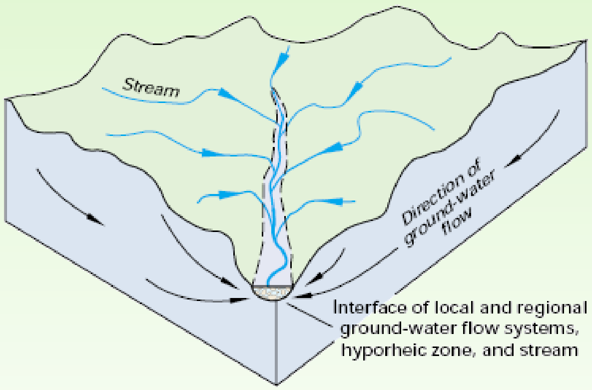
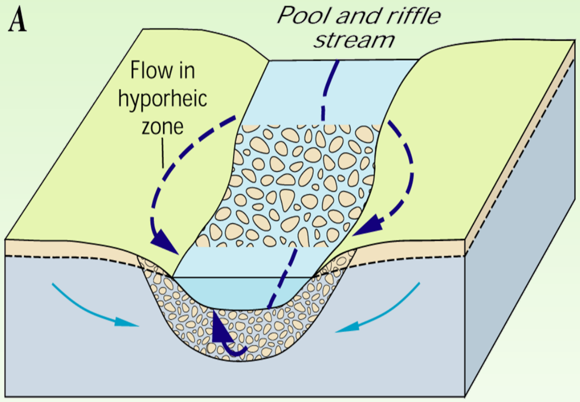
Surface-ground water interaction: From watershed processes to hyporheic exchange



rosenberry@mines.edu
hayashi@ucalgary.ca



University of Granada

Overview of physical settings and processes

- Conceptual
- In addition to how, this discusses why, where, to what extent
- Fill in these slides with plenty of notes so your course handbook will have greater value

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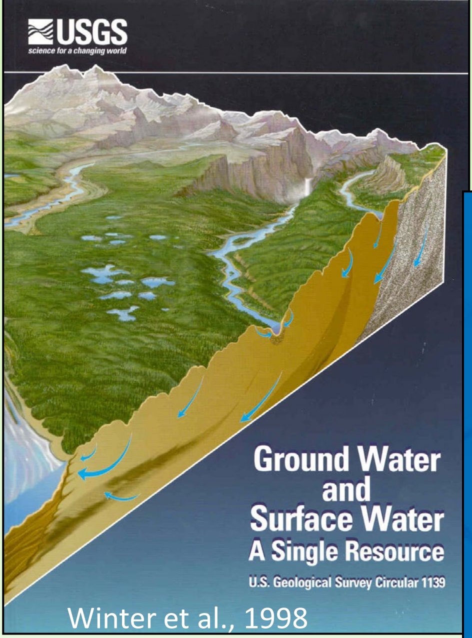
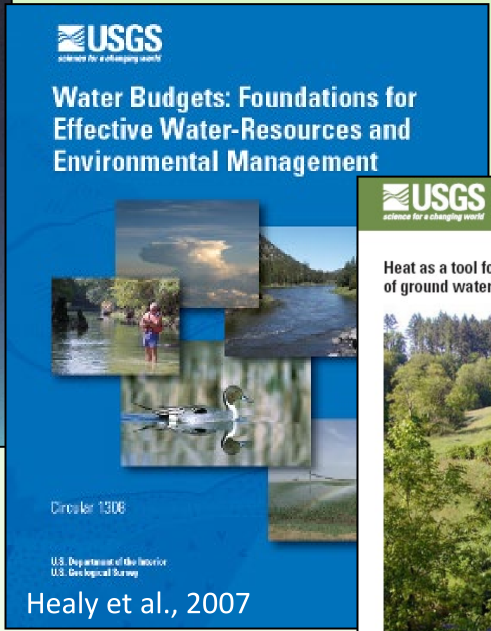
UNIVERSITY OF CALGARY
COLORADO SCHOOL OF MINES @150 | 1874-2024

