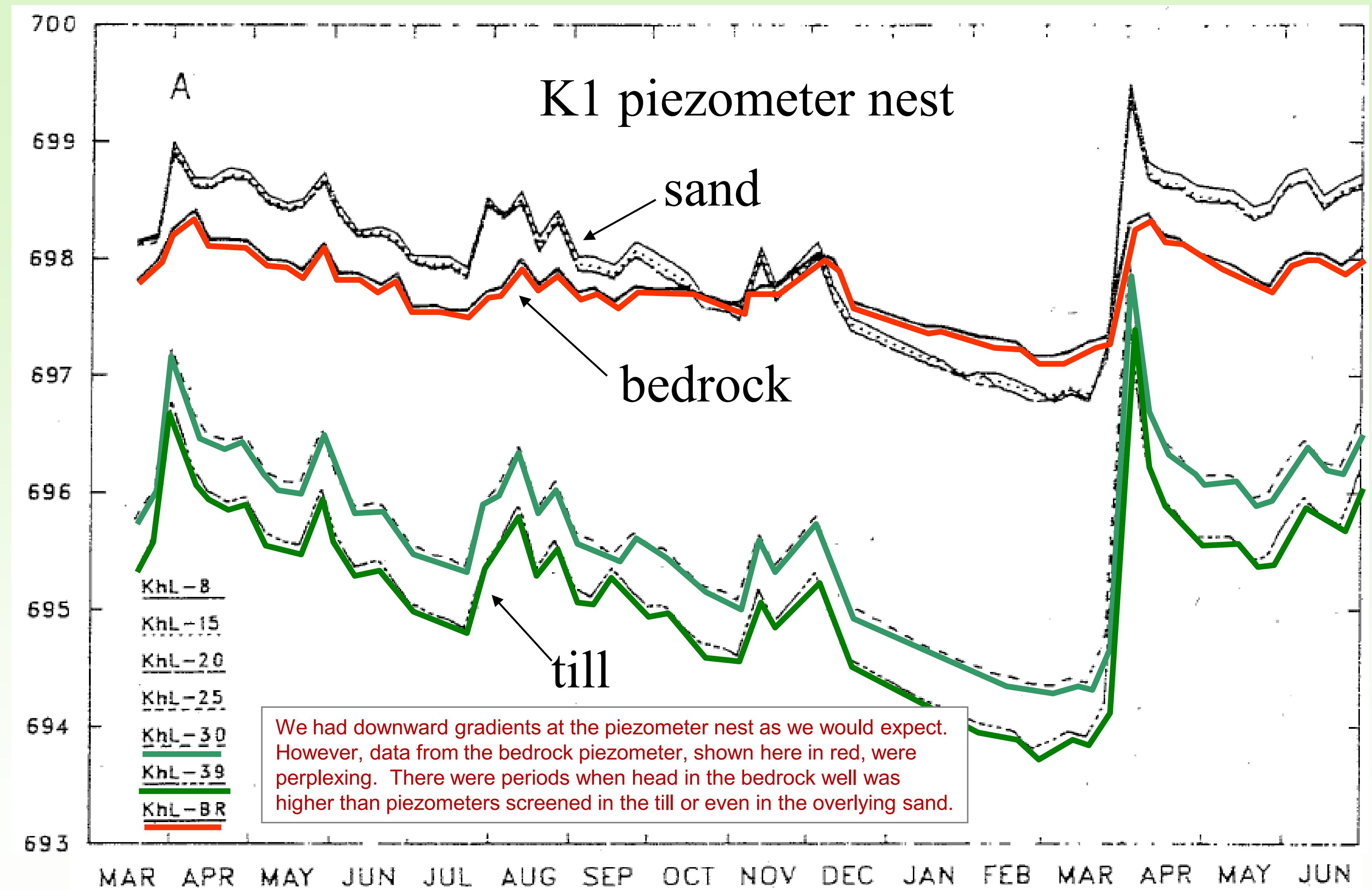
Very interesting data. Why do we have positive values farthest from shore?



Detailed seepage measurements indicate upward seepage offshore but strong downward seepage near shore

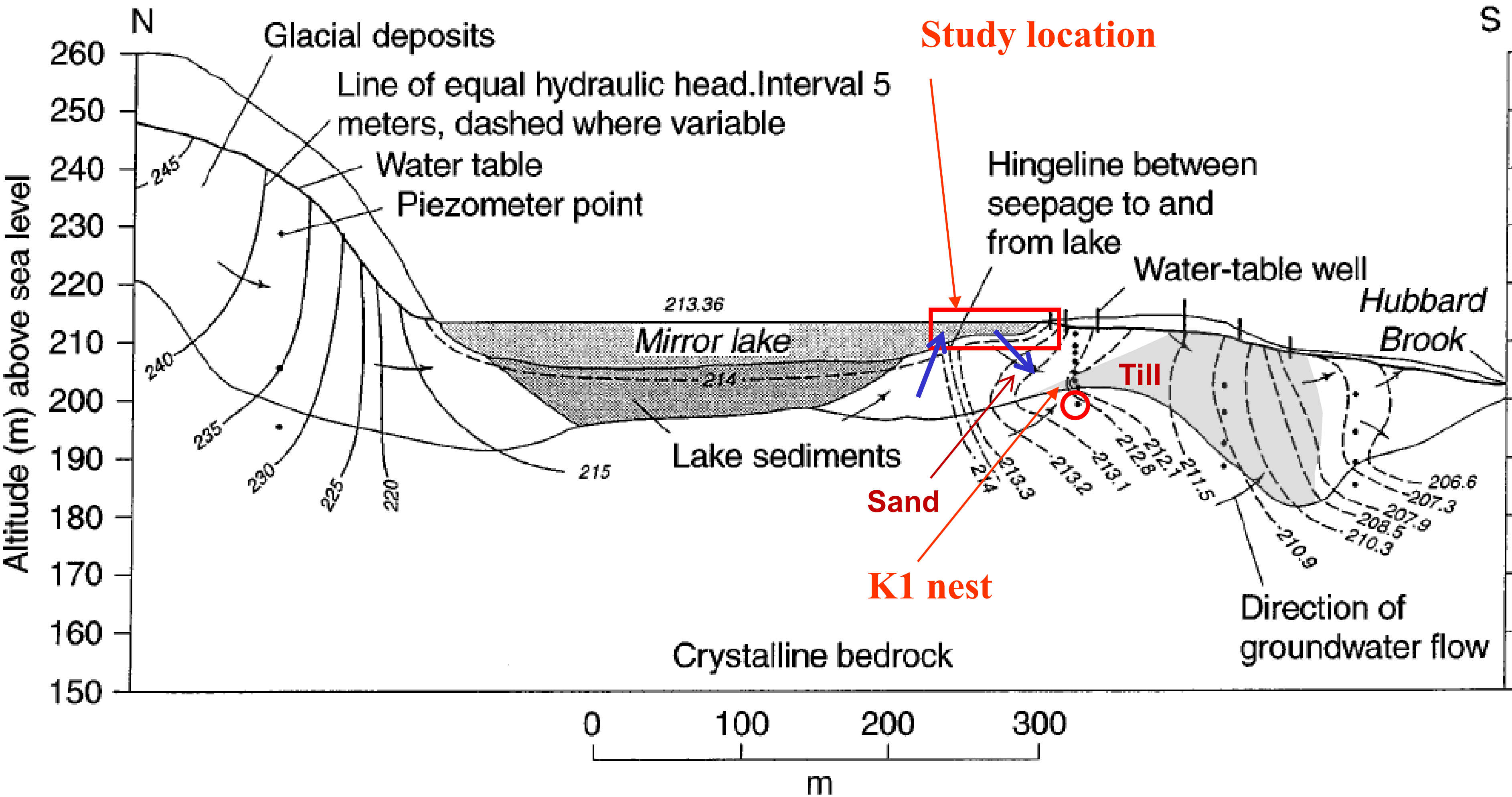
These seepage-meter data indicate something very strange is going on. Negative values indicate downward seepage and positive values indicate upward seepage. The meters farthest from shore indicate upward seepage but everything else closer to the shoreline indicates downward seepage, including some very fast rates of downward seepage. Interesting. What do data from the piezometer nest show?

Rosenberry, 2005, *Limnol. Oceanogr. Methods*



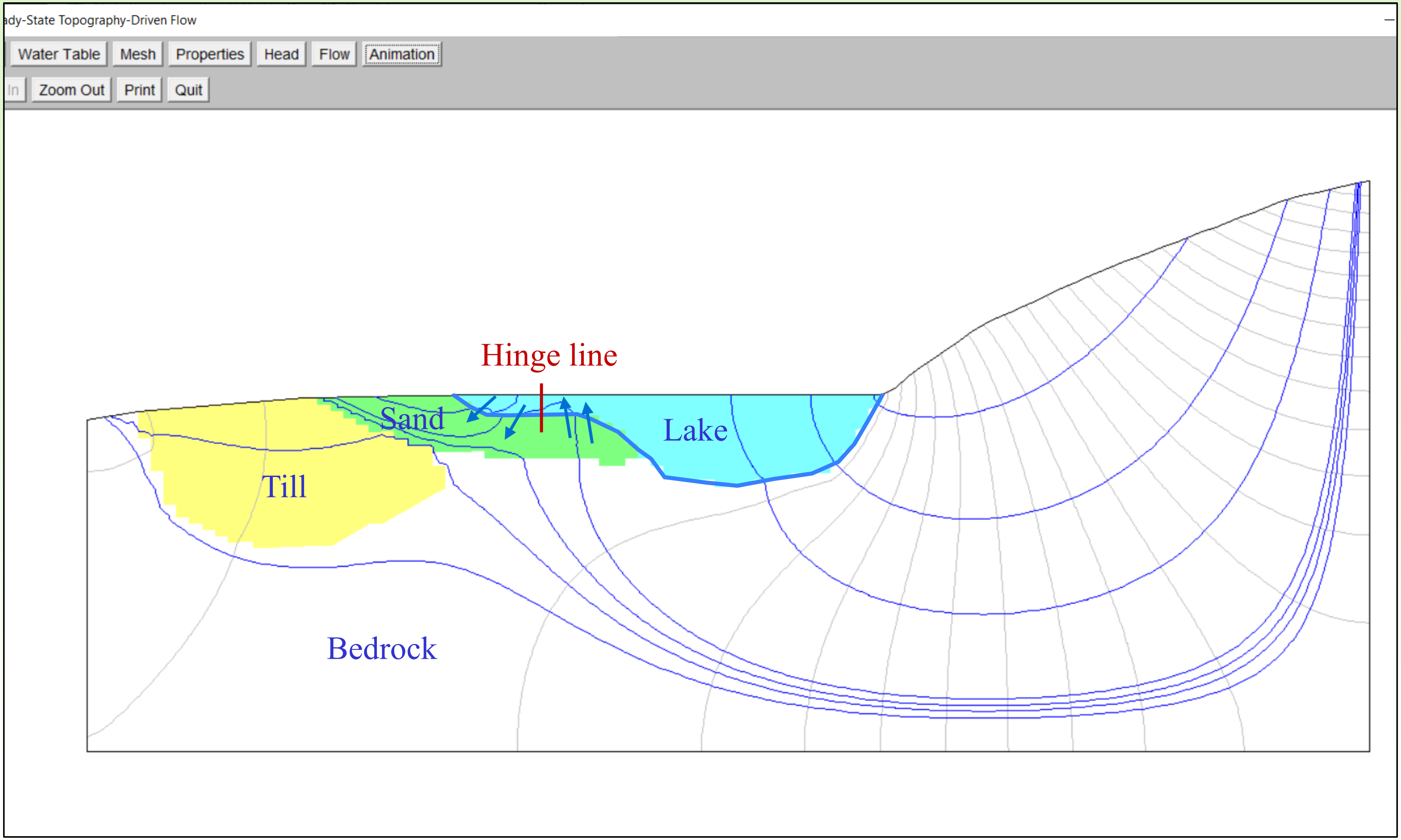
High bedrock head suggests upward GW flow at downgradient side of lake

Additional data indicate a very interesting exchange between the lake and ground water



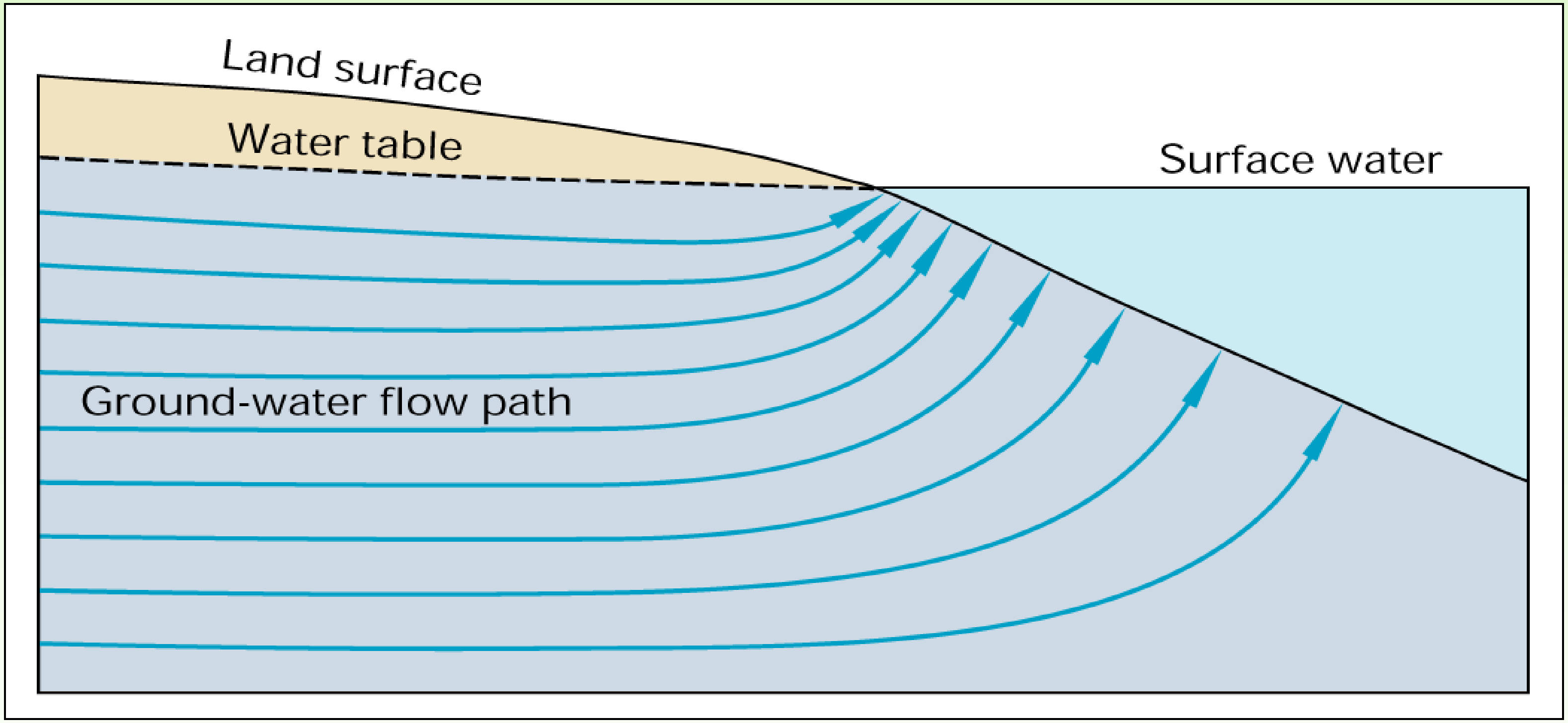
We have a hinge line (a line separating upward flow across the lakebed from downward flow across the lakebed) that exists 10 to 40 m from the south shoreline. GW discharge from high head north of the lake is passing beneath the lake, and beneath very low-K organic sediments beneath the lake, to discharge near the south end of the lake. But a sand deposit extends beneath the south shore of the lake all the way to Hubbard Brook, which has much lower head. This sand lens (another short circuit) allows rapid seepage of water from the lakebed close to the shoreline. So we have a very complex setting and also a complicated flow system in this setting. It took a combination of data and modeling to figure this one out.

Topodrive can show this setting too



Notice the flow line that enters the lake, flows laterally through the lake, and then leaves the lake to flow downward into the sand. That key flowline is proof that a hinge line exists that separates upward flow of groundwater to the lake from downward flow from the lake to groundwater.

Given homogeneity, seepage decreases exponentially with distance from shore



This is a basic tenet in hydrogeology and GW-SW exchange that was first made known to the hydrogeology community with the McBride and Pfannkuch paper. Any numerical model will show this type of distribution with distance from shore of the simulated porous medium is homogeneous.

Olaf Pfannkuch
after a GSA session
held in his honor

McBride and Pfannkuch, 1975, *USGS J. Res*
Pfannkuch and Winter, 1984, *JHydrol.*
Winter and Pfannkuch, 1984, *JHydrol.*

Exponential decrease in lakes and rivers?

Remember the influence of Geology?

Yes

- John, P. H. and M. A. Lock (1977). Journal of Hydrology **33**: 391-395.
- Lee, D. R. (1977). Limnology and Oceanography **22**(1): 140-147.
- Lee, D. R., J. A. Cherry, et al. (1980). Limnology and Oceanography **25**(1): 45-61.
- Erickson, D. R. (1981). MS Thesis. Minneapolis, University of Minnesota**:** 135.
- Attanayake, M. P. and D. H. Waller (1988). Canadian Journal of Civil Engineering **15**: 984-989.
- Fukuo, Y. and I. Kaihotsu (1988). Water Resources Research **24**(11): 1949-1953.
- Rosenberry, D. O. (1990). North American Lake Management Society.
- Schafran, G. C. and C. T. Driscoll (1993). Water Resources Research **29**(1): 145-154.
- Rosenberry, D. O. (2000). Water Resources Research **36**(12): 3401-3409.

But the world is rarely homogeneous. Geology often disrupts the normal distribution of seepage and there are numerous examples in the literature.

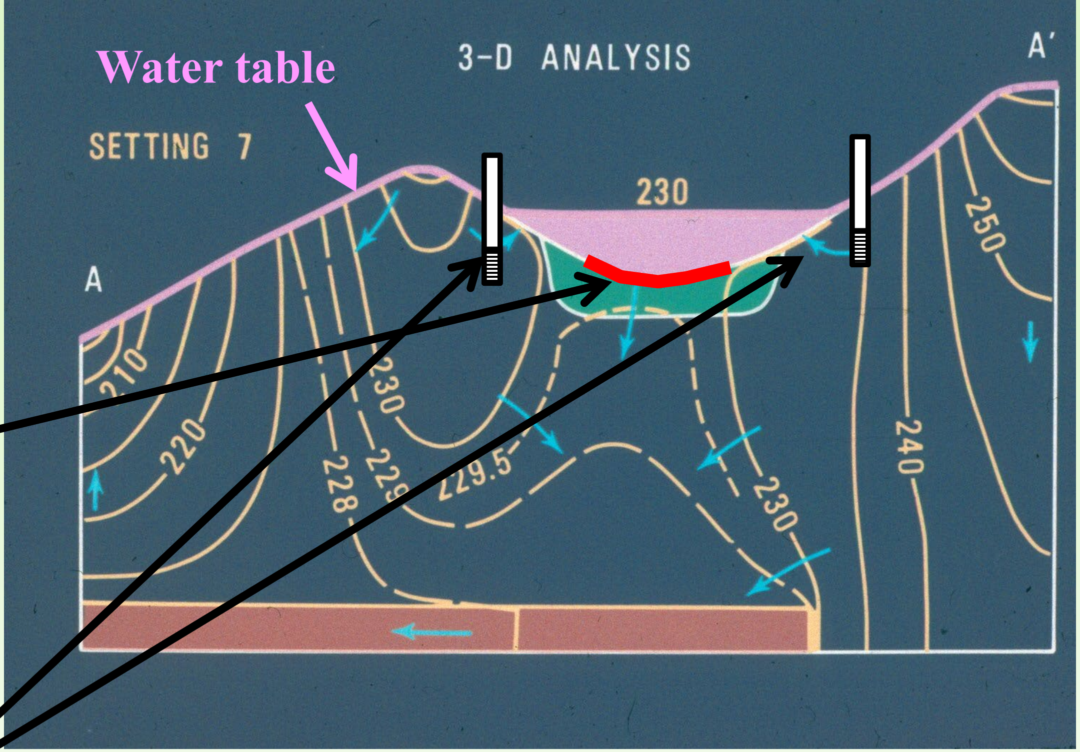
No

- Fellows, C. R. and P. L. Brezonik (1980). Water Resources Bulletin **16**(4): 635-641.
- Connor, J. N. and T. V. Belanger (1981). Water Resources Bulletin **17**(5): 799-805.
- Woessner, W. W. and K. E. Sullivan (1984). Ground Water **22**(5): 561-568.
- Cherkauer, D. S. and D. C. Nader (1989). Journal of Hydrology **109**: 151-165.
- Belanger, T. V. and R. A. Kirkner (1994). Lake and Reservoir Management **8**(2): 165-174.
- Kishel, H. F. and P. J. Gerla (2002). Hydrological Processes **16**: 1921-1934.
- Murdoch, L. C. and S. E. Kelly (2003). Water Resources Research **39**(6): doi:10.1029/2002WR001347.
- Rosenberry, D. O. (2005). Limnology and Oceanography: Methods **3**: 131-142.

Position and areal extent of buried aquifer

Lake can lose water to the aquifer

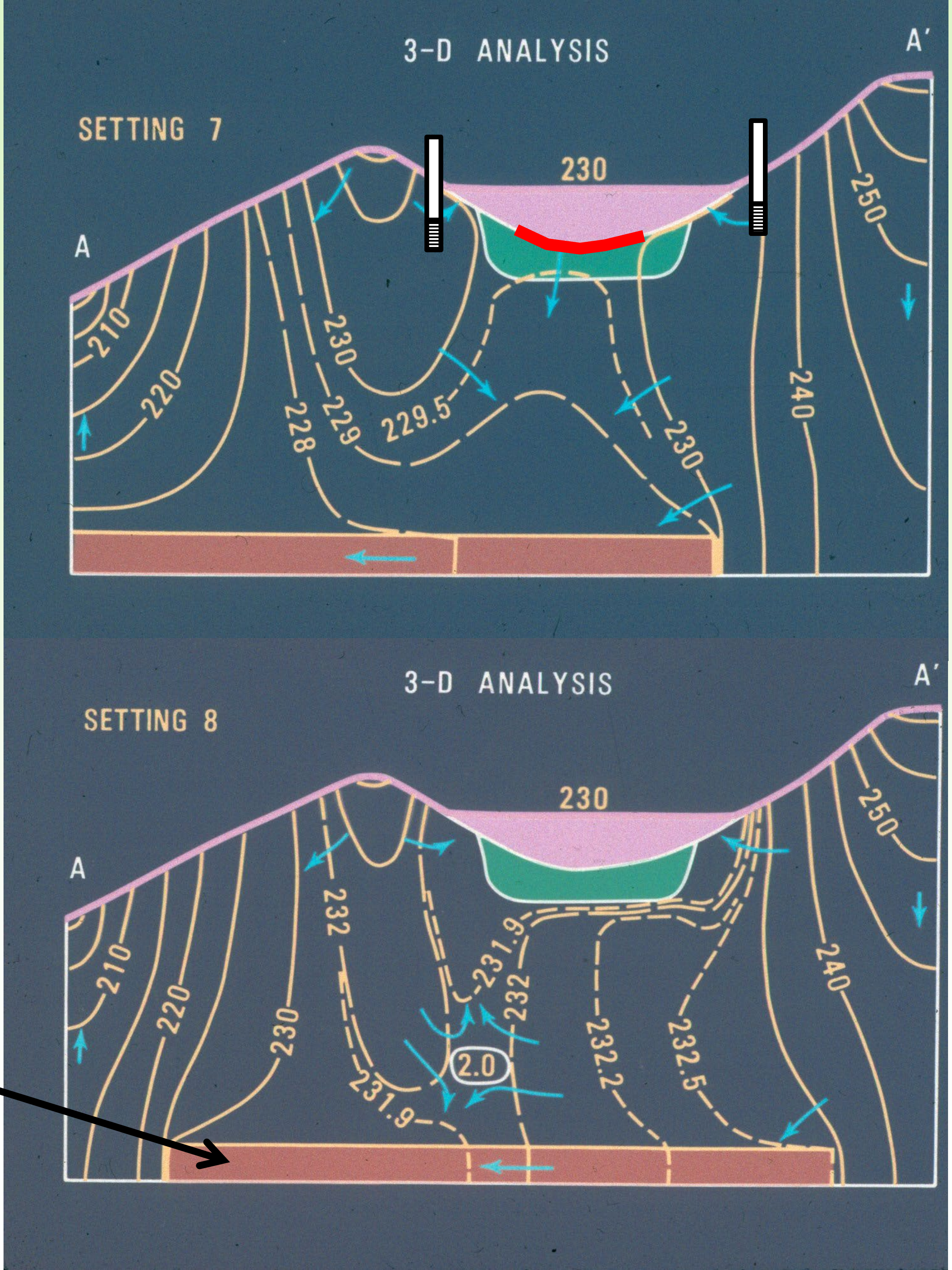
You could have 100 wells around this lake and you'd never know about the "hole" in the middle



Once Tom was up to speed with the very complex model that his colleague down the hall, Dick Cooley, had developed, Tom could simulate all sorts of settings. He had been working with some colleagues who were studying lakes in Florida, where a thin, low-*K* layer separates surficial sands from a deeper massive limestone aquifer that underlies most of the state. Tom wanted to know how breaks in that low-*K* layer might affect exchange between groundwater and an overlying lake. Tom never did publish the results shown in the next five slides, but his colleagues in Florida certainly benefitted from the new insights they provided.

Winter, 1978, *WRR*

Position and areal extent of buried aquifer

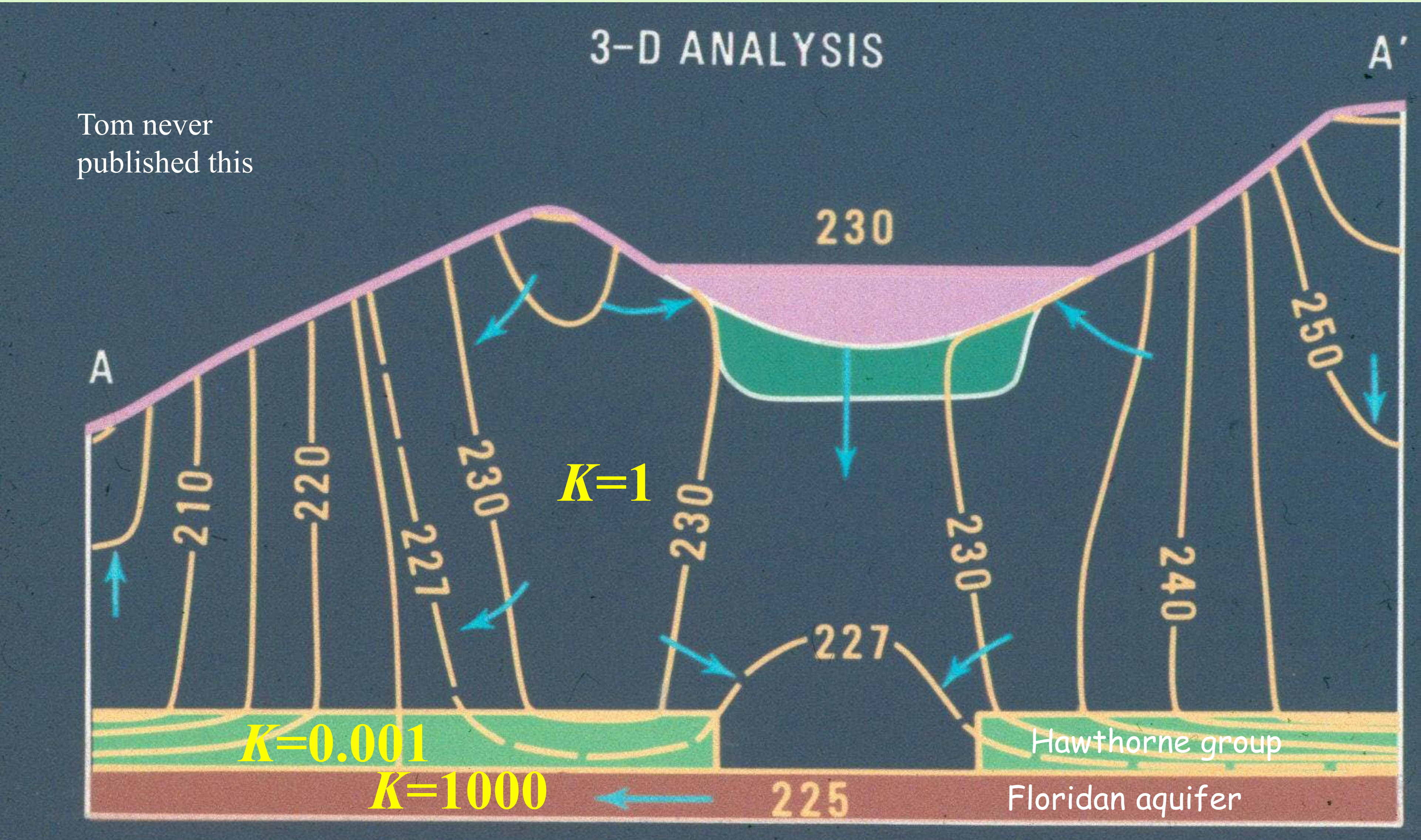


Move the aquifer and now the lake can't lose water

Winter, 1978, *WRR*

What if we have a confined aquifer with a hole in the confining bed

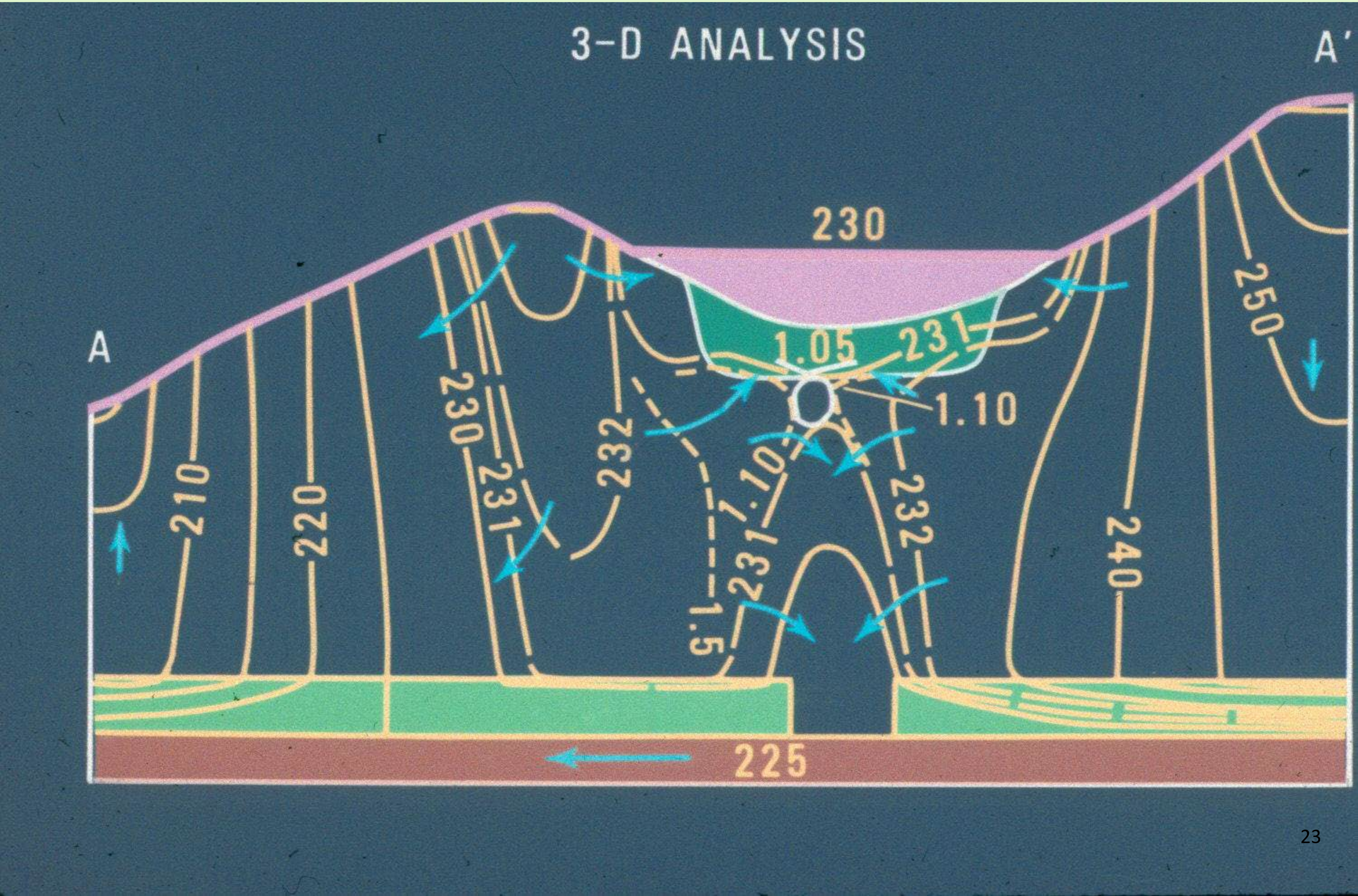
Analogous to the Floridan-Hawthorn system in Florida



Lake loses water to the Floridan aquifer

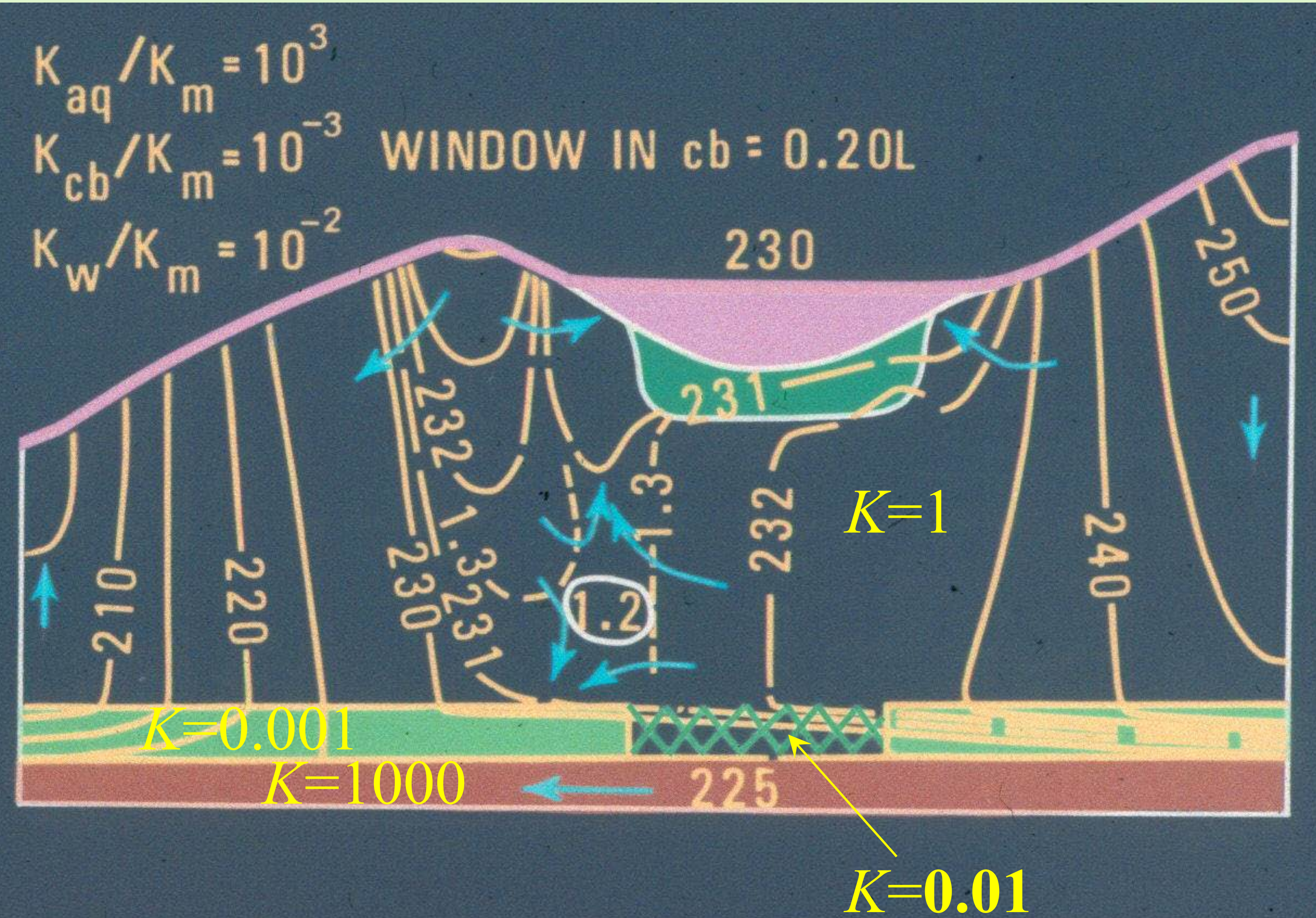
With a smaller "window," the lake no longer seeps to the aquifer

A closed, local-flow system develops

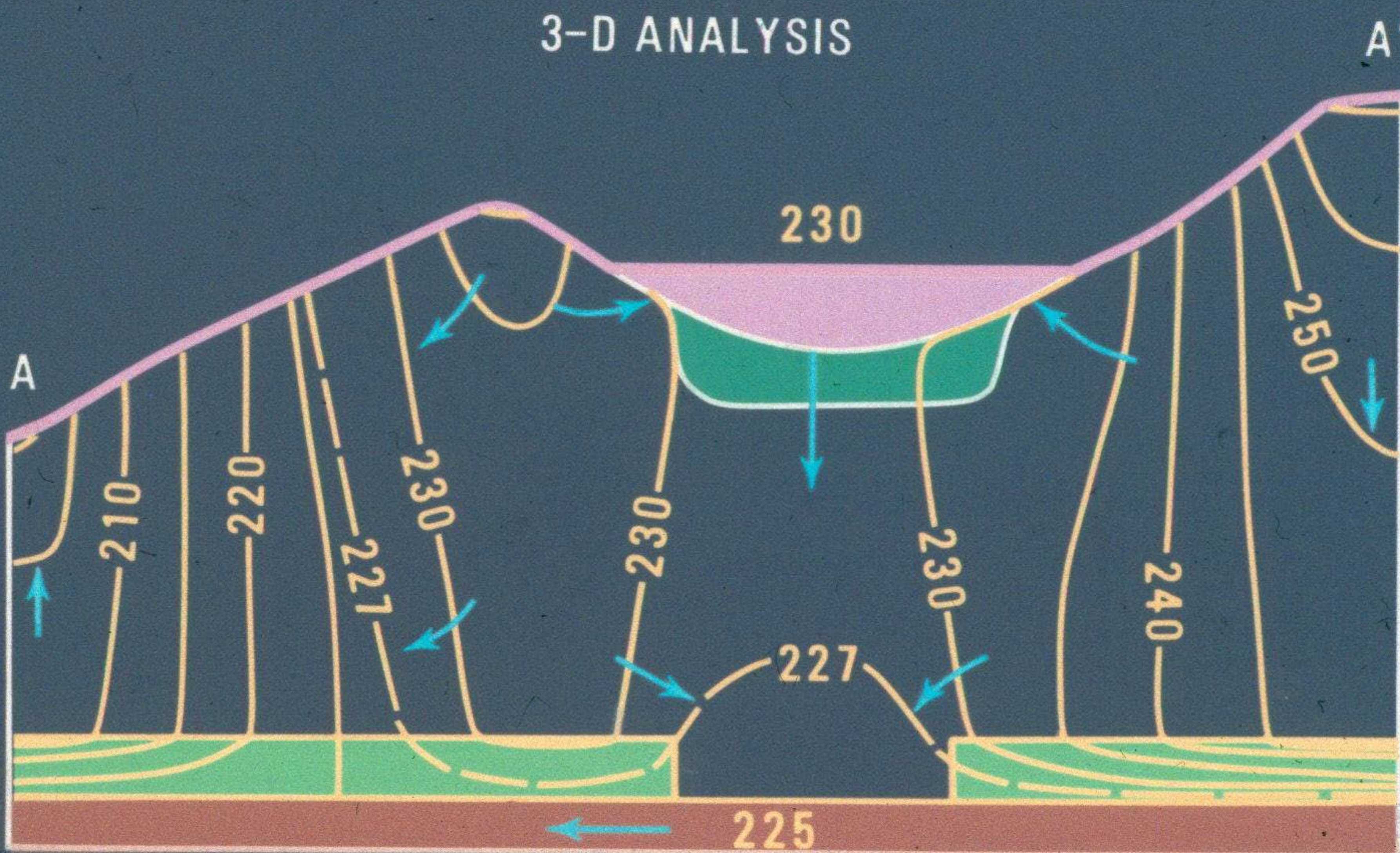


What if the rubble in the hole is really dirty (lower-*K*)?

Now the lake stops losing water and a closed flow system develops.

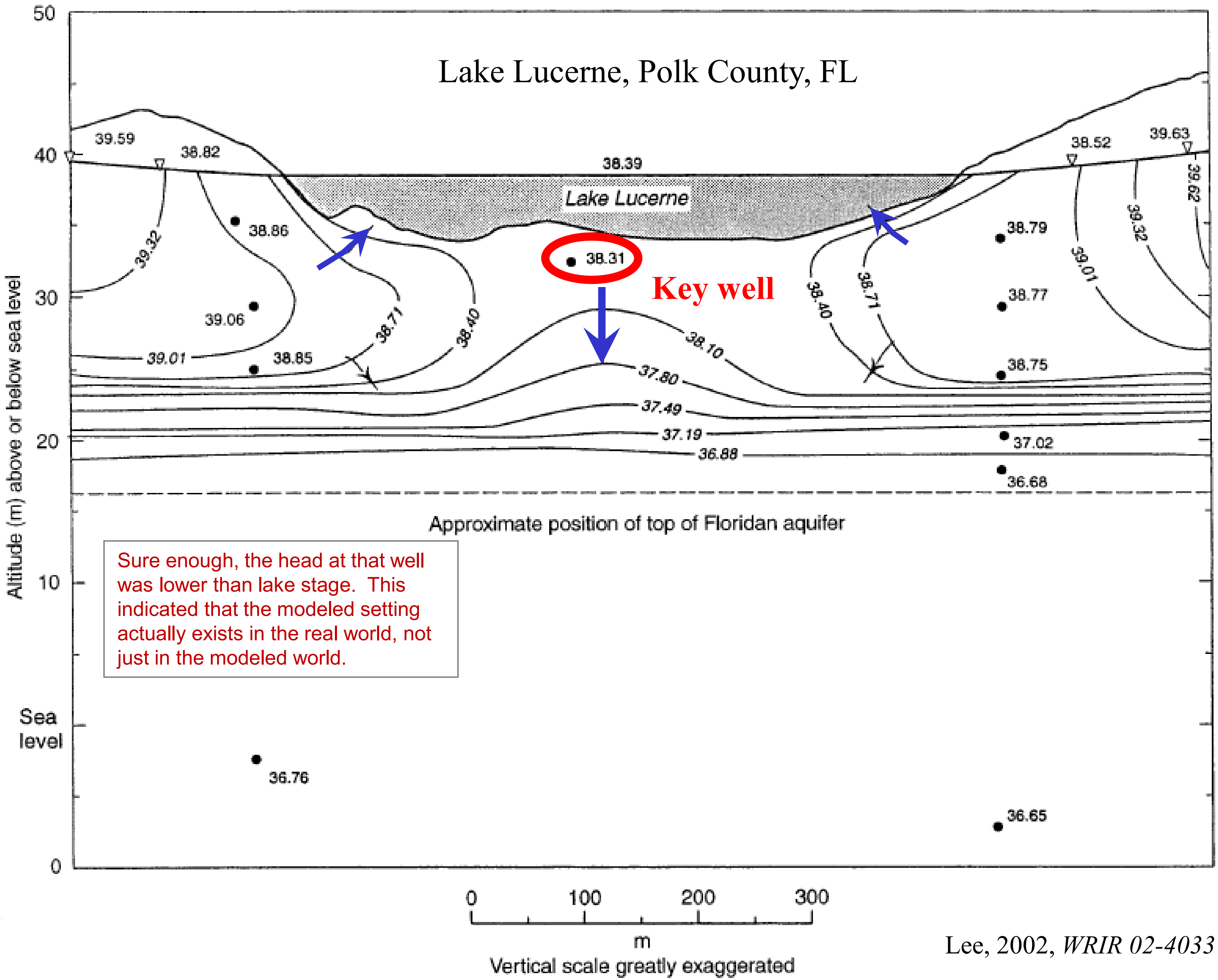


But how to test this? – you'd need a well in the middle of the lake

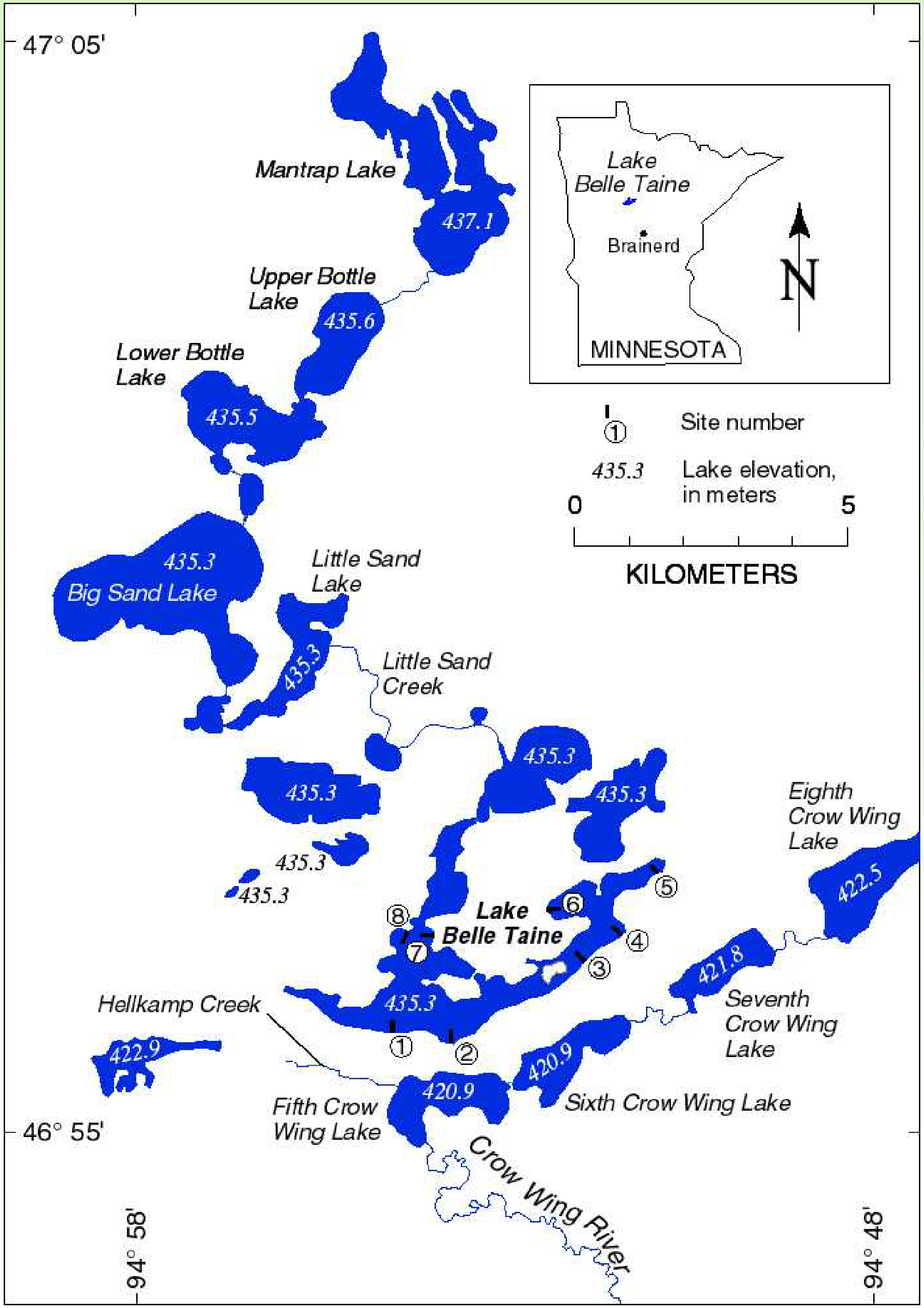


Terrie Lee, Lake Lucerne, Florida

They floated a barge carrying a drill rig out to the center of this lake that is about 6 m deep. They installed a piezometer and measured depth to water inside the casing and compared that with measurements of depth to water outside of the casing (tough to do on a windy day!). This gave them difference in head between the well screen and the lake. The white rectangle is a styrofoam float that rises and falls as the lake level changes. It is a ~~nice~~ rockin' and rollin' platform that can make water-level measurements difficult in a stiff breeze. This photo was taken back in the bad old days before we had personal flotation devices.