Useful background information

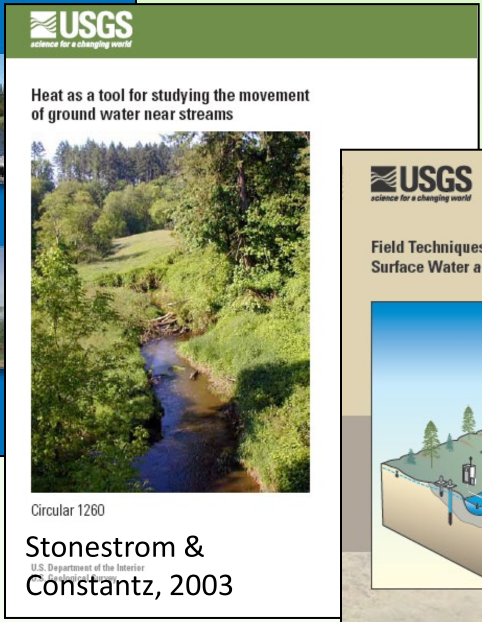


Winter et al., 1998

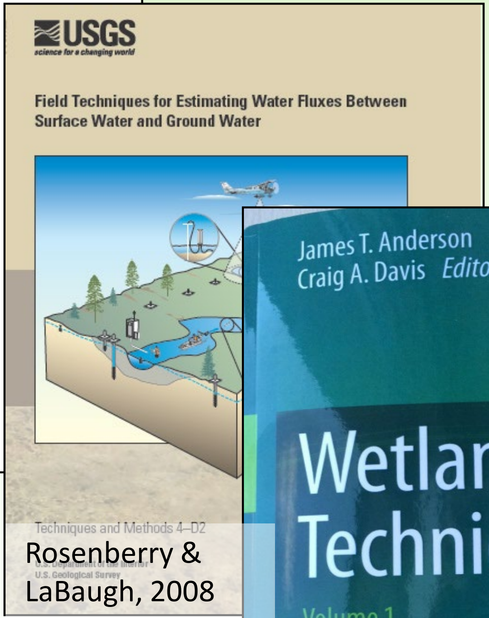
Several of the following slides are taken from this publication.



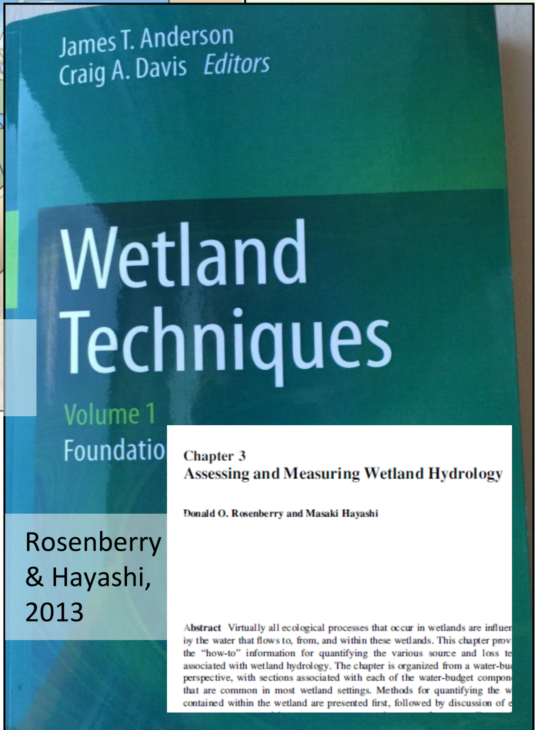
Healy et al., 2007



Stonestrom & Constantz, 2003



Rosenberry & LaBaugh, 2008



Rosenberry & Hayashi, 2013

These reports that Masaki has also shown you are all available online. The Wetland Techniques book chapter is not free, but we can send you a free pdf if you ask. You can also request paper or pdf copies from either Don or Masaki. These 5 documents will be a very useful resource if you wish to get into this in greater detail.