Lee, 2002, *WRIR 02-4033*

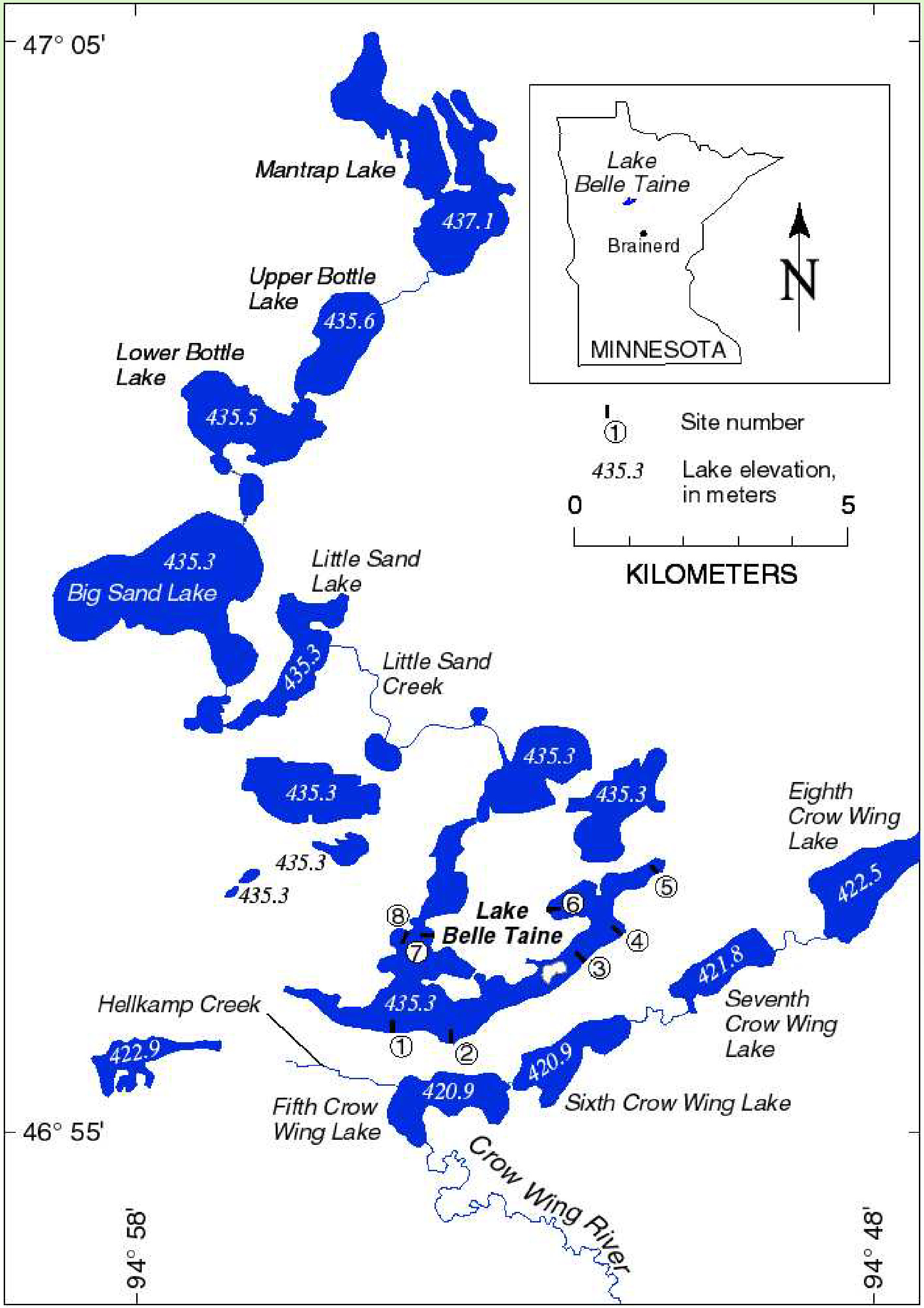


Strange field results + modeling = new understanding

the Lake Belle Taine story

This study provides an example of what can happen in unusual settings. In this case, the field results came first and the modeling helped us understand how this type of setting could exist.

Rosenberry, 2000, *WRR*

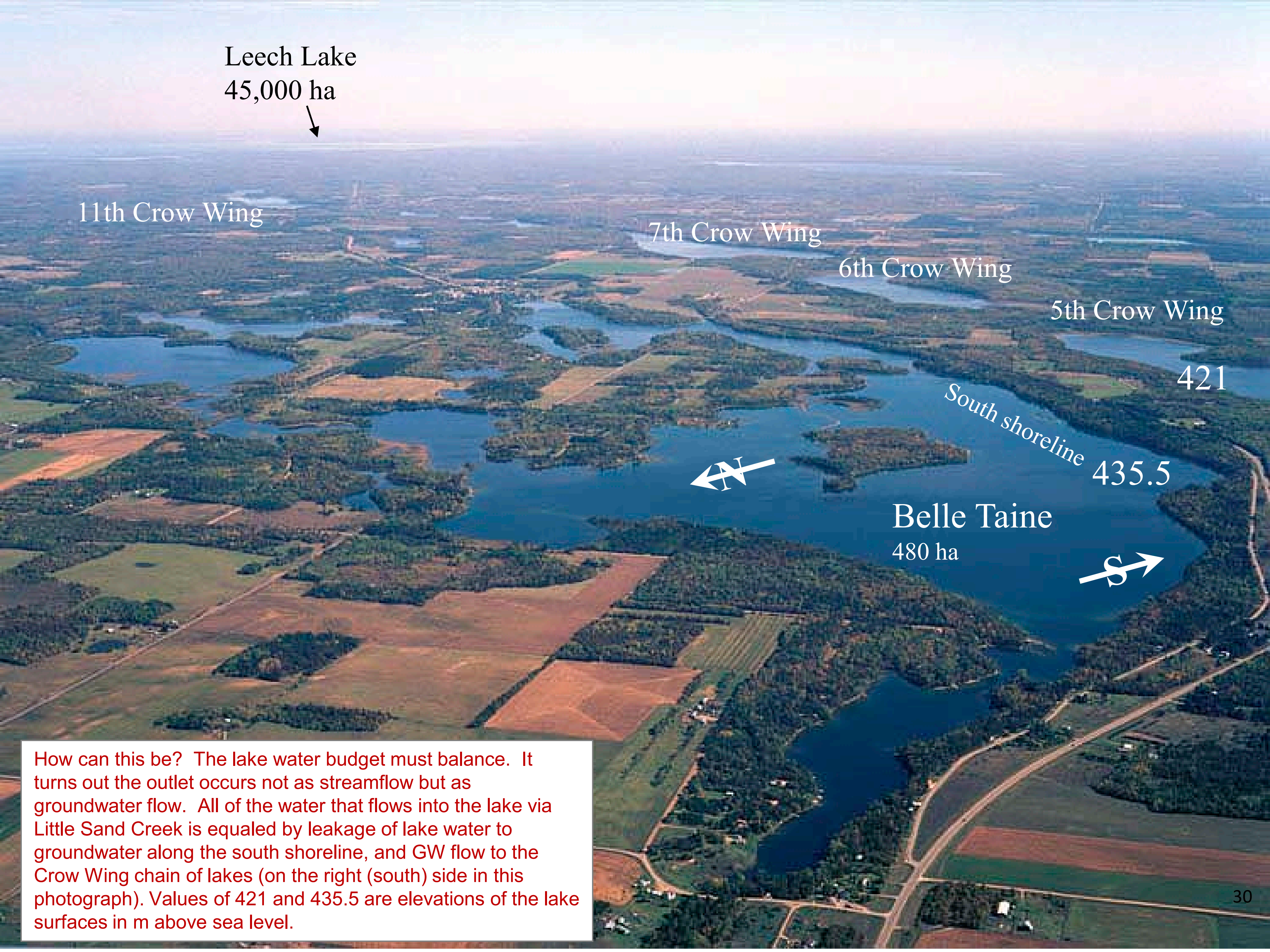


- Ten lakes drain into Belle Taine
- Average streamflow into lake = 1 m^3/s
- No outlet
- $P = E$

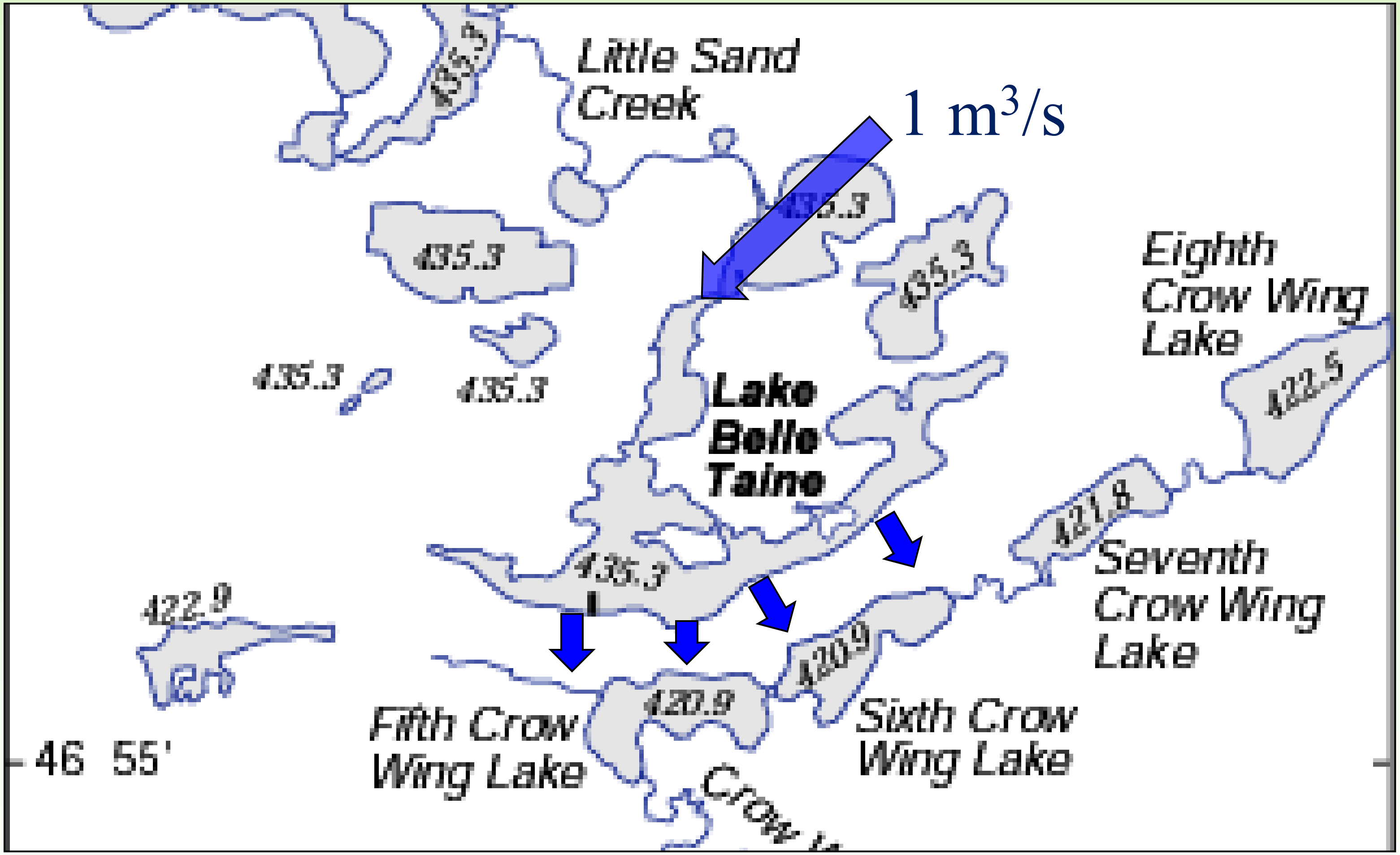
Native translation – "The lake into which the river dies"

- Where does all the water go? There is no outlet
- Lakes as close as 0.5 km away are 15 m lower in stage (a gradient of 0.03)
- Drillers report unusually warm ground water in wells drilled along the south shore of the lake
    - Geothermal activity?
    - GW-SW training class found strange things going on

This landscape is geologically young; it is still adjusting to the retreat of glaciers that occurred about 9000 years ago and the drainage network is still not fully developed. Because of that, Lake Belle Taine does not yet have a surface-water outlet.

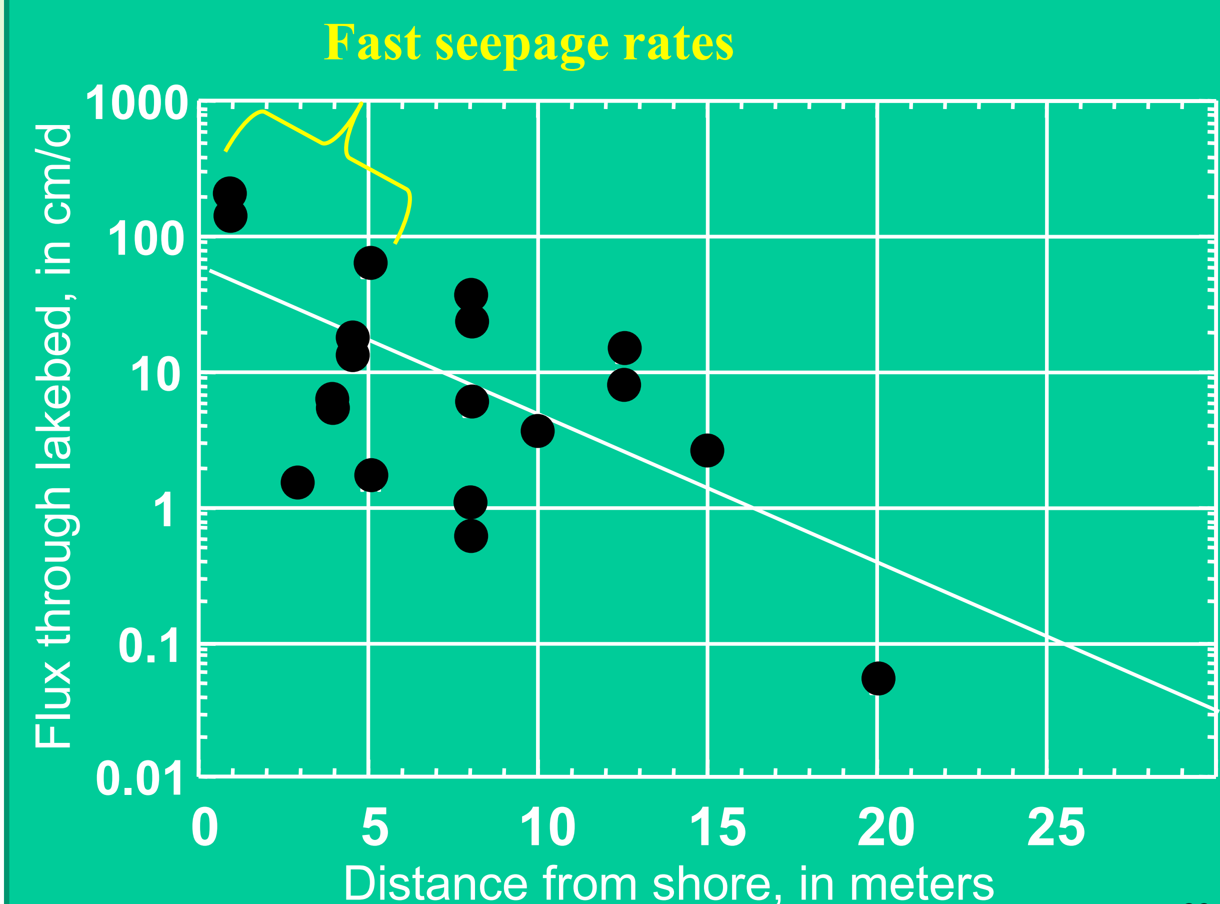


How can this be? The lake water budget must balance. It turns out the outlet occurs not as streamflow but as groundwater flow. All of the water that flows into the lake via Little Sand Creek is equaled by leakage of lake water to groundwater along the south shoreline, and GW flow to the Crow Wing chain of lakes (on the right (south) side in this photograph). Values of 421 and 435.5 are elevations of the lake surfaces in m above sea level.



In order for input of 1 m^3/s to equal output, seepage through the south shoreline that is 8.7 km long should be ~30 to ~90 cm/d.

Measured seepage ranged from 0.1 to 263 and averaged 37 cm/d



Seepage limited by a 20-30 cm thick clogging layer of sand with some organics

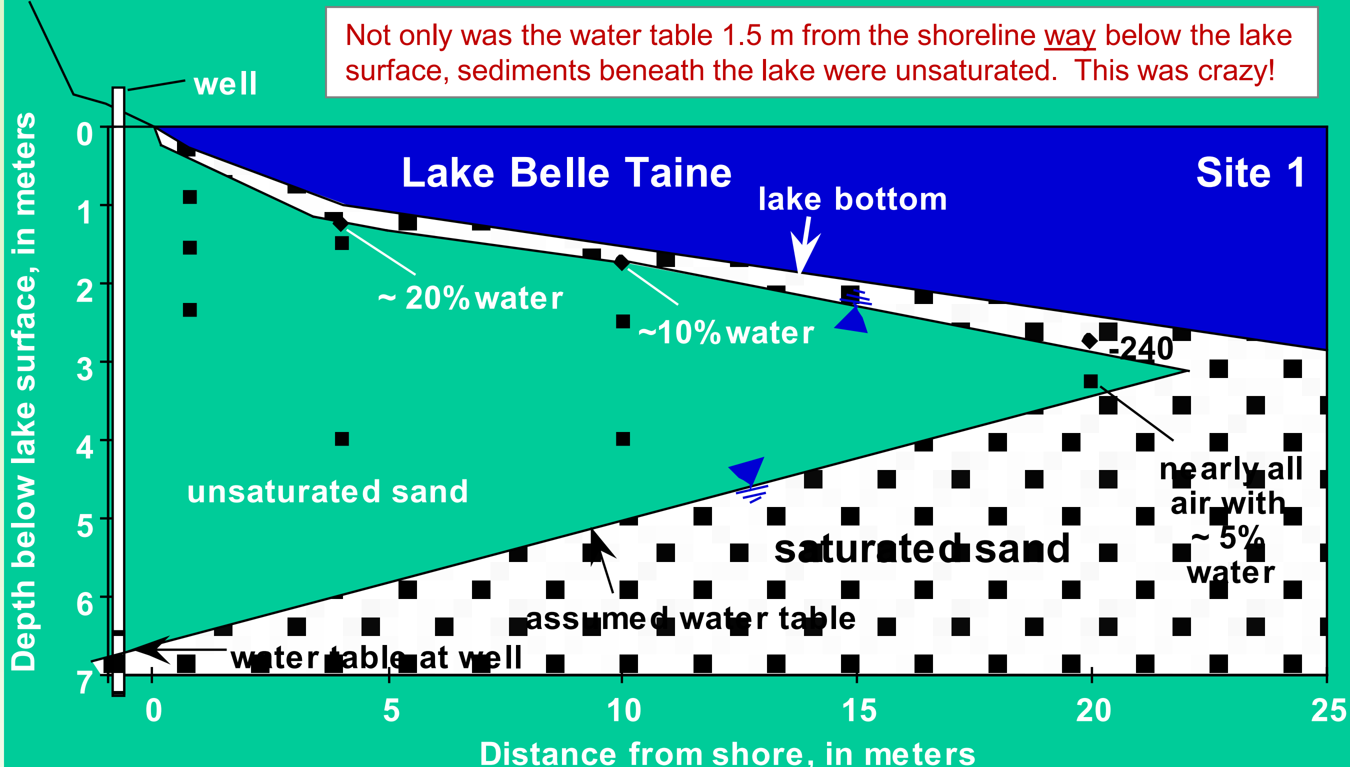
Rosenberry, 2000, *WRR*

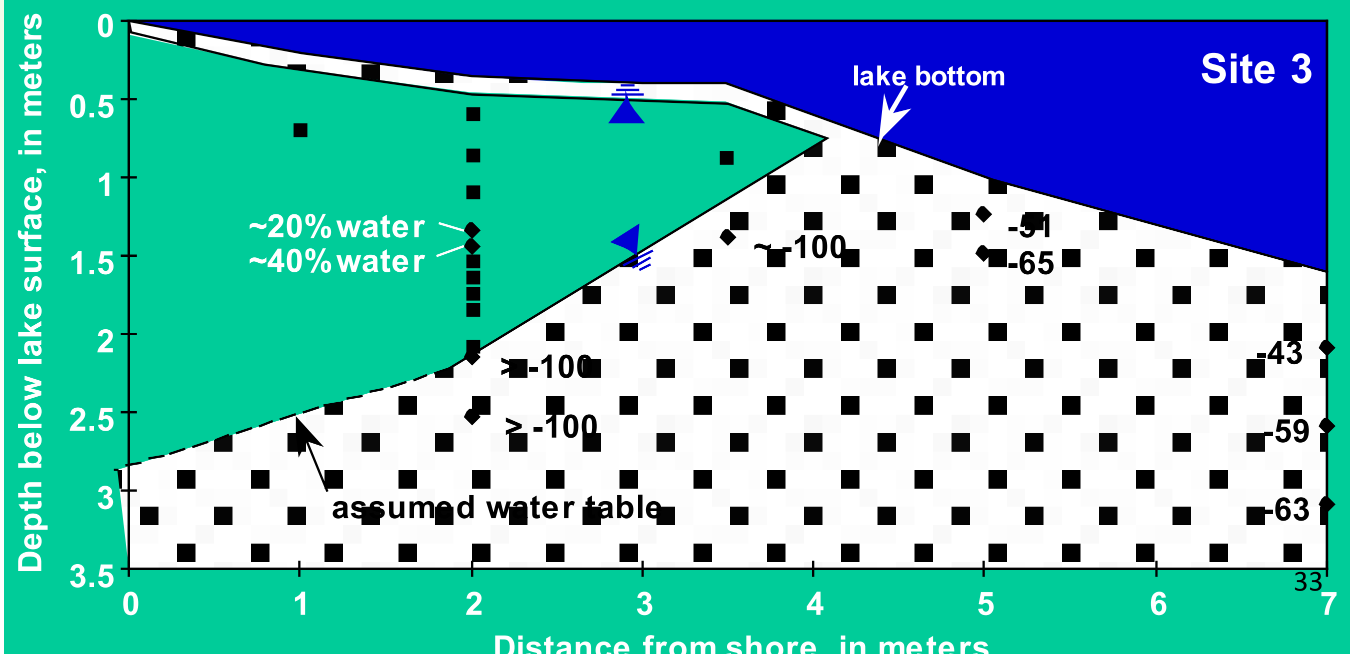
This is the deepest well that I have augered with a hand auger.

Hand-augering a 7-m deep well

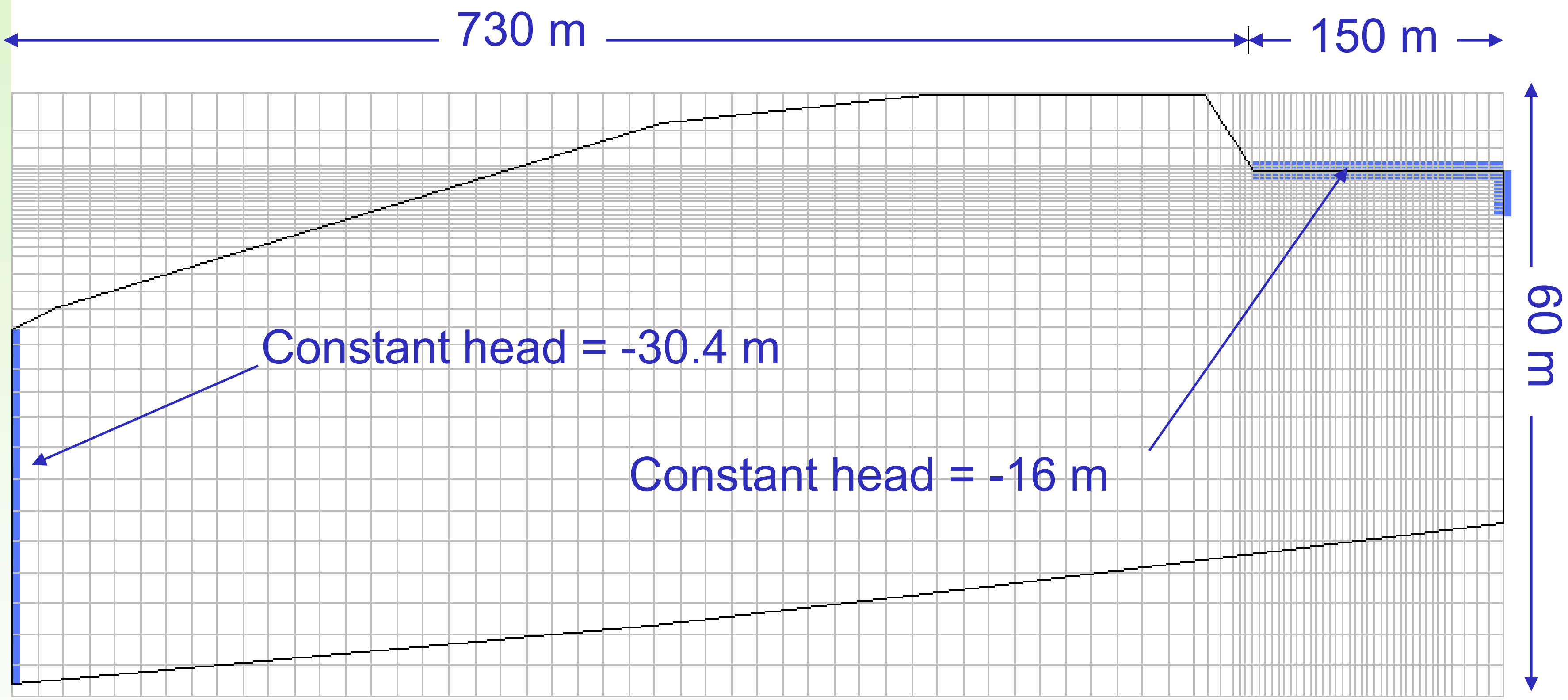
Rosenberry, 2000, *WRR*

Not only was the water table 1.5 m from the shoreline way below the lake surface, sediments beneath the lake were unsaturated. This was crazy!





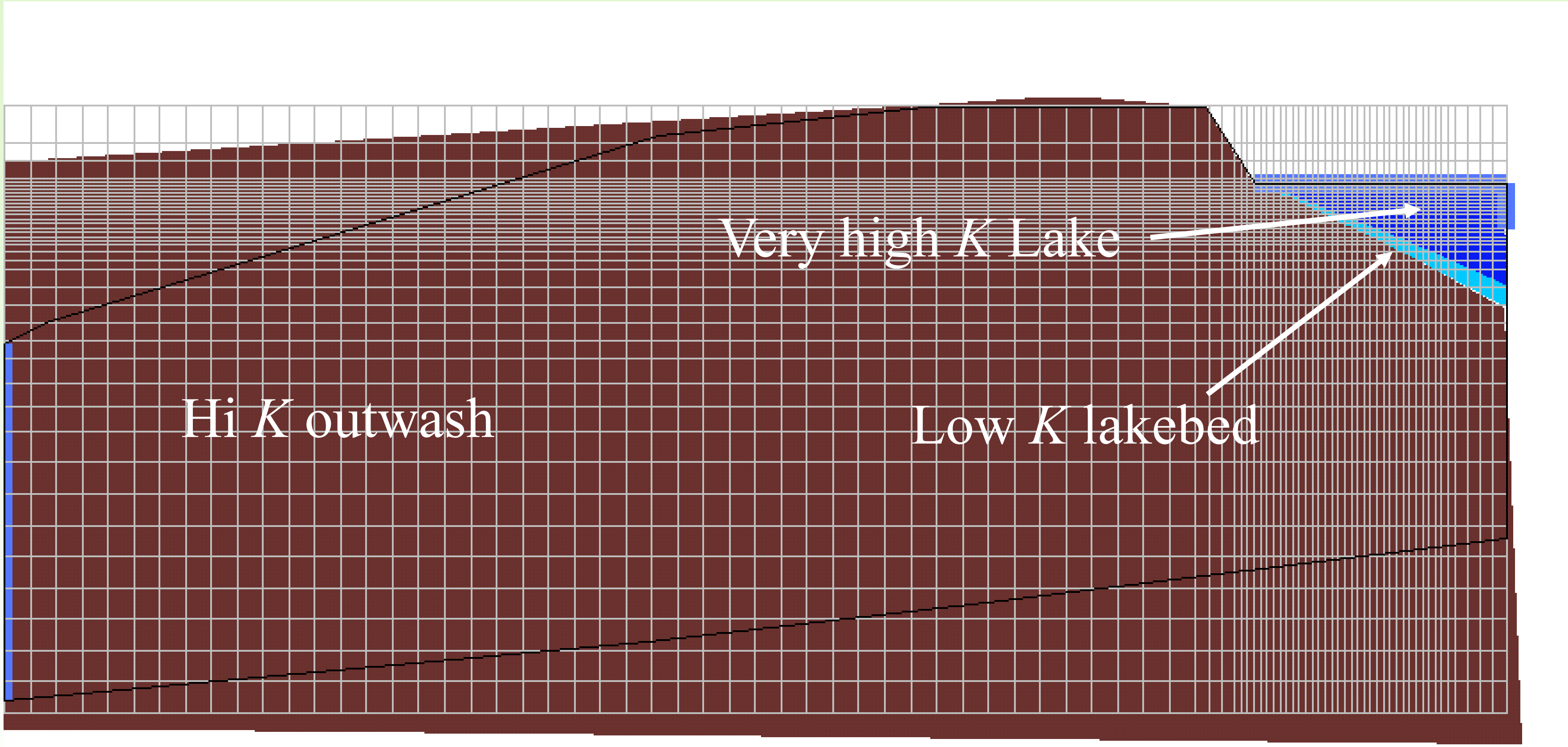
VS2dT Model grid



Tom was fascinated by the data I was collecting, but he said that no journal would publish this unless a model could verify the results.

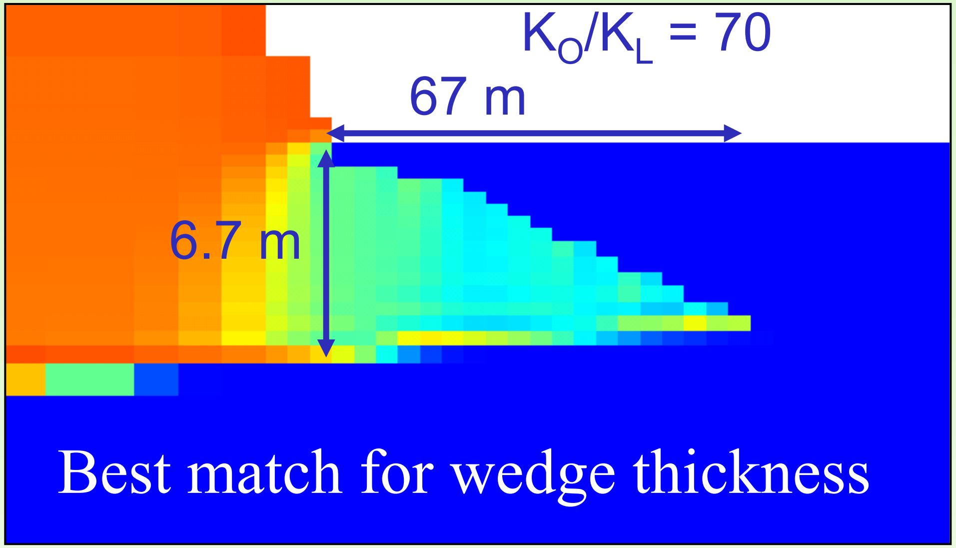
Iterating between field and model results doesn't have to start with modeling results. This time field data were collected that led to a modeling study. Here, a 2-d finite-difference model that can simulate variably saturated flow was created to match field boundary conditions. The constant head simulated on the right would be Lake Belle Taine and the constant head on the left would be one of the Crow Wing lakes.

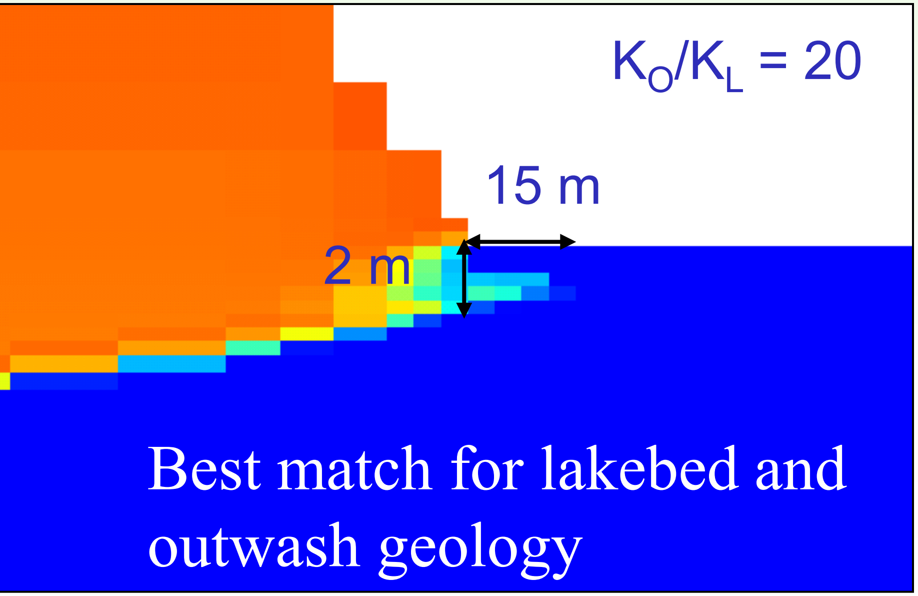
VS2D textures

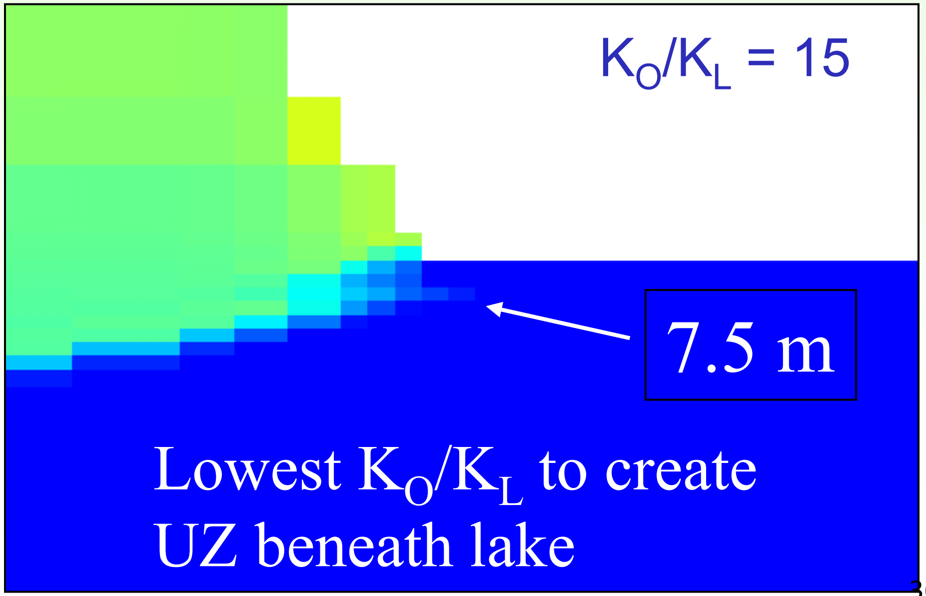


The organic-rich sand of the lakebed was simulated in the light blue zone that increased in thickness with distance from shore. This is under the assumption that waves at the shoreline would wash fine-grained particles into the lower-energy deeper portions of the lake.

The model was able to simulate an unsaturated-zone wedge beneath the lakebed. The extent of the wedge depended on the contrast between *K* of the outwash and *K* of the lakebed sediments. A ratio of 70 created the best match for wedge thickness at the shoreline. The model indicated that the wedge extended 67 m beyond the shoreline, but we were never able to make measurements beyond 20 m from shore. A ratio of 20 was closest to best estimates based on *K* determined from sieving lakebed sediment samples. Model runs with ratios smaller than 15 failed to generate unsaturated sediments beneath the lake. Based on model results, either *K* of the outwash was larger than we determined based on grain size analyses or *K* of the lakebed was smaller than our best estimates from analysis of sediment cores collected from the lake.





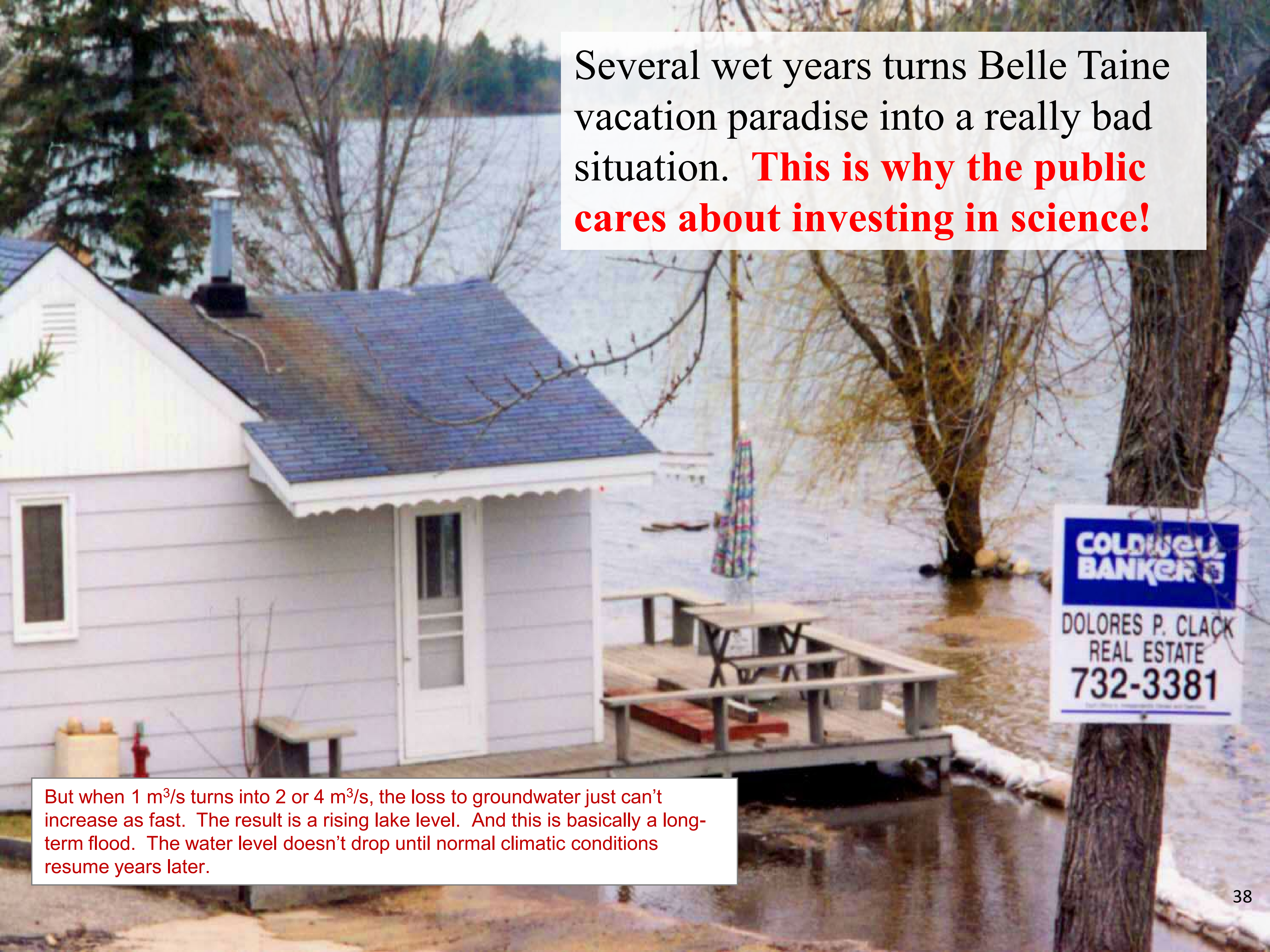


The rest of the story

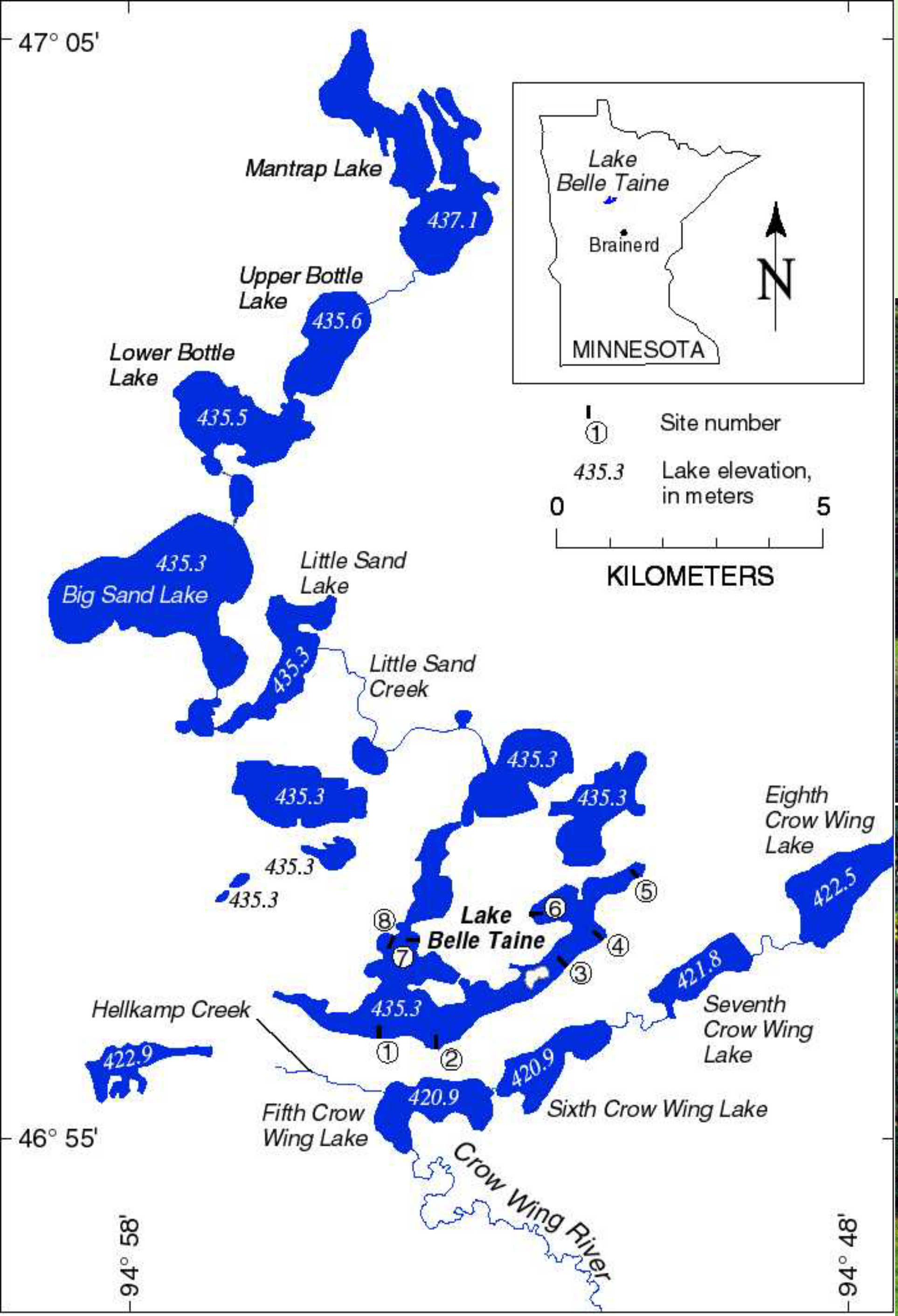
A very nice place to play

Under normal conditions, Lake Belle Taine is a very pleasant lake with beautiful scenery and many recreation opportunities.

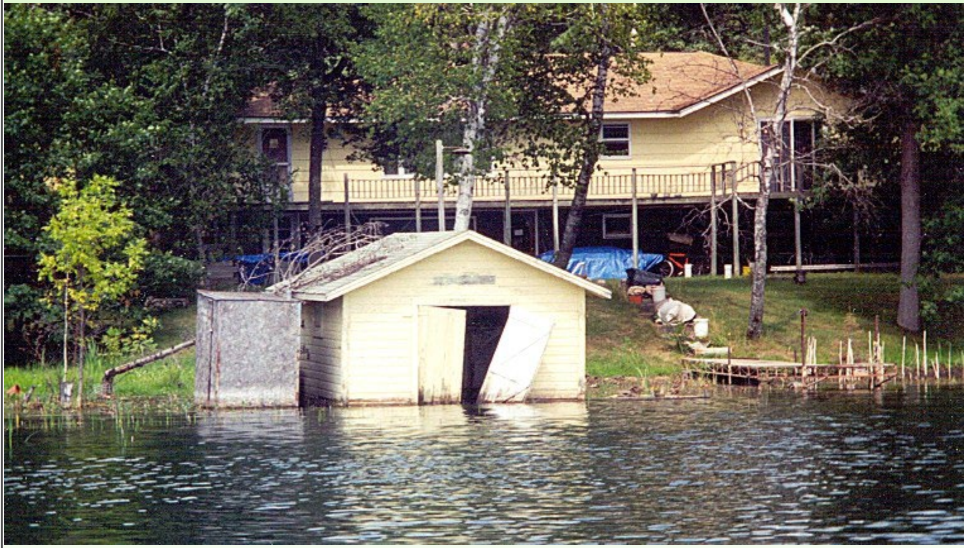
Several wet years turns Belle Taine vacation paradise into a really bad situation. **This is why the public cares about investing in science!**

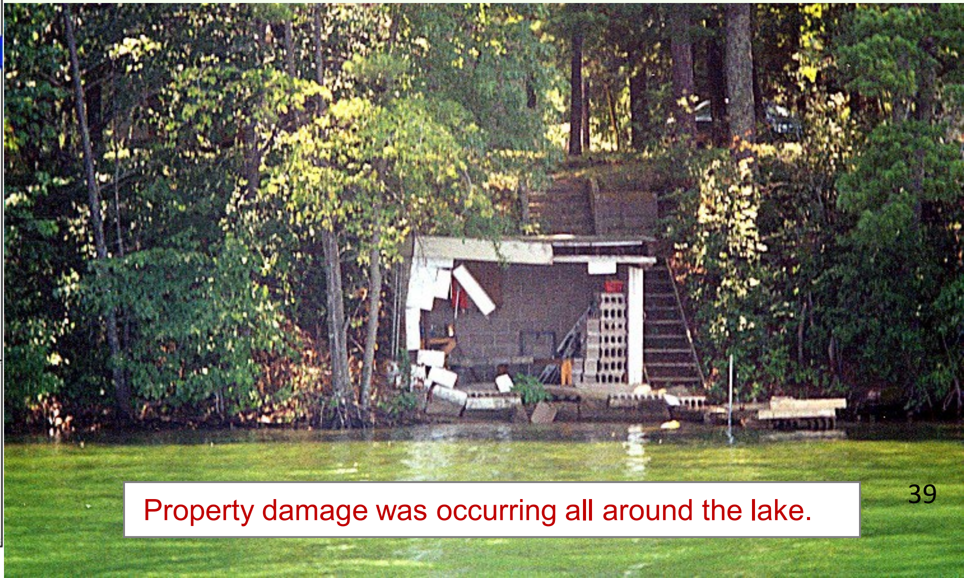


But when 1 m^3/s turns into 2 or 4 m^3/s, the loss to groundwater just can't increase as fast. The result is a rising lake level. And this is basically a long-term flood. The water level doesn't drop until normal climatic conditions resume years later.



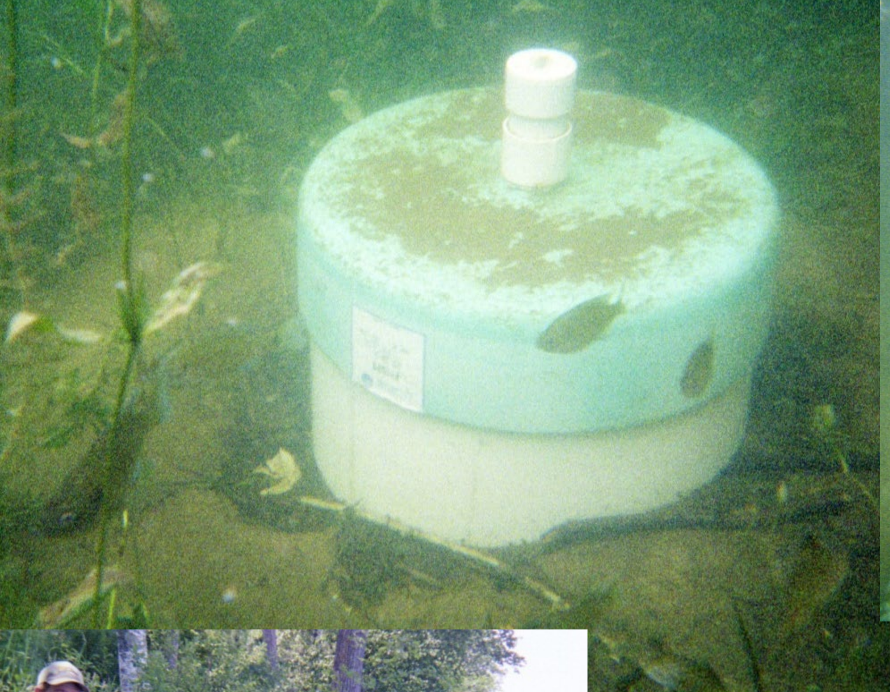
High water is countered by loss to groundwater, but it's not enough

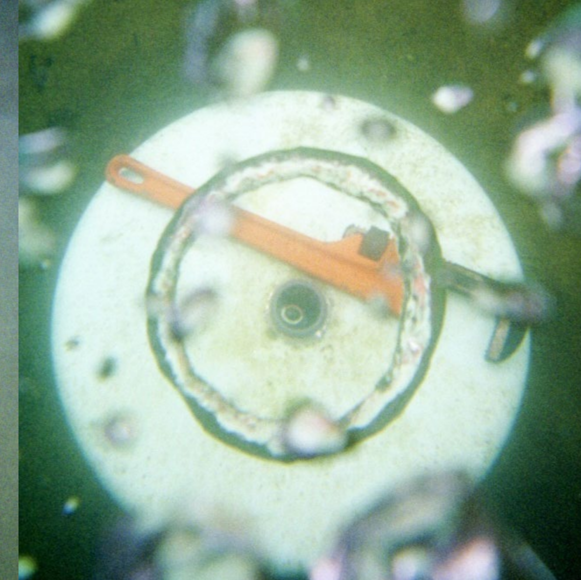




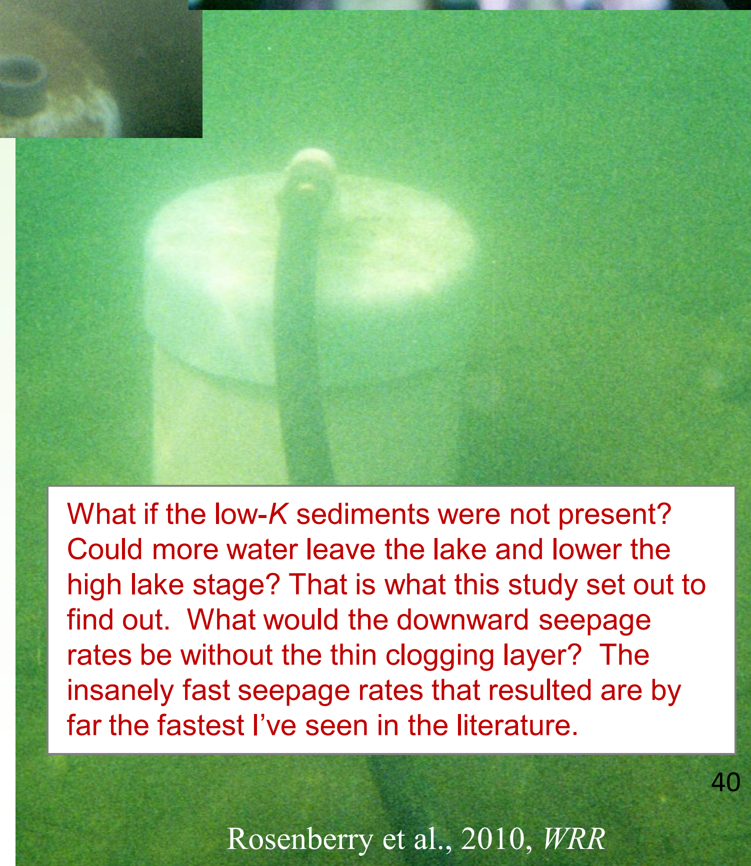
Property damage was occurring all around the lake.