Physical settings

- Lakes
- Wetlands
- Estuaries
- Rivers and streams
- Submarine Groundwater Discharge (coastal settings)

- Hypothetical models
- Field examples

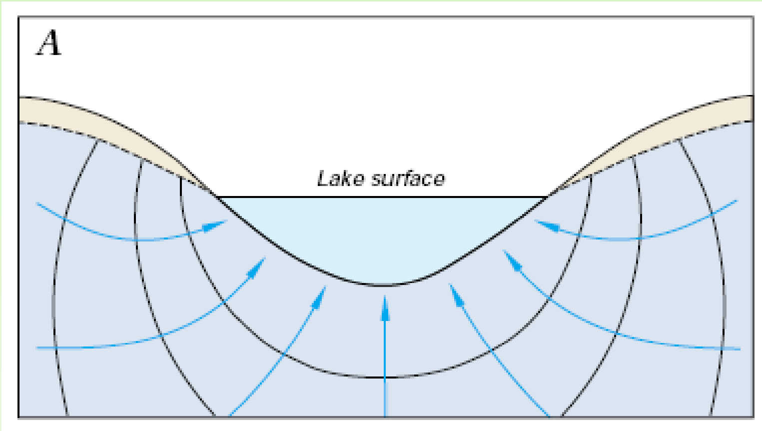
In this section, we provide a general overview of the various physical settings where exchange between groundwater and surface water occurs. We will cover several of these topics in much greater detail during the next few days.

Considerations

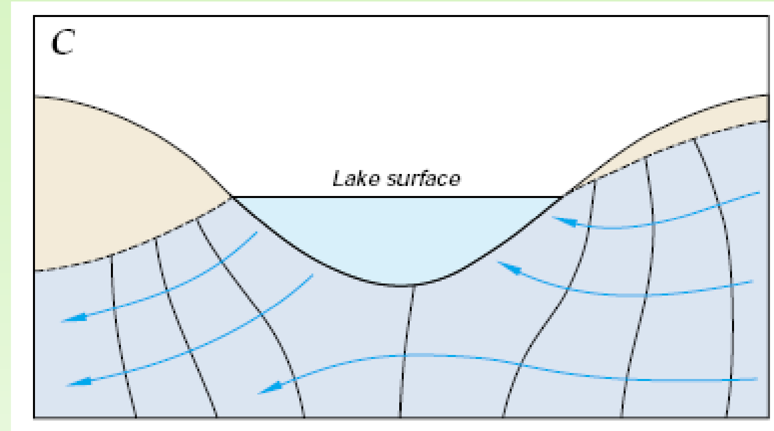
- Geological controls
- Time of travel (age)
- Local-scale topography
- *Heterogeneity*
- *Temporal variability*

The two topics highlighted in orange are particularly relevant and will be covered in greater detail throughout this course. Physical variability (heterogeneity) and temporal variability are very important conditions or features related to exchange between groundwater and surface water that often are not adequately addressed. These points will be empasized throughout the course.