. . So what to do about this?



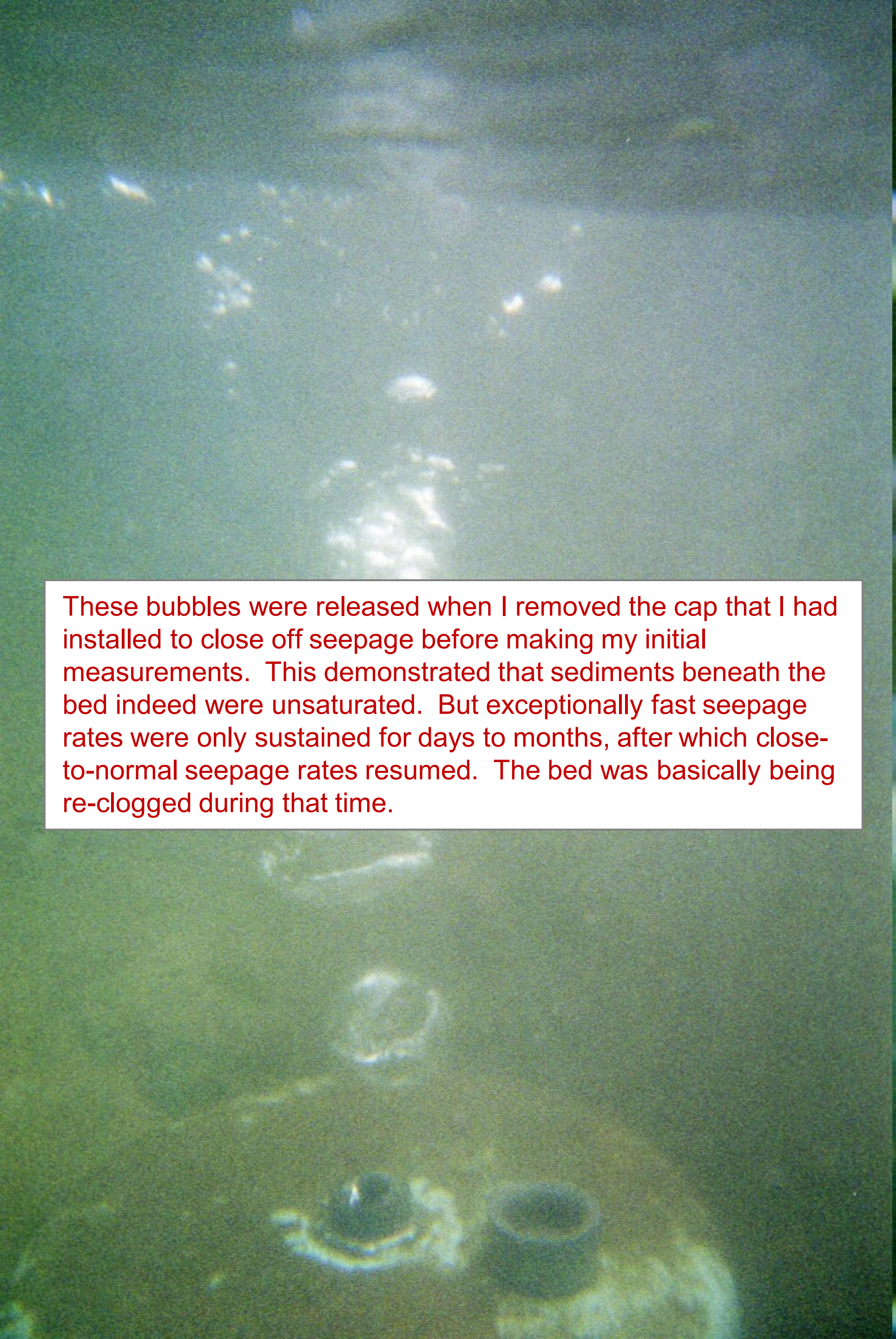


- Jetted in 30 cm dia. PVC pipe ~30 cm through the lakebed
- Seepage baggie was instantly sucked inside the pipe
- Connected seepage cylinder to an inverted floating seepage tub with 5.5-cm-diameter hose
- Measured seepage rates up to **25,000 cm/d!**
- Seepage rates were back to normal after 2 months (10 to 100 cm/d)

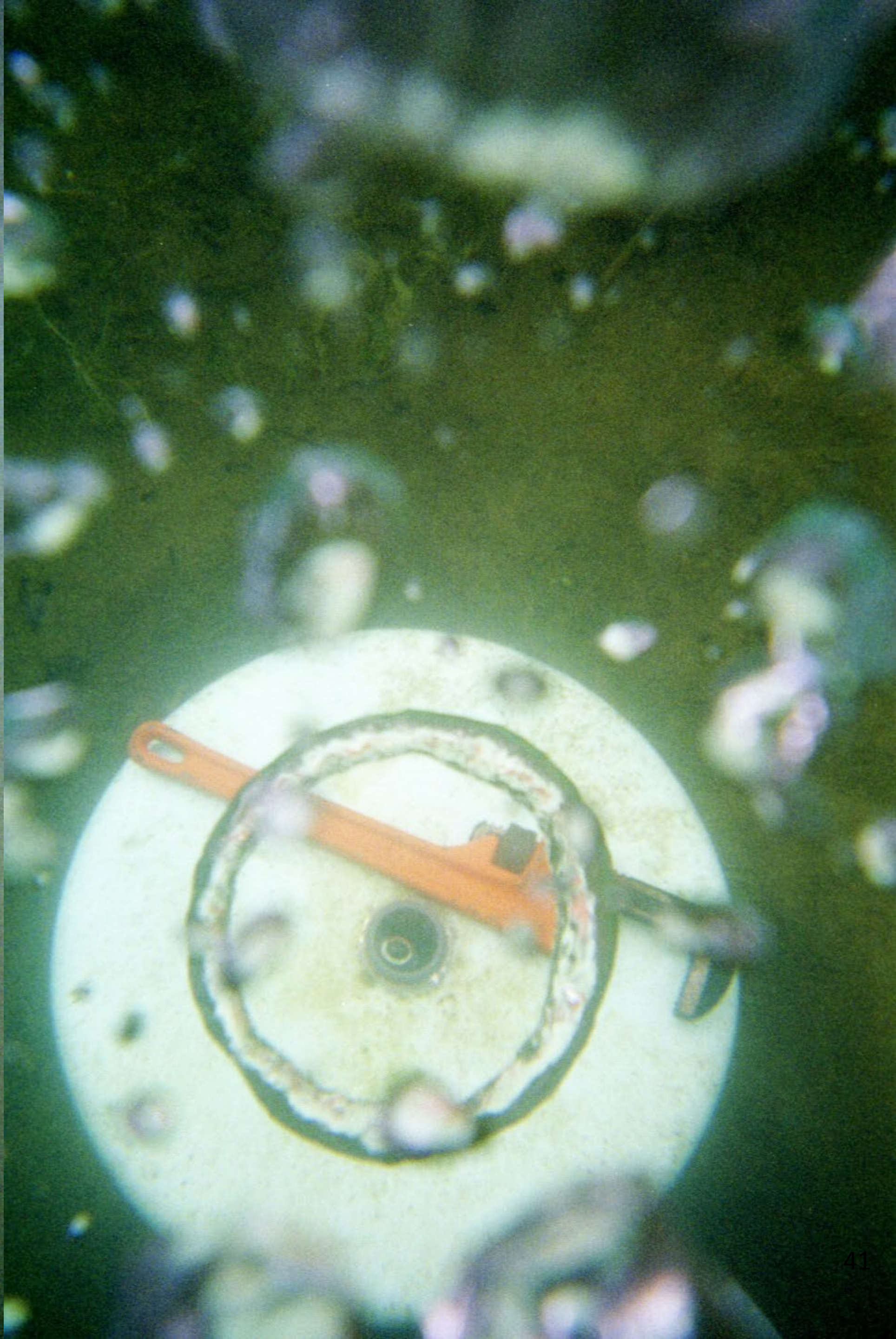


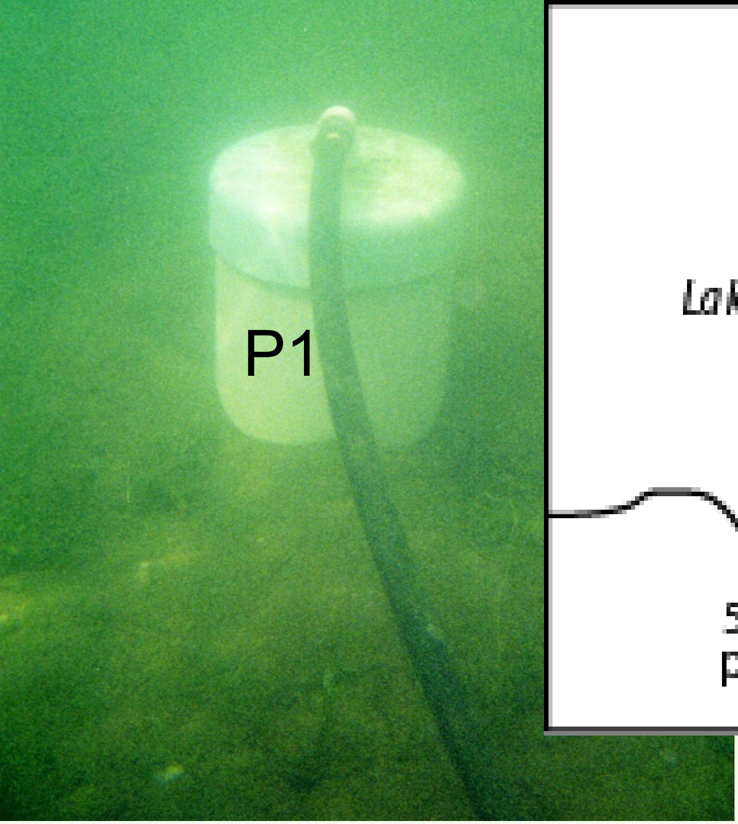
What if the low-*K* sediments were not present? Could more water leave the lake and lower the high lake stage? That is what this study set out to find out. What would the downward seepage rates be without the thin clogging layer? The insanely fast seepage rates that resulted are by far the fastest I've seen in the literature.

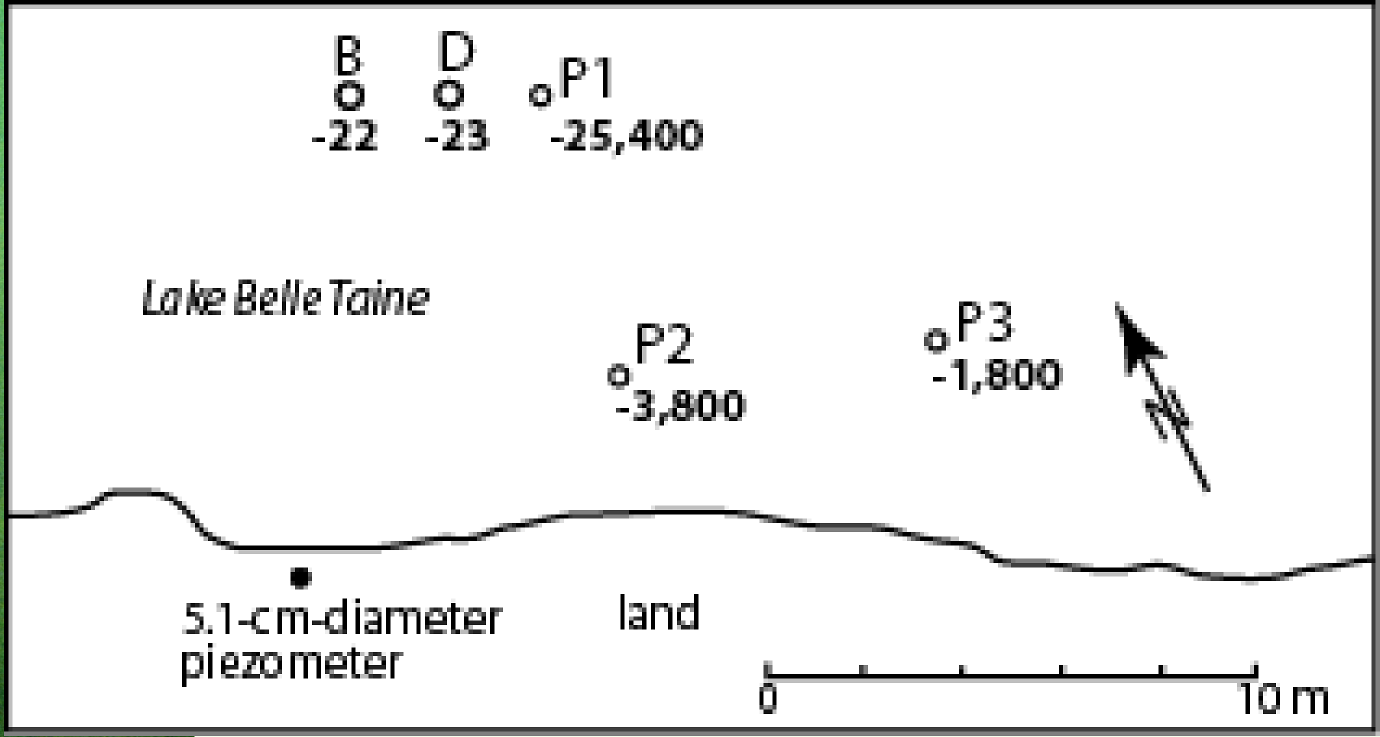
Rosenberry et al., 2010, *WRR*

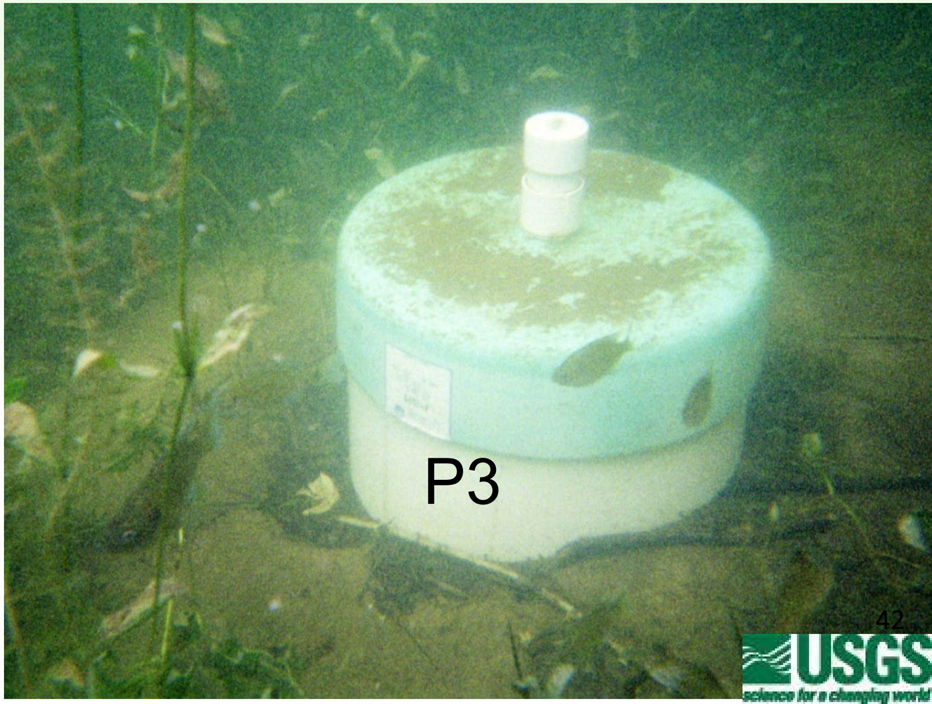


These bubbles were released when I removed the cap that I had installed to close off seepage before making my initial measurements. This demonstrated that sediments beneath the bed indeed were unsaturated. But exceptionally fast seepage rates were only sustained for days to months, after which close-to-normal seepage rates resumed. The bed was basically being re-clogged during that time.



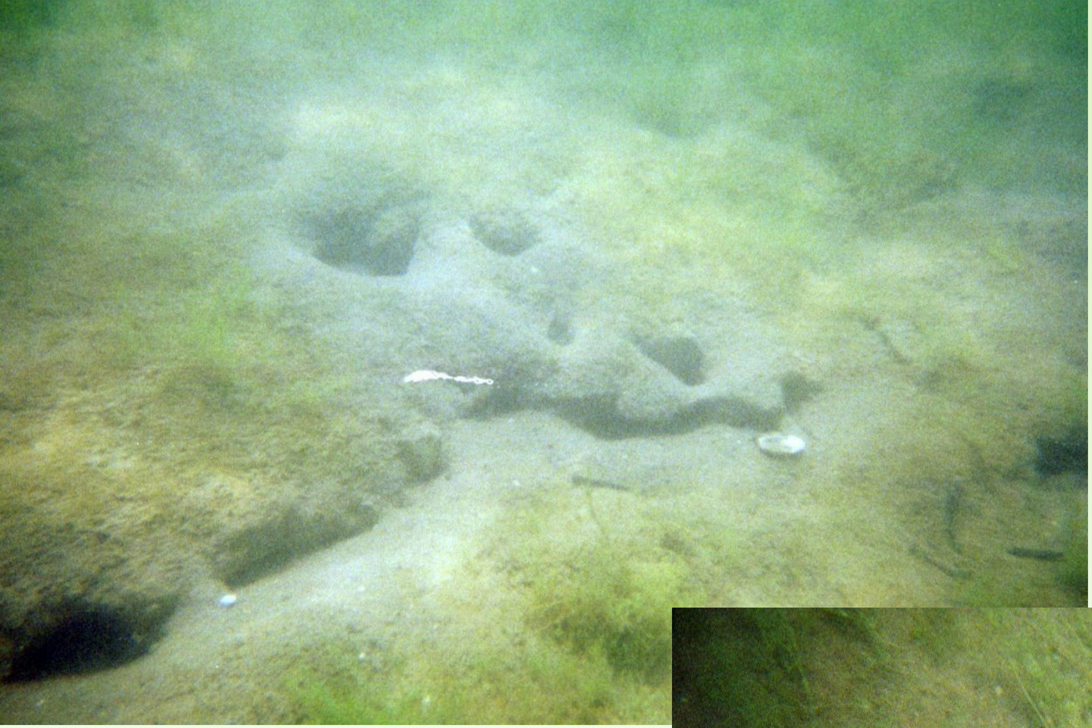






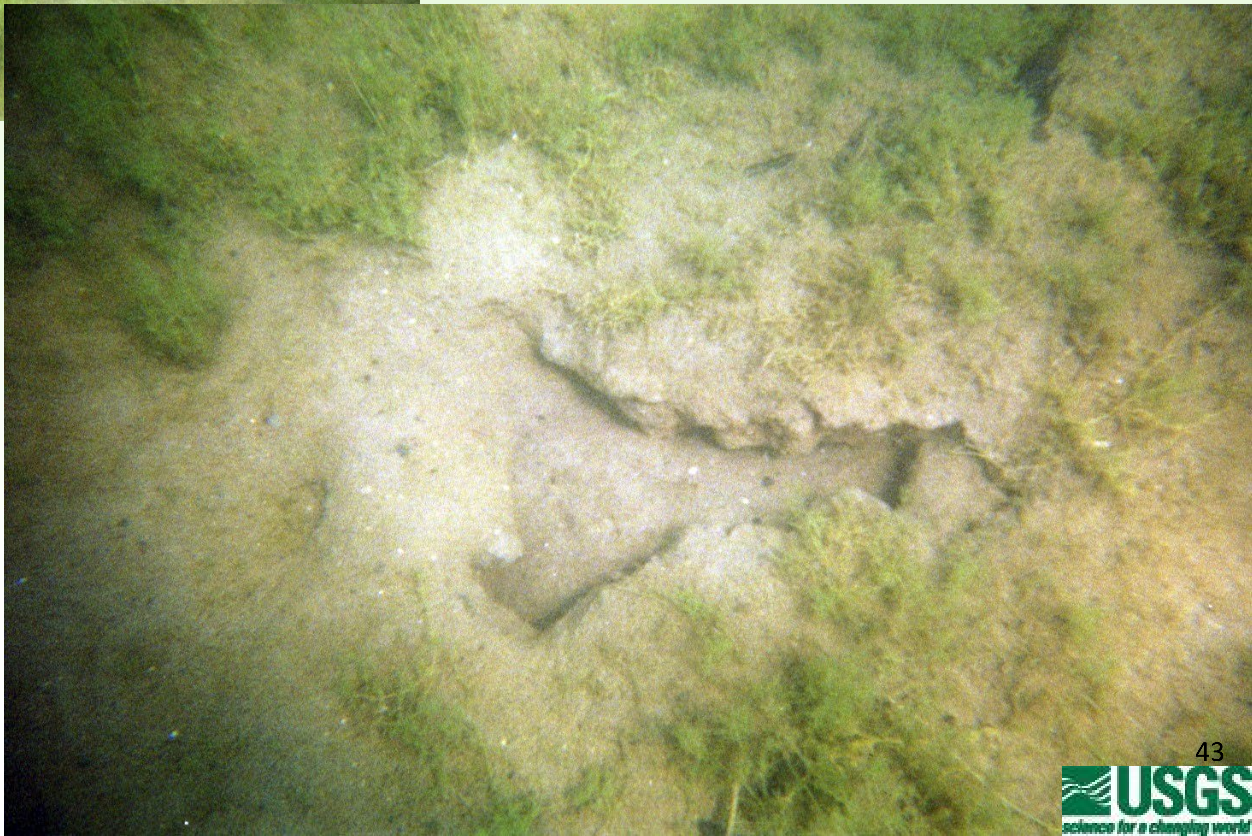
- Post-disturbance seepage was 2 to 3 orders of magnitude faster than pre-disturbance seepage
- After 47 days P1 was still 1500 cm/d

Rosenberry et al, 2010, *WRR*



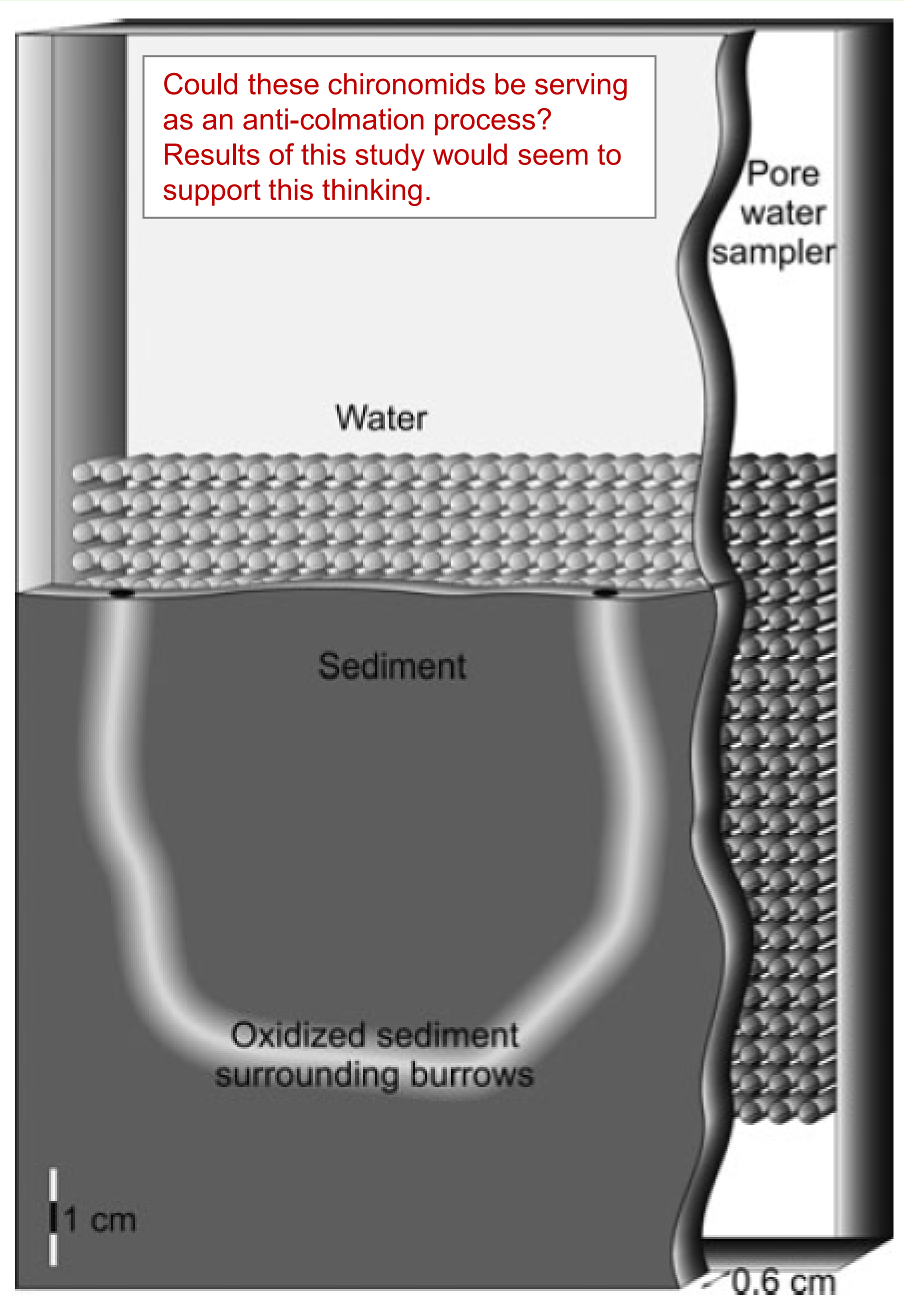
This raises the question, is the bed self-sealing? We've seen these holes or depressions in other lakes where seepage is downward and rapid. But when we place seepage meters over these areas, most of the time the seepage rates are not unusually large. Why not? Also, we have observed small holes that appear to be connected to other holes, some of which are occupied by crayfish and other benthic animals. What effect might they have on lakebed permeability? More about that later when we talk about biological effects.