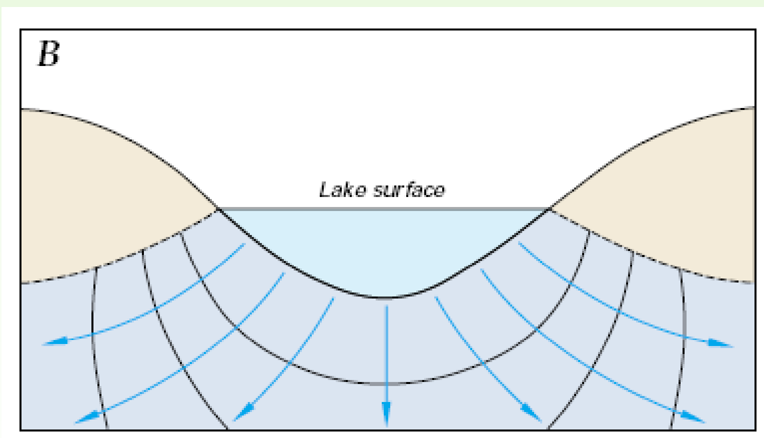
Interaction of Ground Water and Lakes



Discharge



Seepage lake



Recharge

Lakes can

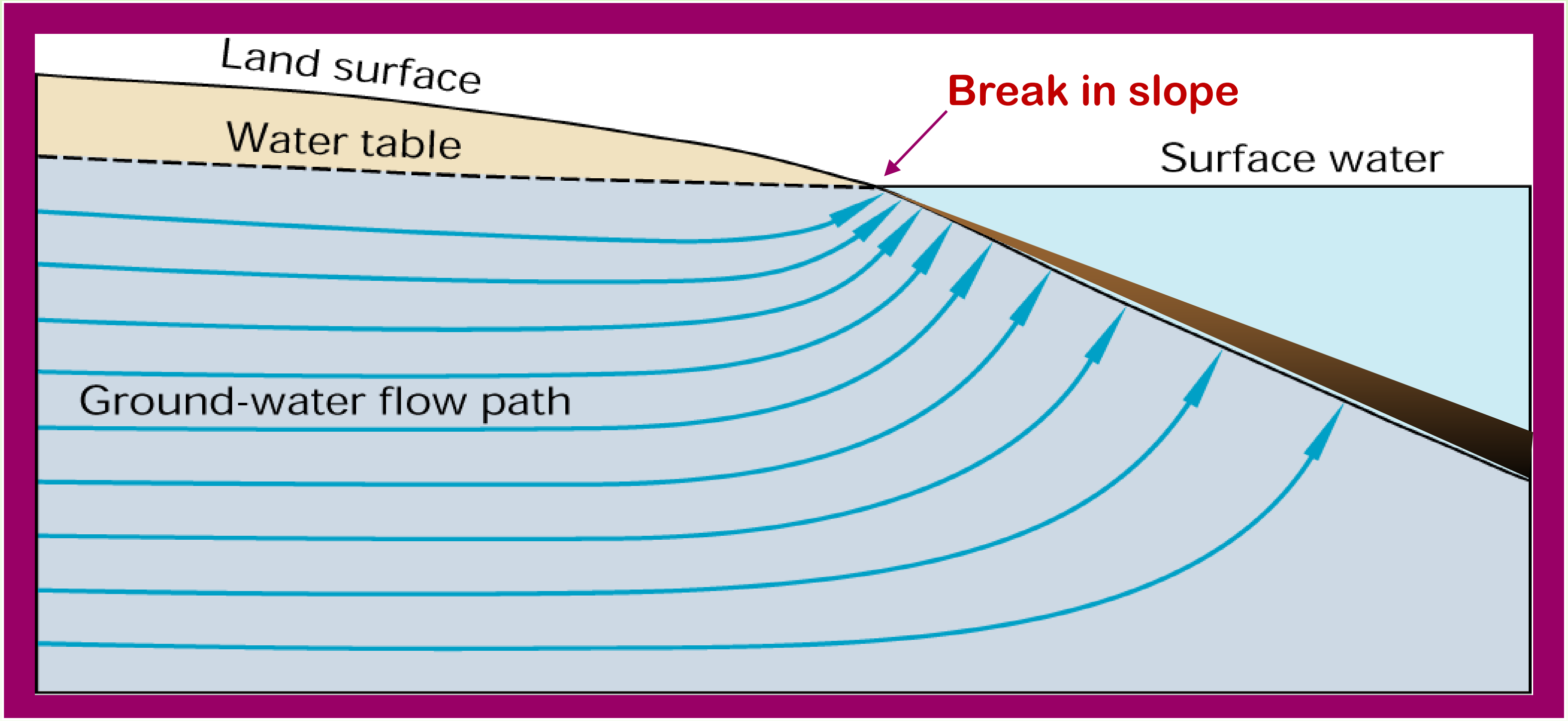
A. ***receive ground-water inflow,***
B. ***lose water to ground water, or***
C. ***both (often termed a "seepage lake")***

D. ***The type of interaction also can change with time***

But these descriptions are from a groundwater perspective

When we say discharge, we mean discharge of groundwater. This is common terminology in hydrogeology. Recharge means recharge to the groundwater system with surface water as the source. Based just on the terminology, it is obvious that these concepts evolved from a hydrogeological perspective.

Ground-Water Seepage Into Surface Water

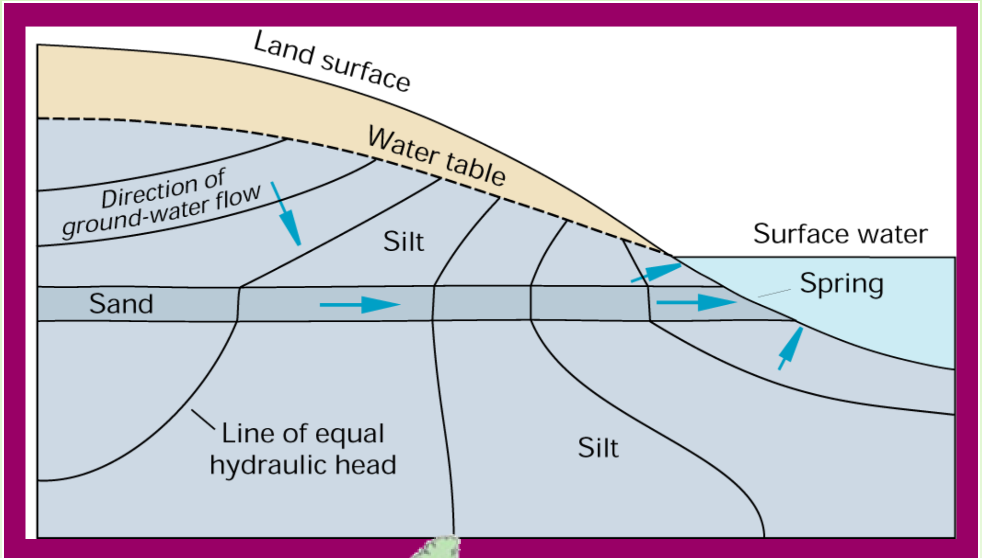


Seepage rates are usually greatest near shore and decrease nonlinearly with distance from the shoreline

If geologic properties are uniform, this is the type of seepage distribution one should see. Because of the change in slope between a sloping water table and a flat lake surface, seepage is focused at the break in slope. However, as you will see repeatedly, there are many settings where geology is definitely not uniform. Here, fine-grained, organic sediments tend to become thicker with distance from the shoreline, which further enhances the focusing of groundwater discharge close to the shoreline.

McBride and Pfannkuch, 1975, *Journal of Research*

Geology is often responsible for unexpected distribution of exchange, including locations of springs