- Is natural bed self sealing?
- Crayfish burrows
  - Macro equivalent to chironomids?

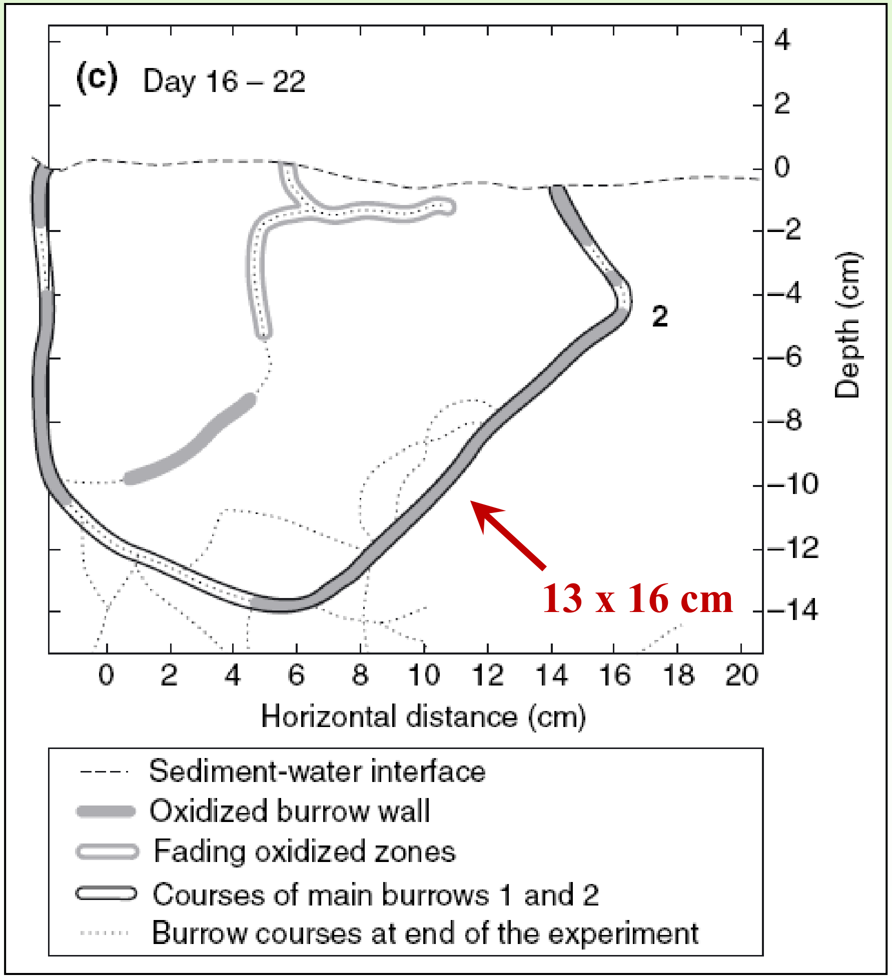


Chironomid larvae

Lake Arendsee, Germany



1 to 2 cm long

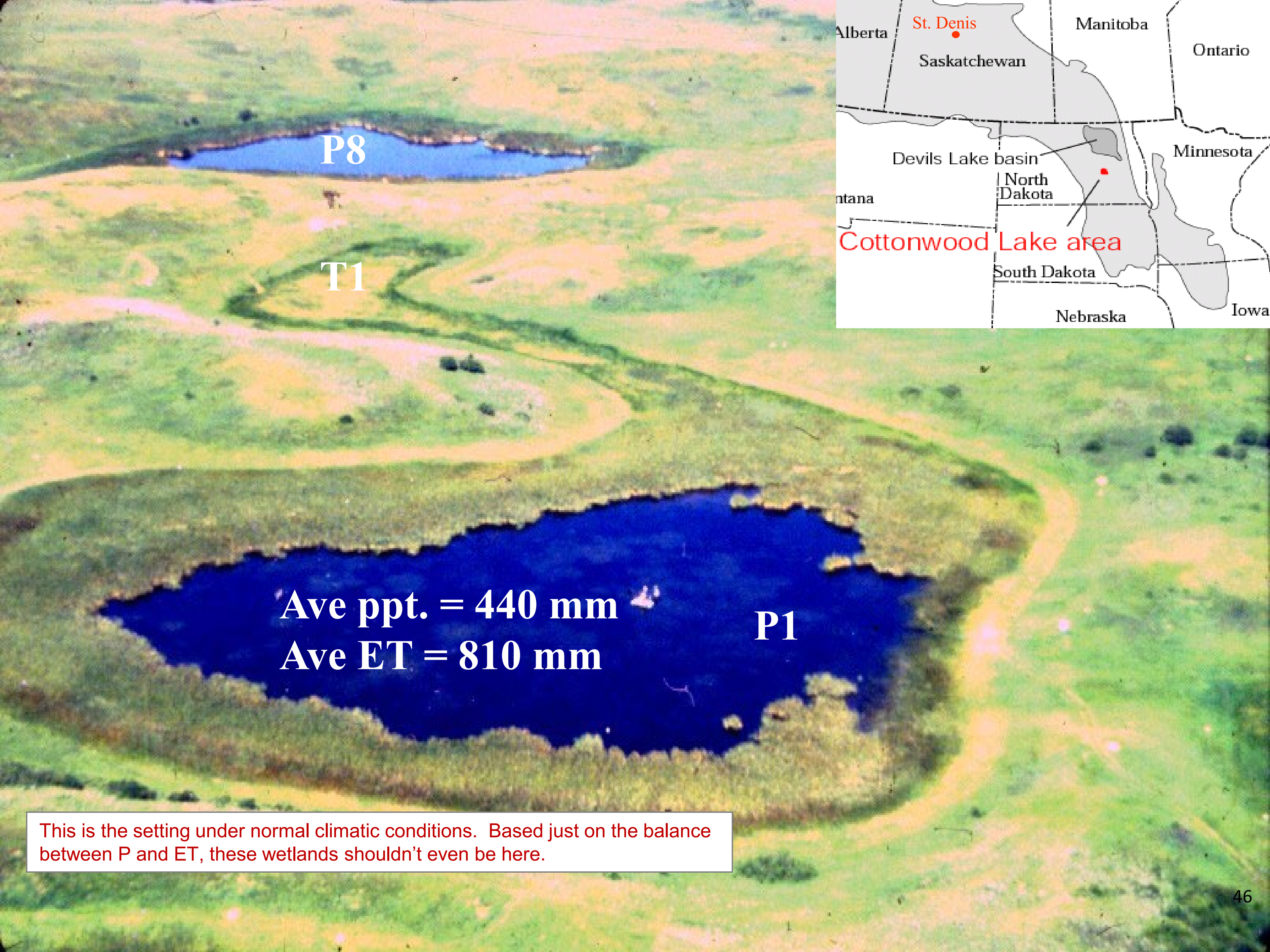


Lewandowski et al., 2007, Freshwat. Biol

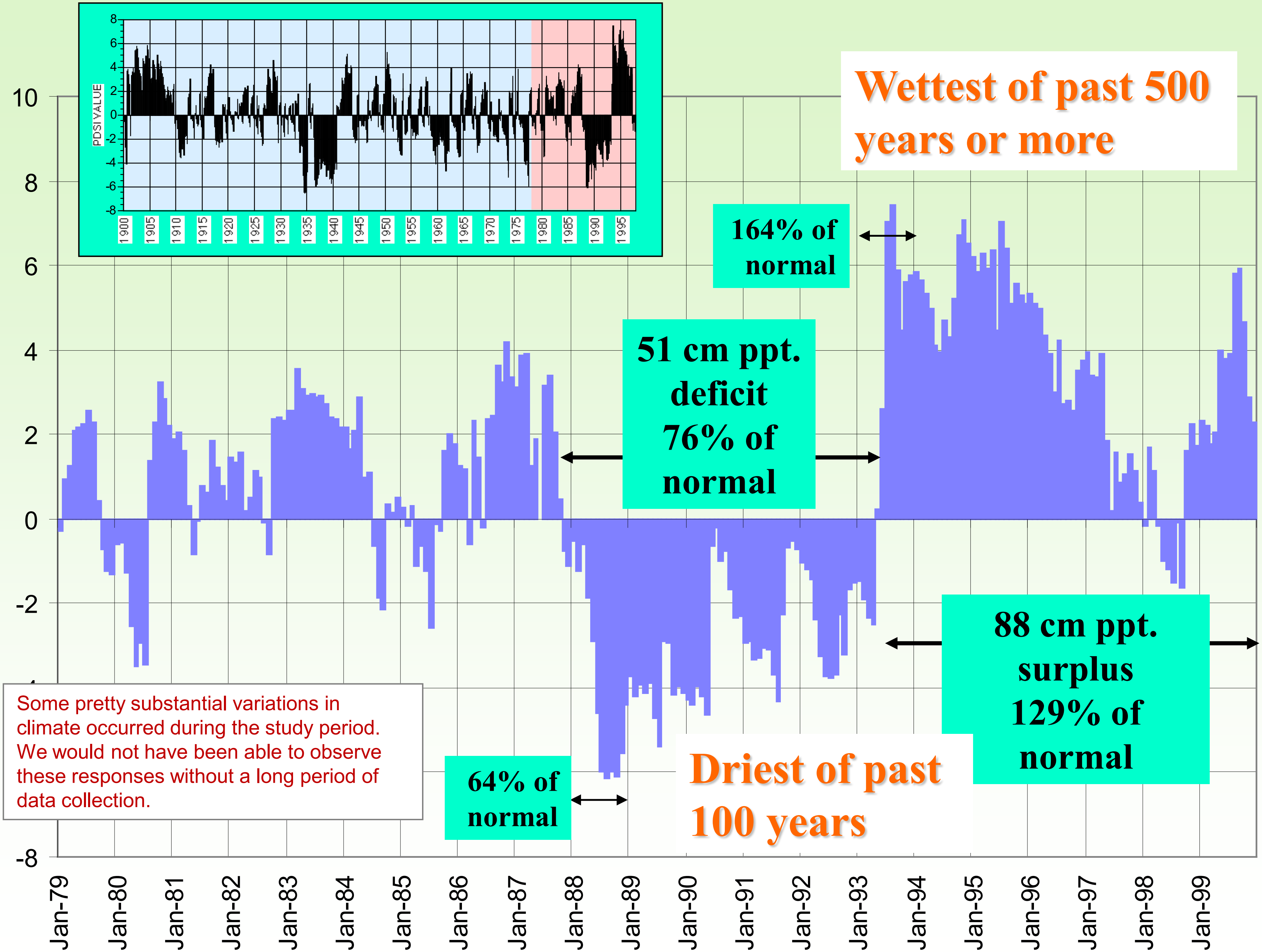
Stage change in closed basins as an indicator of climate change

ground-water interaction enhances wetland response

This is an example of positive feedback in the hydrologic system that would be difficult to model without prior knowledge of the mechanisms involved (prior knowledge that resulted from collection of field data).

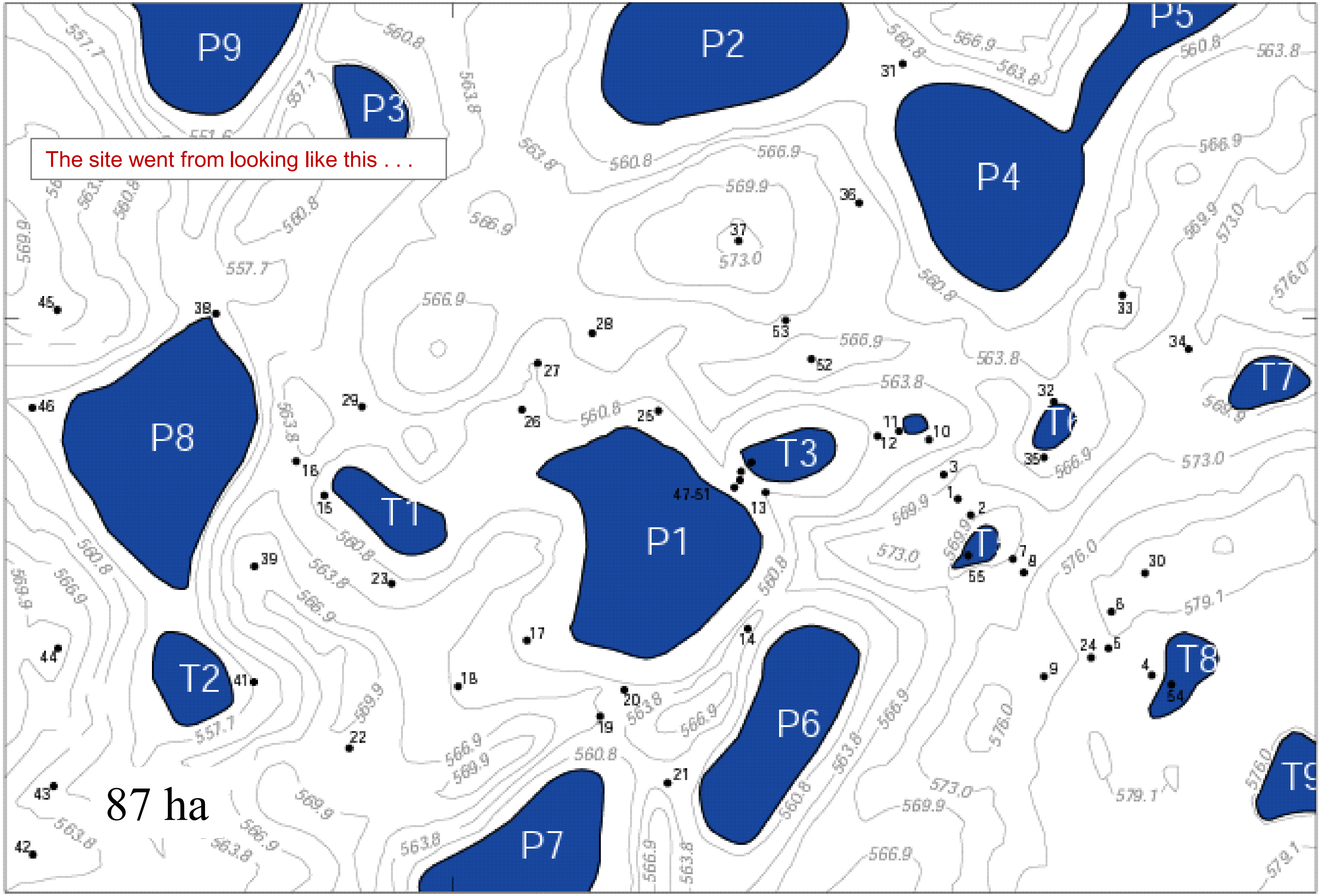


This is the setting under normal climatic conditions. Based just on the balance between P and ET, these wetlands shouldn't even be here.



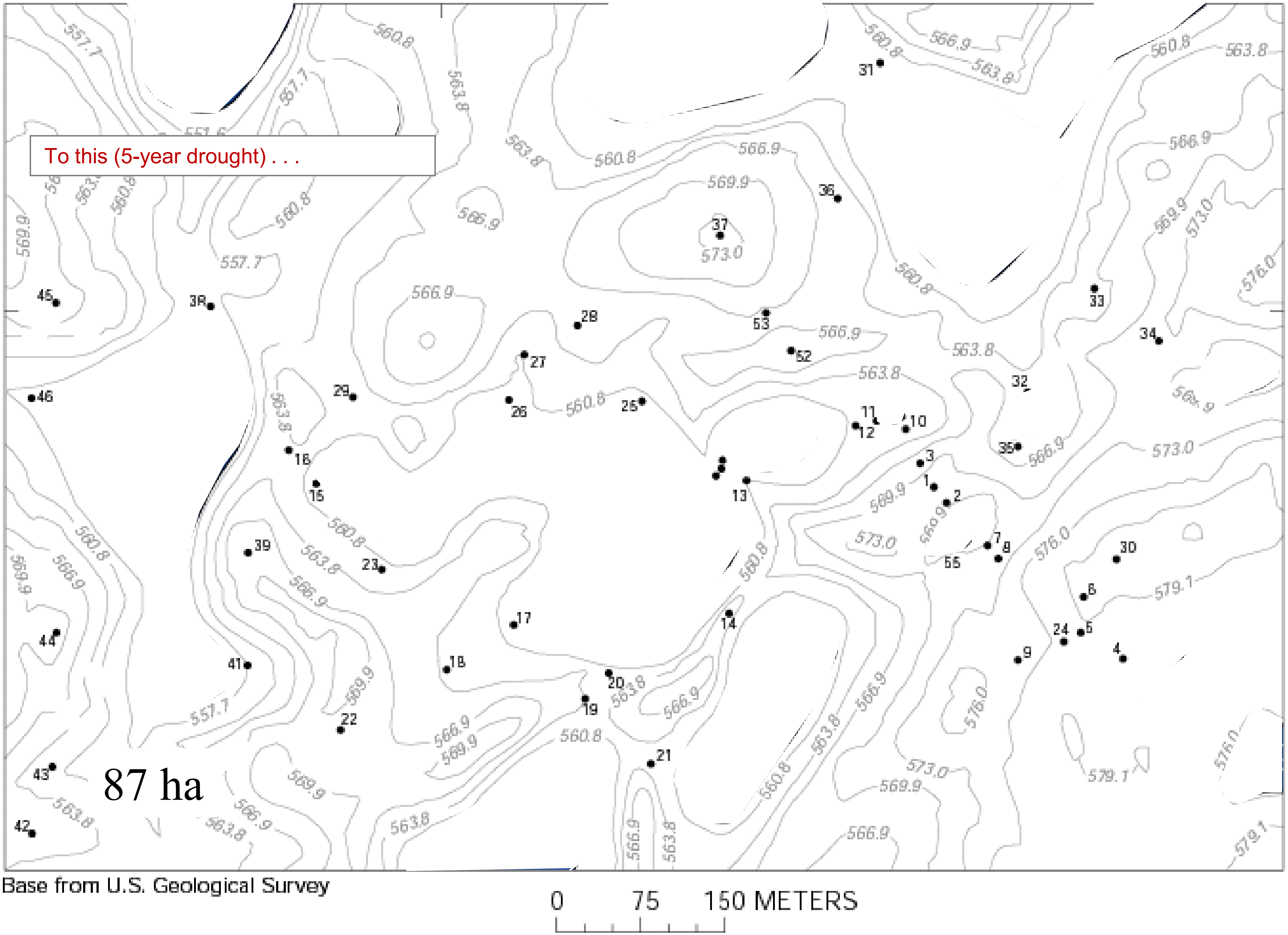
Some pretty substantial variations in climate occurred during the study period. We would not have been able to observe these responses without a long period of data collection.

Winter and Rosenberry, 1998, *Climatic Change*



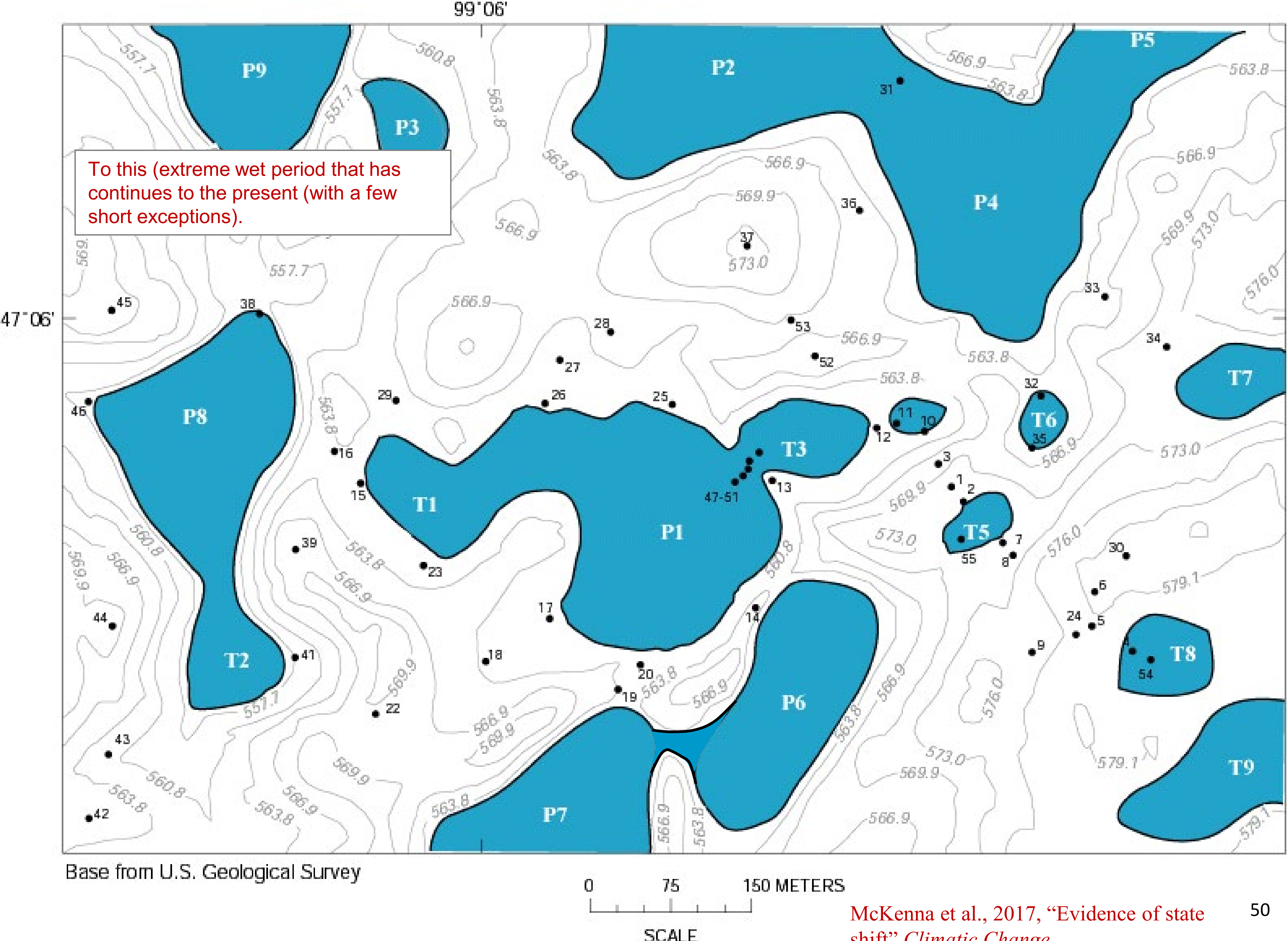
Base from U.S. Geological Survey

0 75 150 METERS

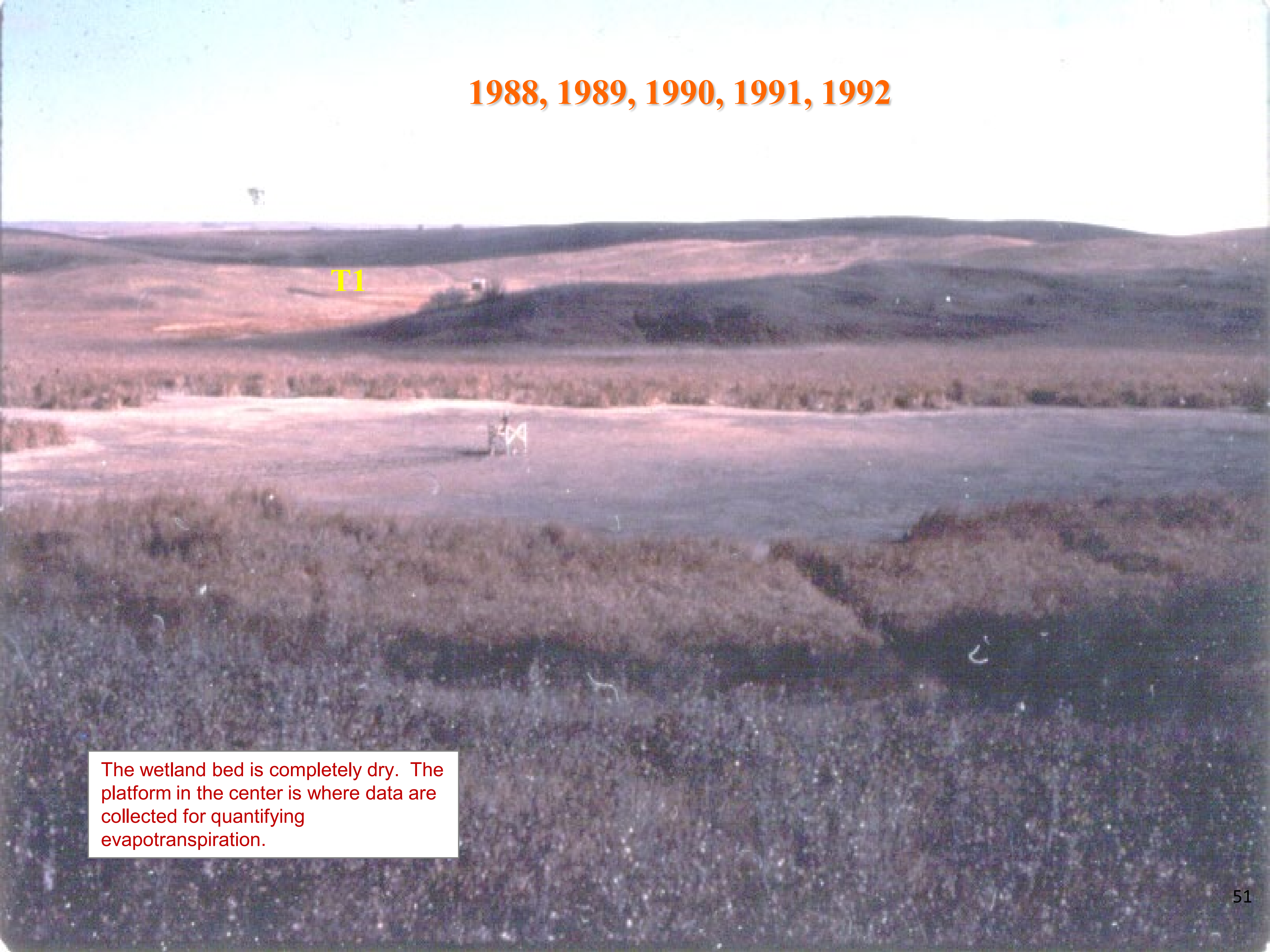


Every one of these wetlands dried up during the drought

To this (extreme wet period that has continues to the present (with a few short exceptions).