Heterogeneity

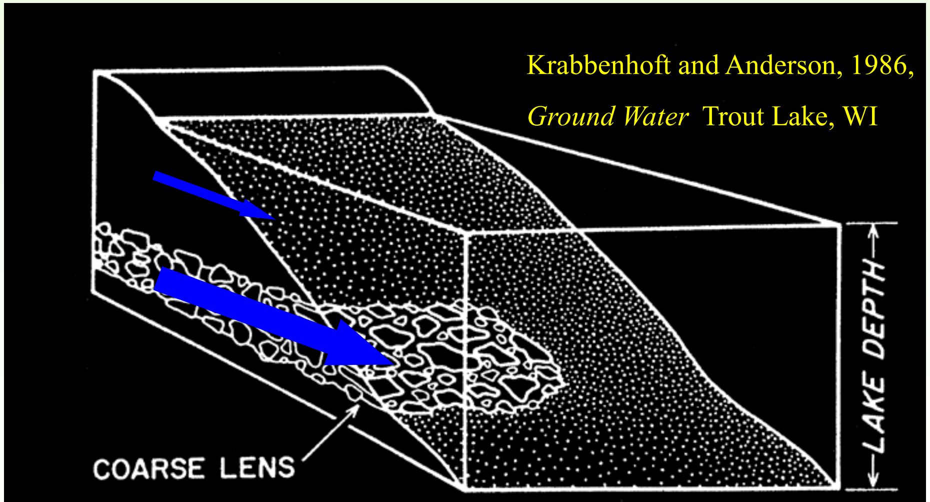


Fig. 5. Three-dimensional schematic drawing of the hypothesized situation at Trout Lake showing a coarse lens intersecting the lakebed.

The location of exchange between GW and SW can change dramatically over time (shoreline migration)

The location of the spring or buried gravel could become irrelevant if the shoreline migrates.

Dock on Crooked Lake in central Florida in the 1970's.

The same dock in 1990.

Temporal variability

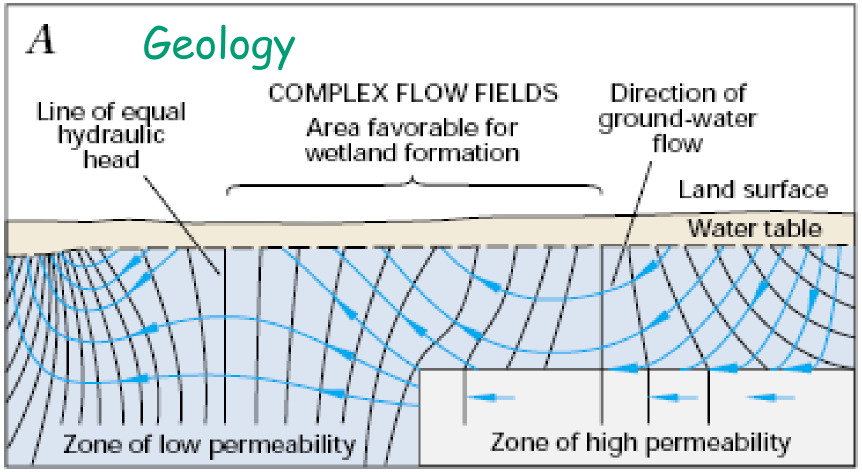
There are many reasons why geologic conditions are not uniform in near-shore settings, among them alternating periods of erosion and sedimentation as shorelines move laterally when surface-water stage changes over time.

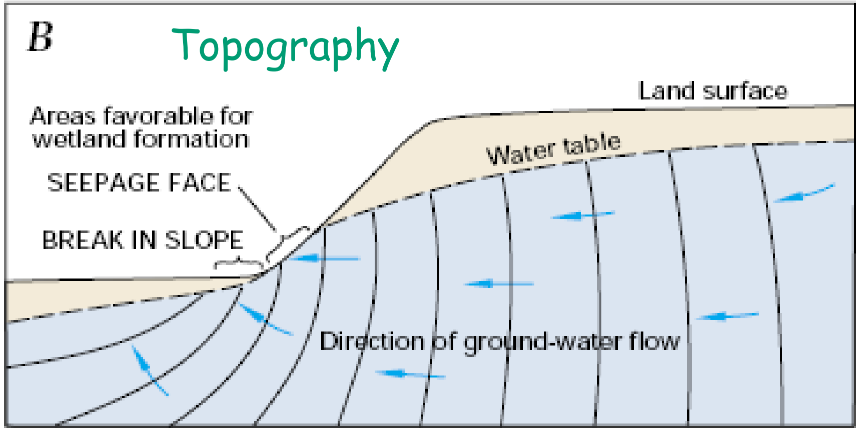
This 20-year example can also happen over just a few years.