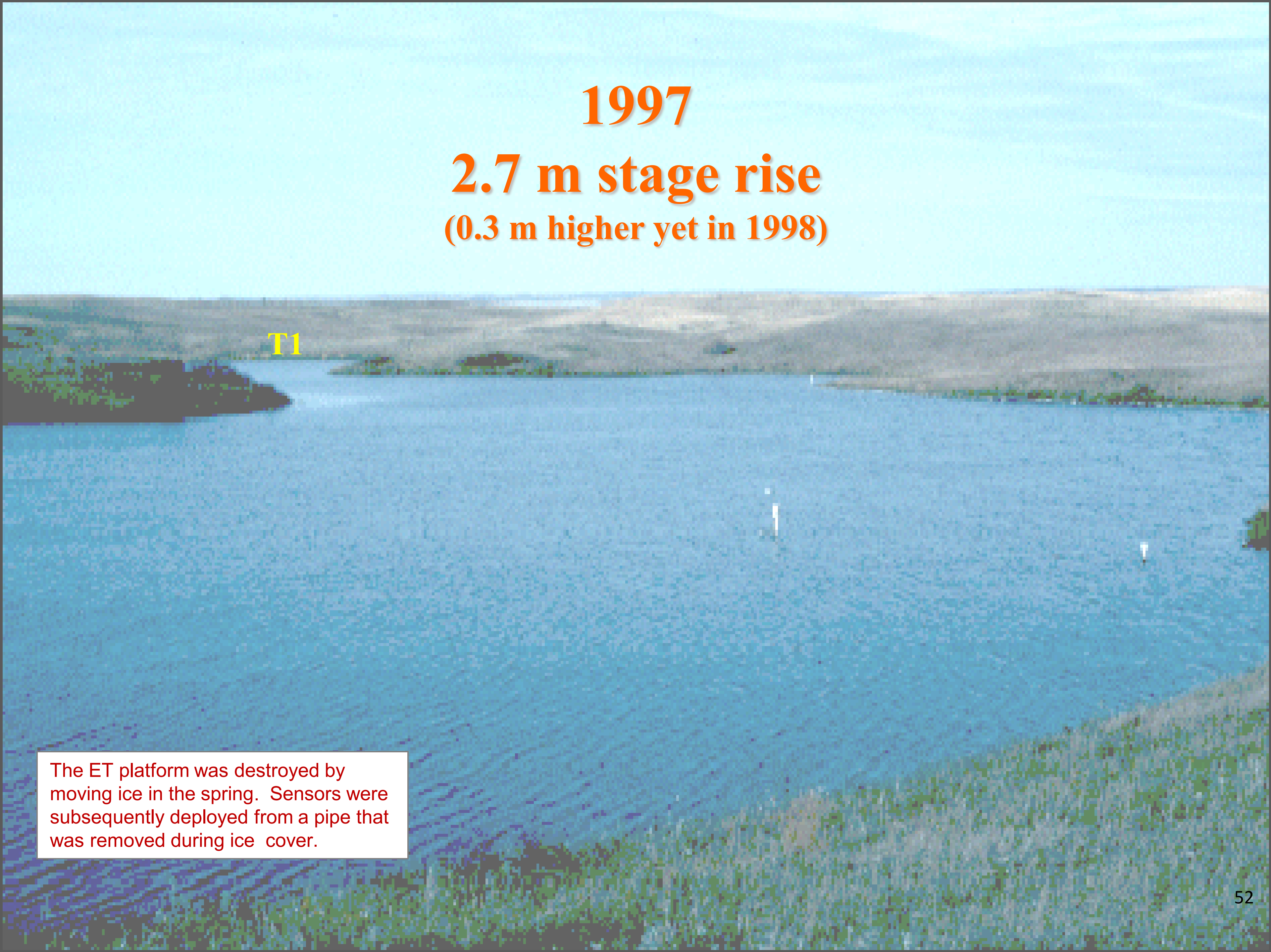
McKenna et al., 2017, "Evidence of state shift" *Climatic Change*


1988, 1989, 1990, 1991, 1992
T1
The wetland bed is completely dry. The platform in the center is where data are collected for quantifying evapotranspiration.

1997

2.7 m stage rise

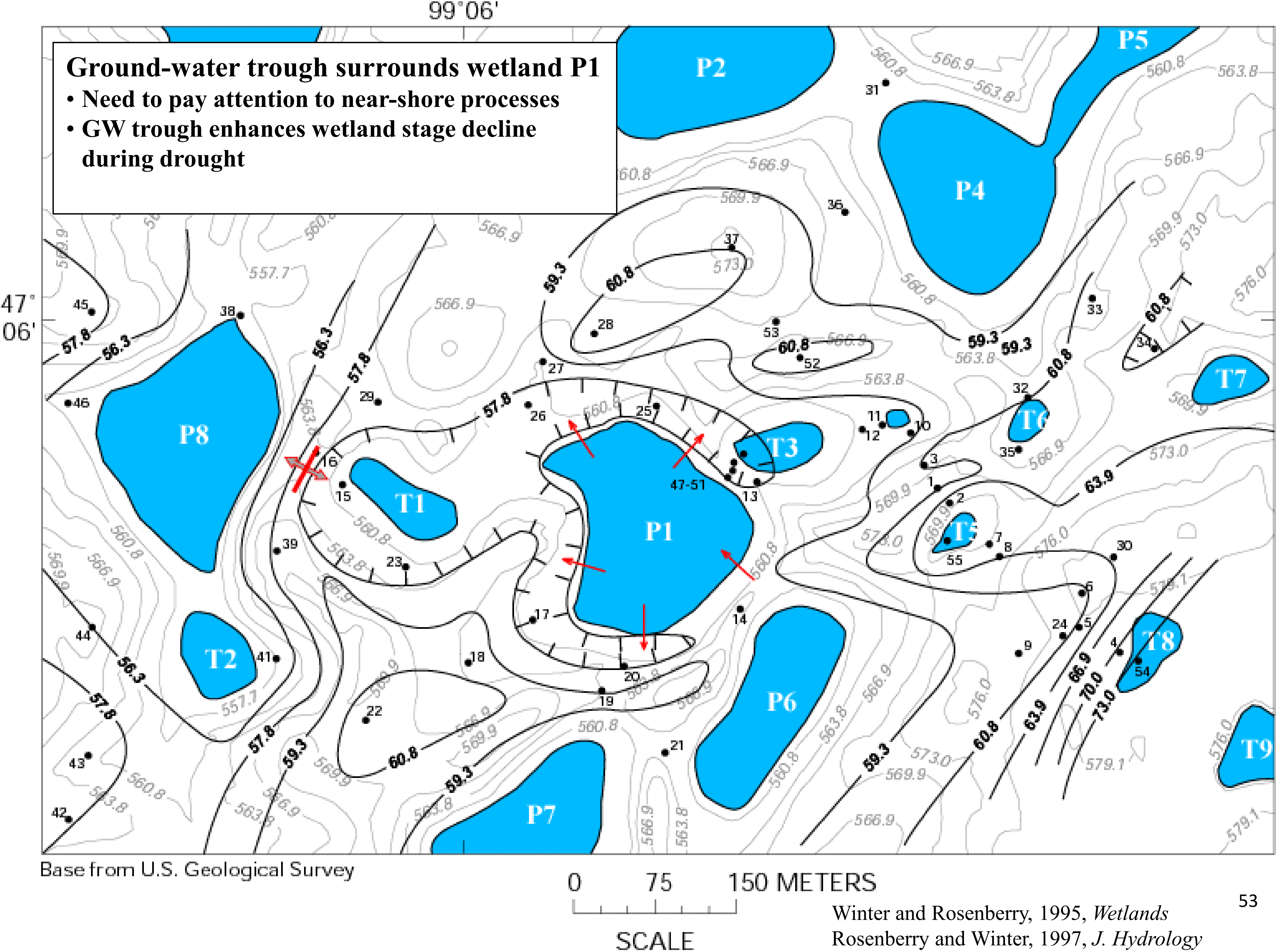
(0.3 m higher yet in 1998)



The ET platform was destroyed by moving ice in the spring. Sensors were subsequently deployed from a pipe that was removed during ice cover.

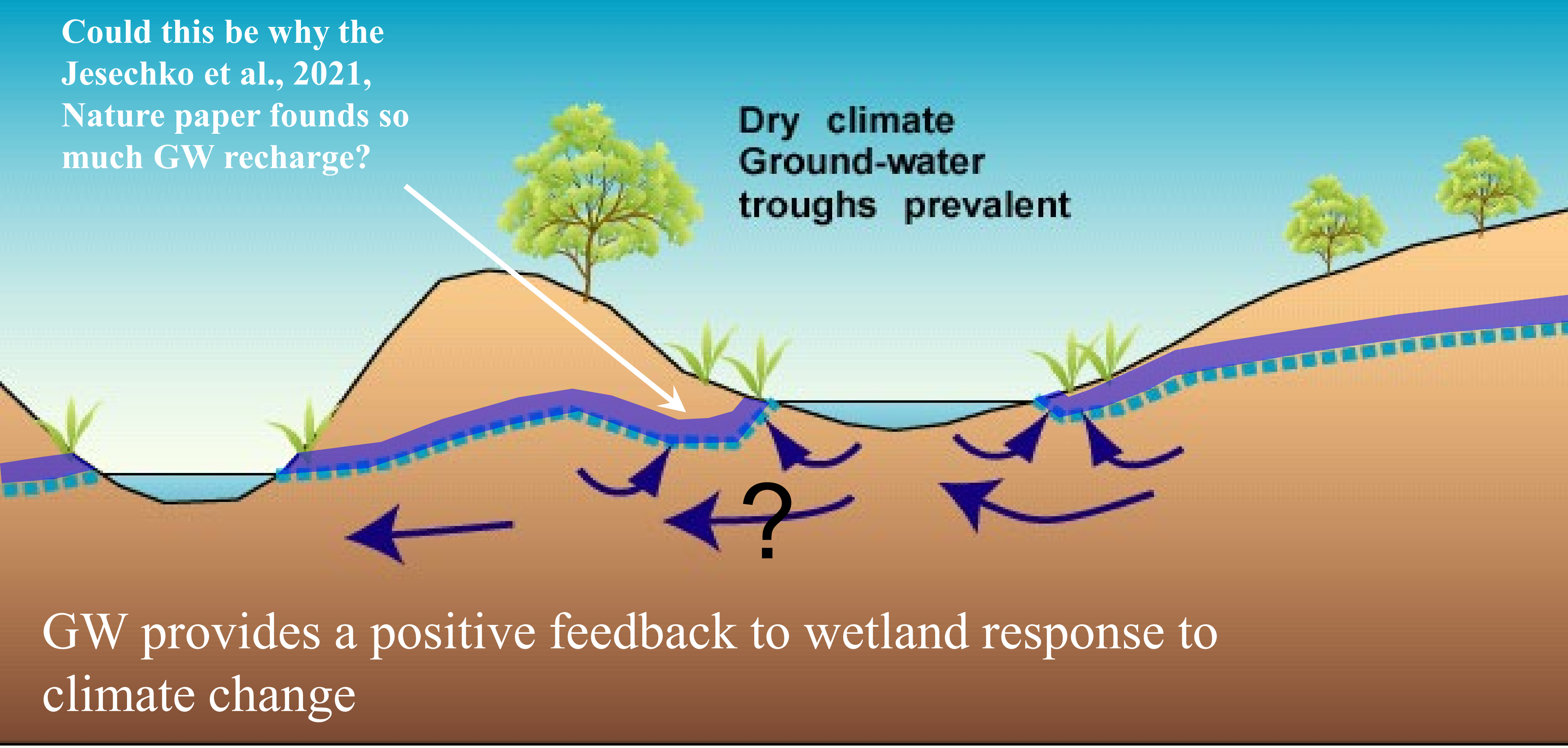
Ground-water trough surrounds wetland P1

- Need to pay attention to near-shore processes
- GW trough enhances wetland stage decline during drought



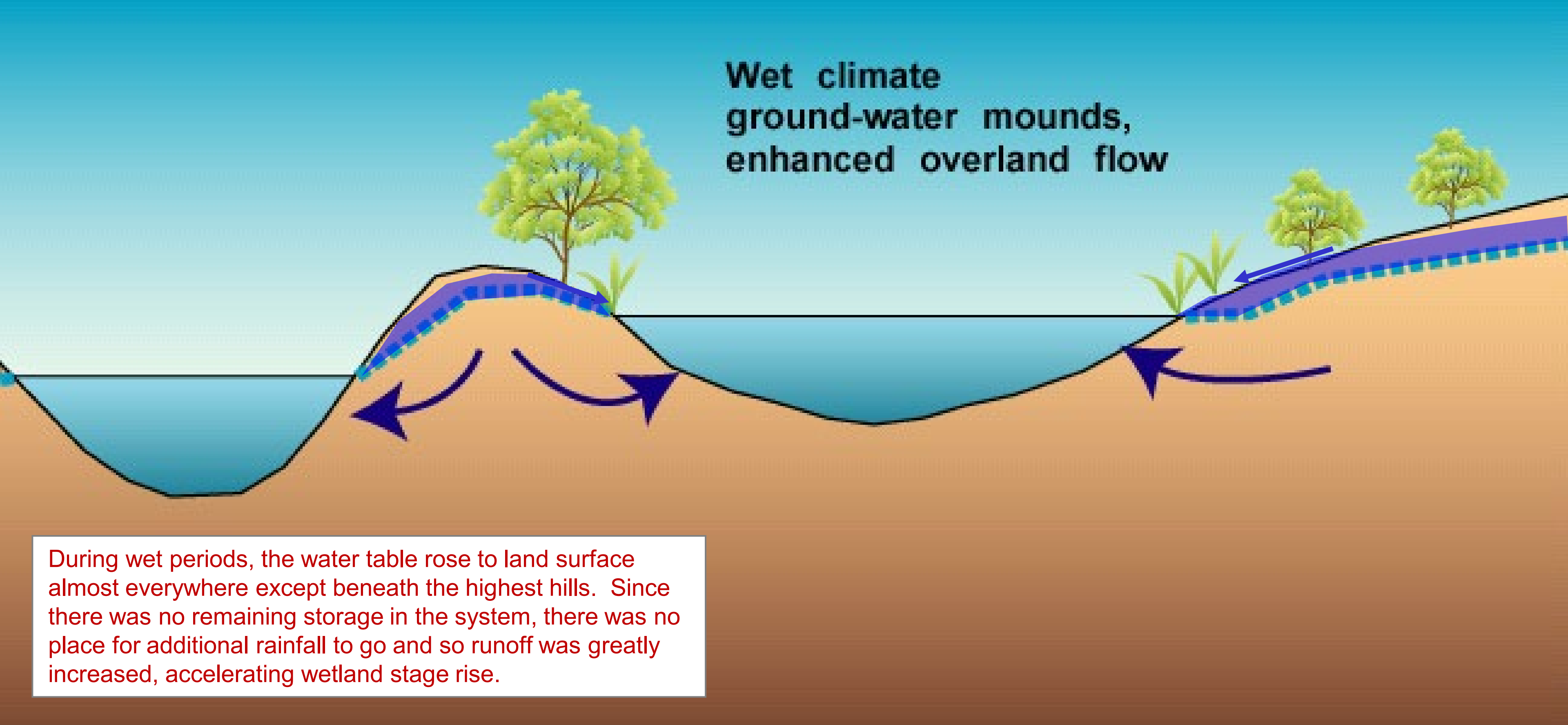
Winter and Rosenberry, 1995, *Wetlands*
Rosenberry and Winter, 1997, *J. Hydrology*

Could this be why the Jesechko et al., 2021, Nature paper founds so much GW recharge?



GW provides a positive feedback to wetland response to climate change

During the drought, ET from plants surrounding the wetland pulled the water table down to levels lower than wetland stage (stage also was declining due to direct evaporation). This reversal in gradient at the wetland shoreline caused wetland water to flow toward the water-table troughs, which accelerated the decrease in wetland stage. This process also occurred during wet periods, but gradients were much smaller as was flow from the wetland to groundwater.

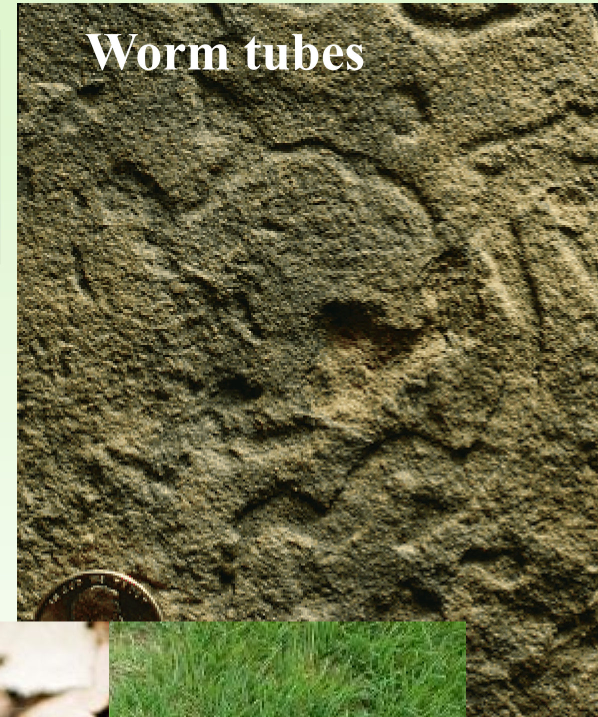


Ground-water mounds surrounds wetland P1 during deluge

- **Need to pay attention to near-shore processes**
- **Water table rose to or near land surface during wet period. No storage left. Virtually all precip. Falling on the basin ended up in the wetland.**

Hydraulic conductivity gets really large right at the surface

Remember what Masaki said about *K* being largest near land surface?



In these prairie-wetland settings, *K* increases close to land surface. Therefore, even if we don't have the water table at land surface, and even if we don't have overland flow everywhere, we can still have greater flow to the wetland through the shallowest (uppermost) portion of the groundwater flow system.

The wetter the period, the greater the enhancement of overland flow available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/apsoil

ELSEVIER

Applied Soil Ecology

Distribution of northern pocket gopher burrows, and effects on earthworms and infiltration in a prairie landscape in Alberta, Canada

Beryl Zaitlin [a,*], *Masaki Hayashi* [a], *Jill Clapperton* [b]

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There can be many preferential flowpaths generated by pocket gophers. Depressions within an alfalfa field had the most gopher burrows with an average **of 9 burrow mounds per m^2**. However, soil infiltrability was somewhat complex and not as sensitive to gopher burrowing as one might expect. This is because "pocket gophers are known to plug up to 50 cm lengths of tunnel to avoid undesirable conditions." It appears that gophers can both increase and decrease soil infiltration.

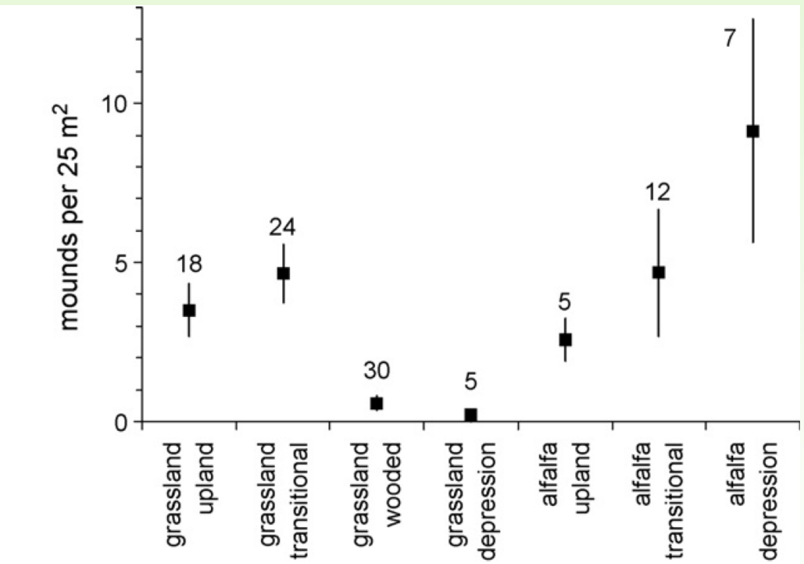


Fig. 2 – Numbers of northern pocket gopher burrow mounds per 25 m^2 quadrat in relation to topography and land use. Squares represent the mean number, lines above and below squares represent one standard error above and below the mean, and numbers above the lines represent the number of quadrats sampled in each location.

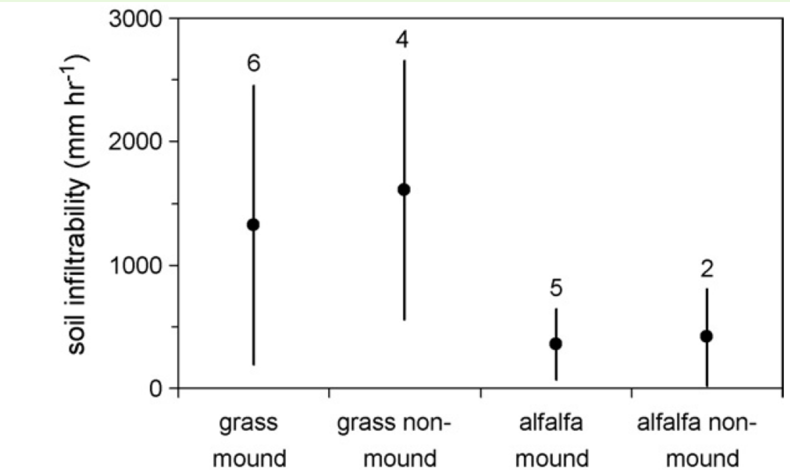


Fig. 5 – Soil infiltrability measured under northern pocket gopher burrow mounds and in areas with no mounds in grassland or alfalfa. Dots represent the mean infiltrability and lines represent one standard deviation above and below the mean. Numbers above the lines represent the number of measurements.

Zaitlin et al., 2007, *Appl. Soil Ecol.*

While North Dakota and Minnesota were wet, Michigan was dry – the public took notice

This is the last example. Phew!

An example of how modeling first could have saved a lot of money

Long Lake, near Kalamazoo, MI

JERRY CAMPBELL / GAZETTE

Dale Bothwell, 8939 Waruf, walks in the former lakebed from the direction of Long Lake. He is standing approximately half way between the current shoreline and the former shoreline.

3-6-00

Long Lake during normal conditions

Long Lake after several dry years

Long Lake, MI shoreline retreat

When you have to walk ½ km past the end of your dock to get to the lake something has to be done!

Long Lake residents sink hopes in new well

Unit will pump two-plus million gallons of groundwater into lake daily.

BY TOM HAROLDSON
KALAMAZOO GAZETTE

A steel tower that could be ready to pump in a couple of weeks offers hope for hundreds of Long Lake residents living on the shrinking lake or trying to sell their homes there.

It's a deep water well with a pump that will run constantly, paid for by the lake property owners with help from Pavilion Township and the city of Portage. When fully operational, it will draw more than two million gallons of groundwater into the lake each day.

Now five feet lower than normal, the parched, muck-rimmed lake is a victim of years of dry conditions and the fact it's a bit higher than other area lakes so it cannot gain from their water runoff.

All that could change, but it may take some time.

Meanwhile, homes are selling for thousands of dollars less than when the lake level was normal.

JERRY CAMPBELL / GAZETTE

Long Lake's low water level is dramatically indicated in this aerial photo taken Friday from the south end of the lake. The lake is located in the city of Portage and Pavilion Township.

"We can maintain and improve it this year, and next year we may have it stabilized," said Julie Ellis, a Long Lake resident and head of the Long Lake Board who has been working diligently on the lake-level dilemma for more than three years.

"We figure the pump takes 82 days to gain a foot, but that's not taking into consideration evaporation. It's up to evaporation and rainfall – and we're not expected to have a good rainfall year. It will probably be a year before it's close to normal. And that's just a guess," Ellis said.

The water from a deep aquifer comes none too soon for residents who have dry docks or a lake that

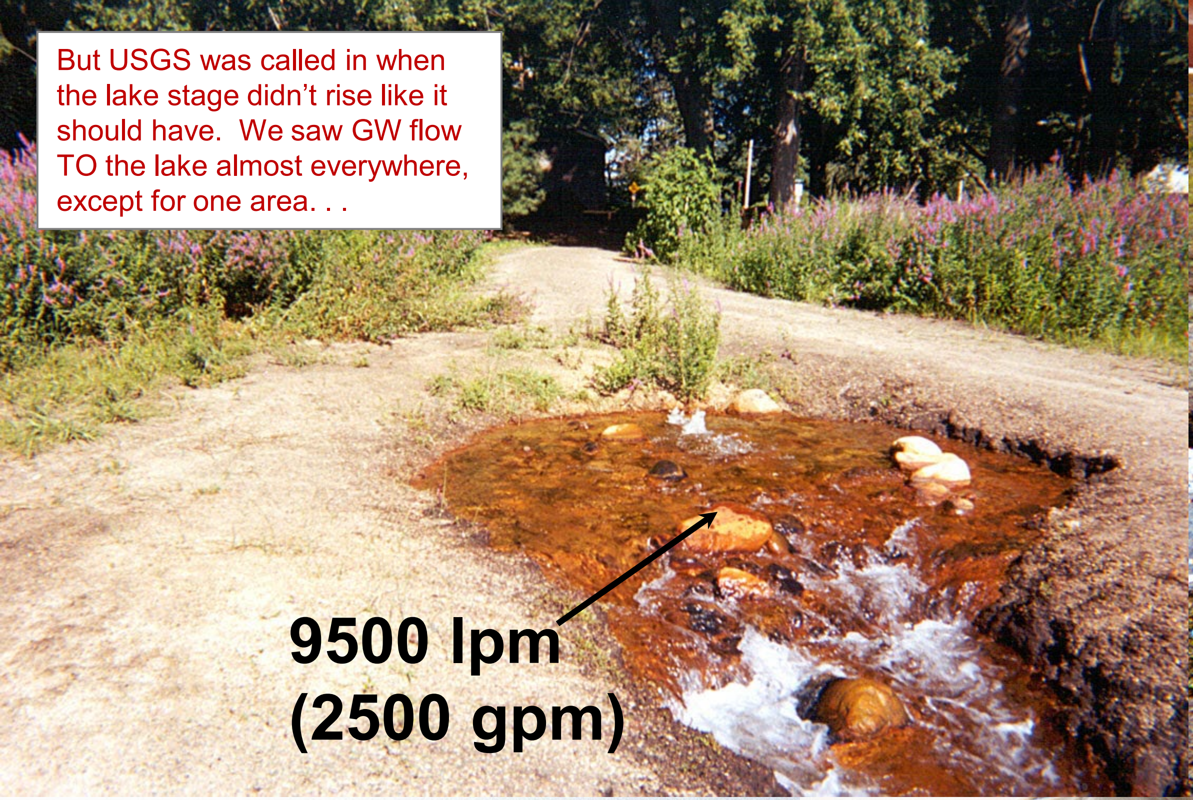
A very pro-active lake association took matters into their own hands and installed a lake-augmentation well.

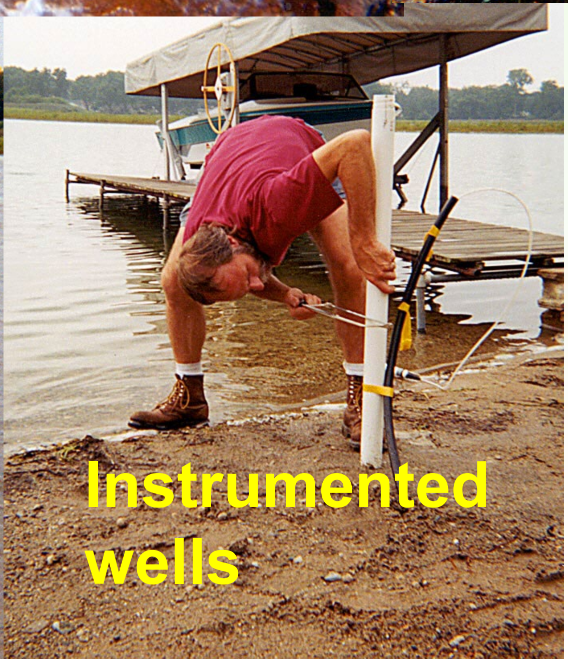
Todd Overbeek, a Long Lake resident and Realtor for ReMax, has studied home sales on Long Lake the past 10 years and finds a disturbing trend traced to the low lake level since 1997.

In 1997, when the lake level was about three feet below normal, the average size of a Long Lake home sold was about 1,137 square feet and its average sale price was $121,000. In 1998, that same-size home sold for $112,000.

In 1999, when the lake again was drained by a drought and a record

Please see **LAKE,** A4

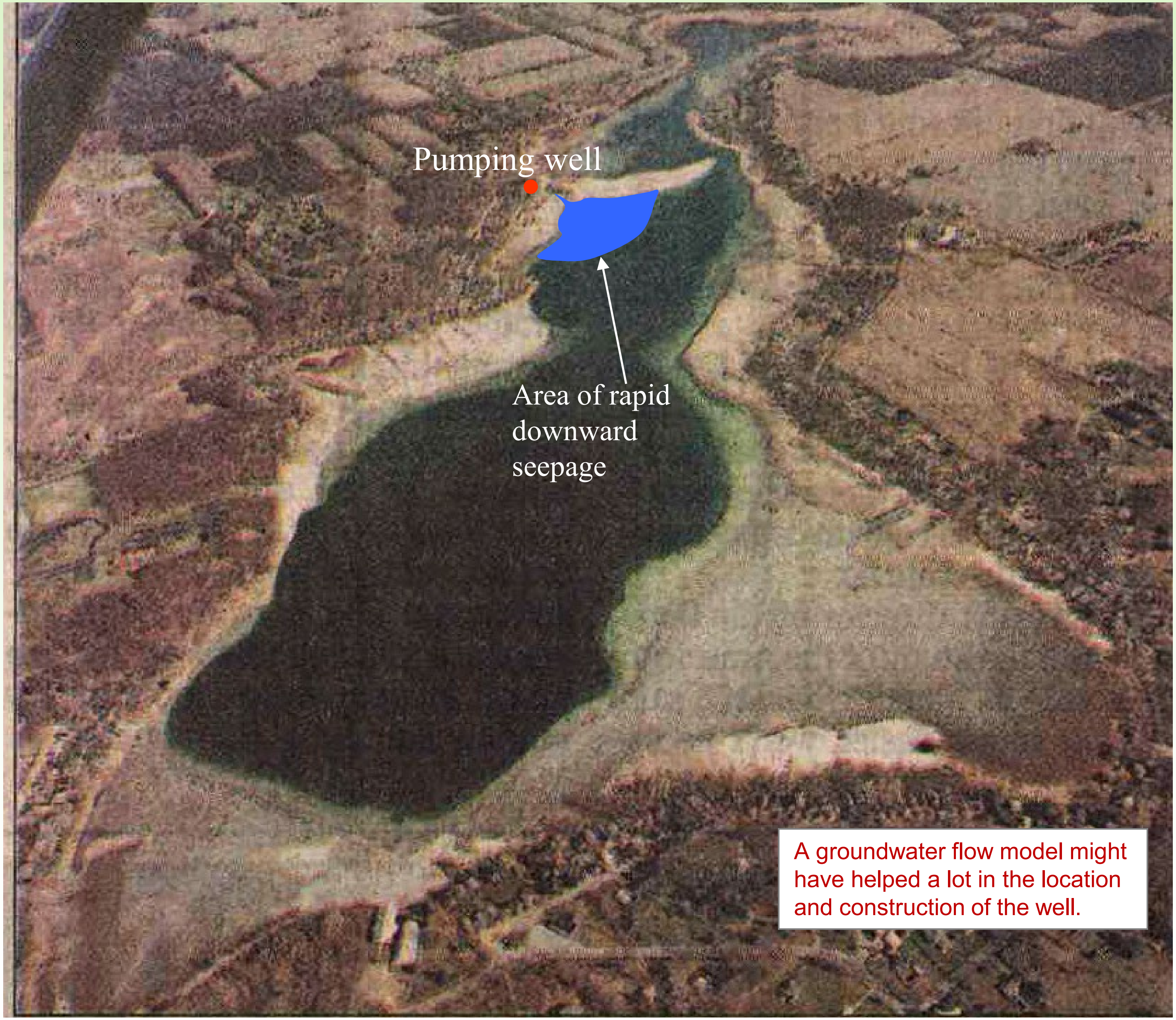




Pumped over 7500 m^3/d (2500 gpm) into the lake for months

- Lake stage did not rise
- Why?

Didn't account for return flow

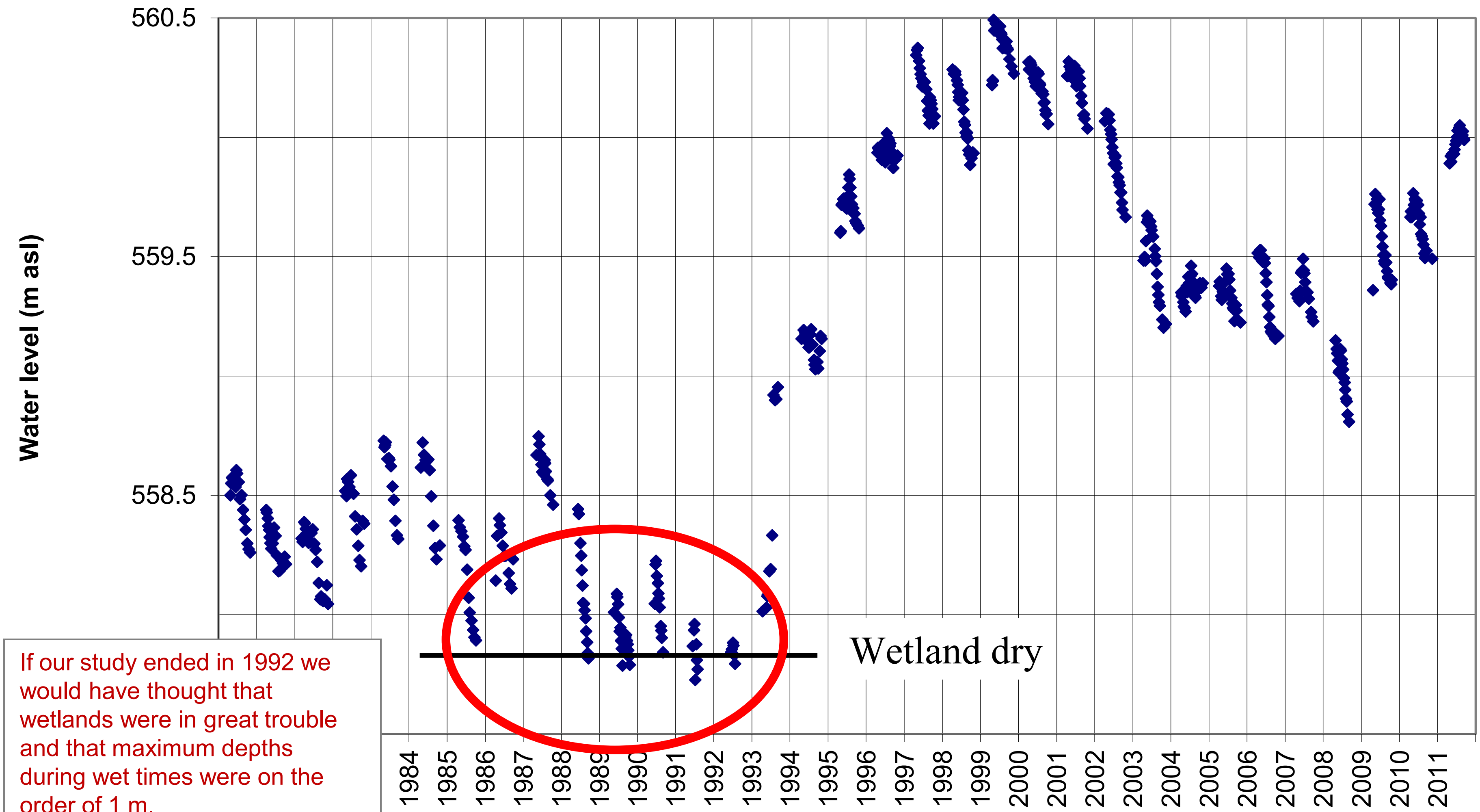


Rosenberry, Luukkonen, unpublished data

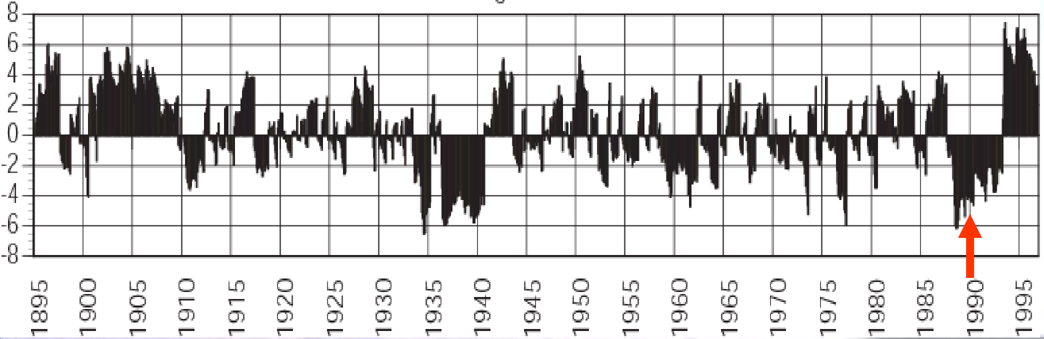
Lessons learned

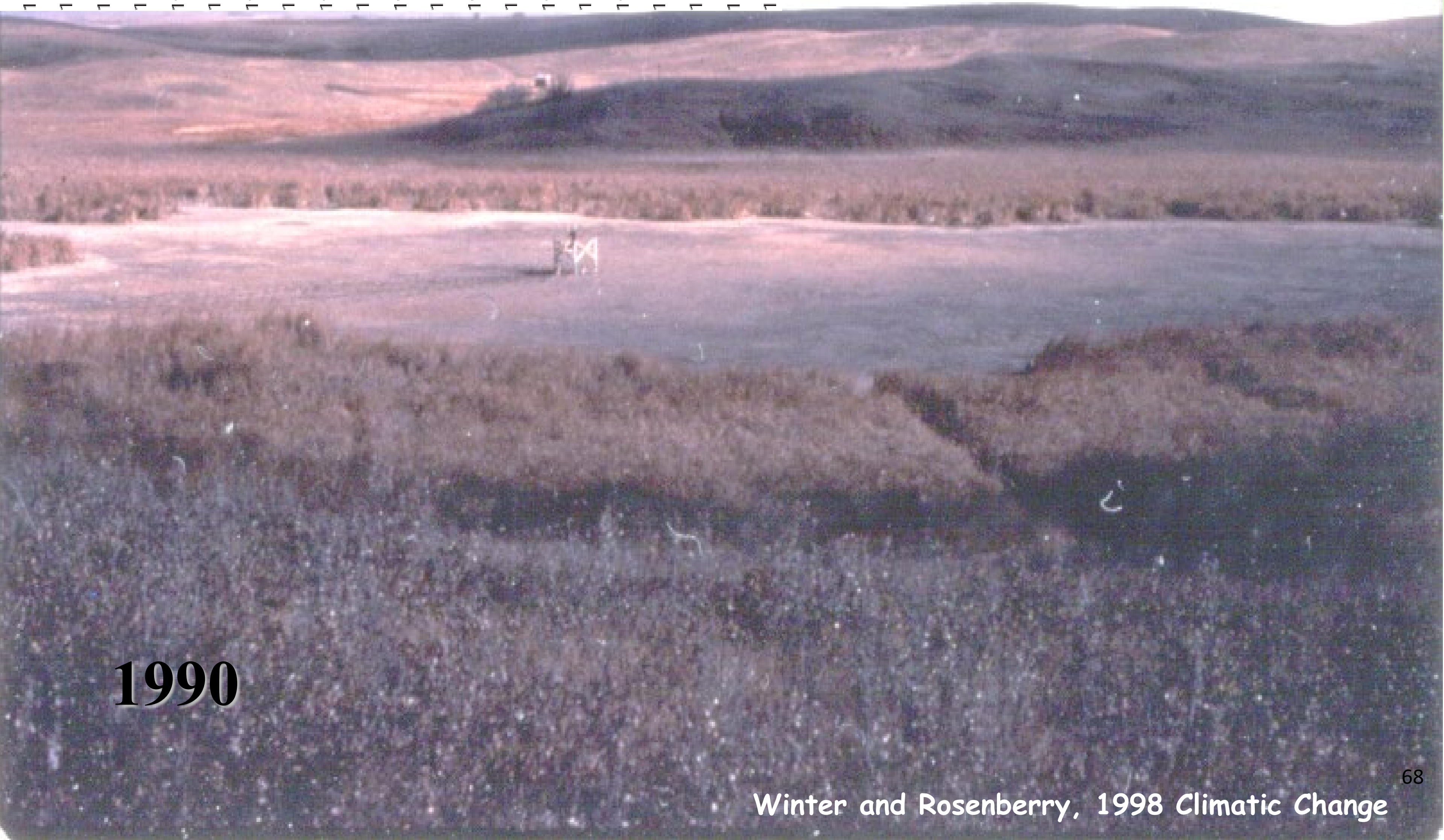
- Do modeling and field work iteratively
- Field work can consume you
- You'll never really figure it out (geologic complexity)
- Expect the unexpected
- Geology rules (and is almost always more complex than you thought)
- Bring in young scientists with new ideas
- Work with other disciplines, even (gasp!) Geochemists!

And think long-term

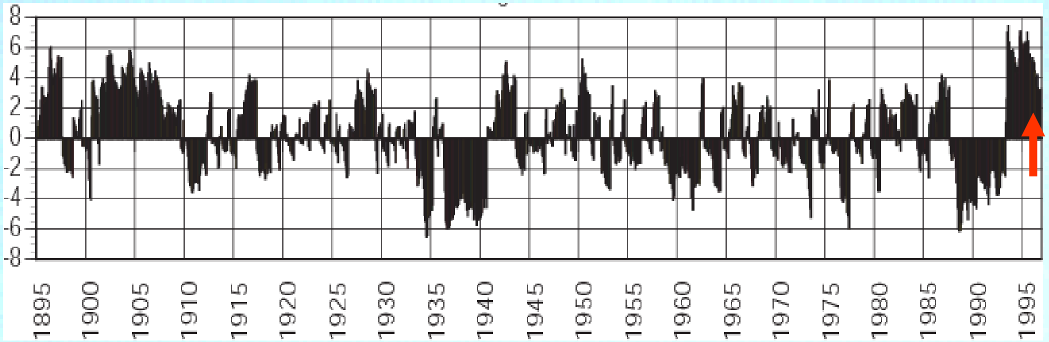


If our study ended in 1992 we would have thought that wetlands were in great trouble and that maximum depths during wet times were on the order of 1 m.





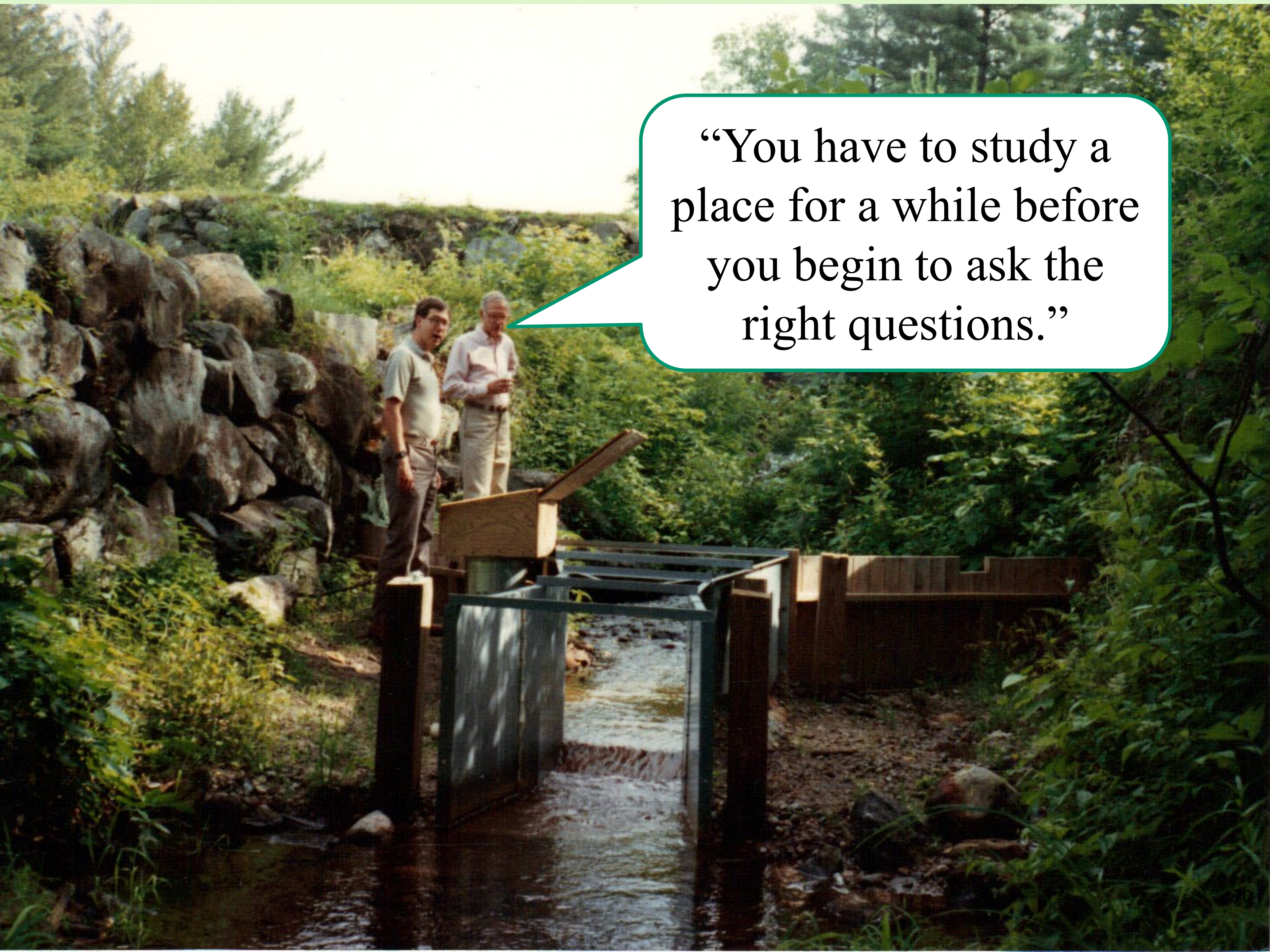
Winter and Rosenberry, 1998 Climatic Change



After nearly 30 years of high stages, has there been a "state shift" to a wetter climate?

These high stages have persisted to the present. This has been sufficiently long that a couple of papers have since been published that discuss a "state shift," essentially a change to a wetter climate.

Winter and Rosenberry, 1998 *Climatic Change*
McKenna et al., 2017 *Climatic Change*
Mushet et al., 2018, *Wetlands*


"You have to study a place for a while before you begin to ask the right questions."

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