In highly developed areas of west-central Florida, lake levels declined and lakes and wetlands dried out over a two-decade period as a result of both extensive pumping from the Floridan aquifer and low precipitation as a result of drought conditions.

Shoreline-focused erosion and deposition migrates as the shoreline migrates, adding to heterogeneity of the bed sediment.

Interaction of Ground Water and Wetlands





The situation where the water table extends to land surface above the break in slope is actually fairly common. Tall, lush vegetation may be a good indicator.

Wetlands are present in climates and landscapes that cause ground water to discharge to land surface or that prevent rapid drainage of water from the land surface.

Even though there is no surface depression on the landscape, a wetland can be present because of subsurface changes in geology.

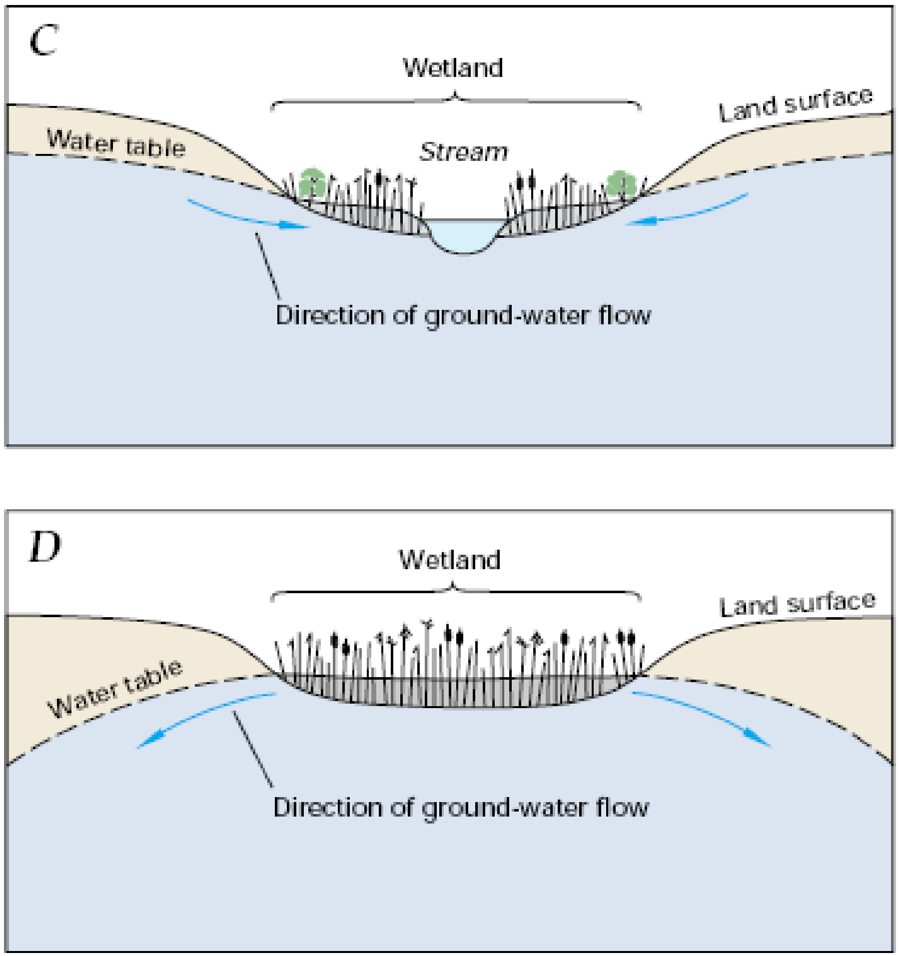
The source of water to wetlands can be

- ***A. from GW discharge where the land surface is underlain by complex GW flow fields,***
- ***B. from GW discharge at seepage faces and at breaks in slope of the water table***

This is a fairly common vegetative indicator for groundwater near land surface. In this case, it is remarkable because it is SO much higher than the lake that is only about 10 m to the left of the road.

Horsetail (Equisetum)

Interaction of Ground Water and Wetlands

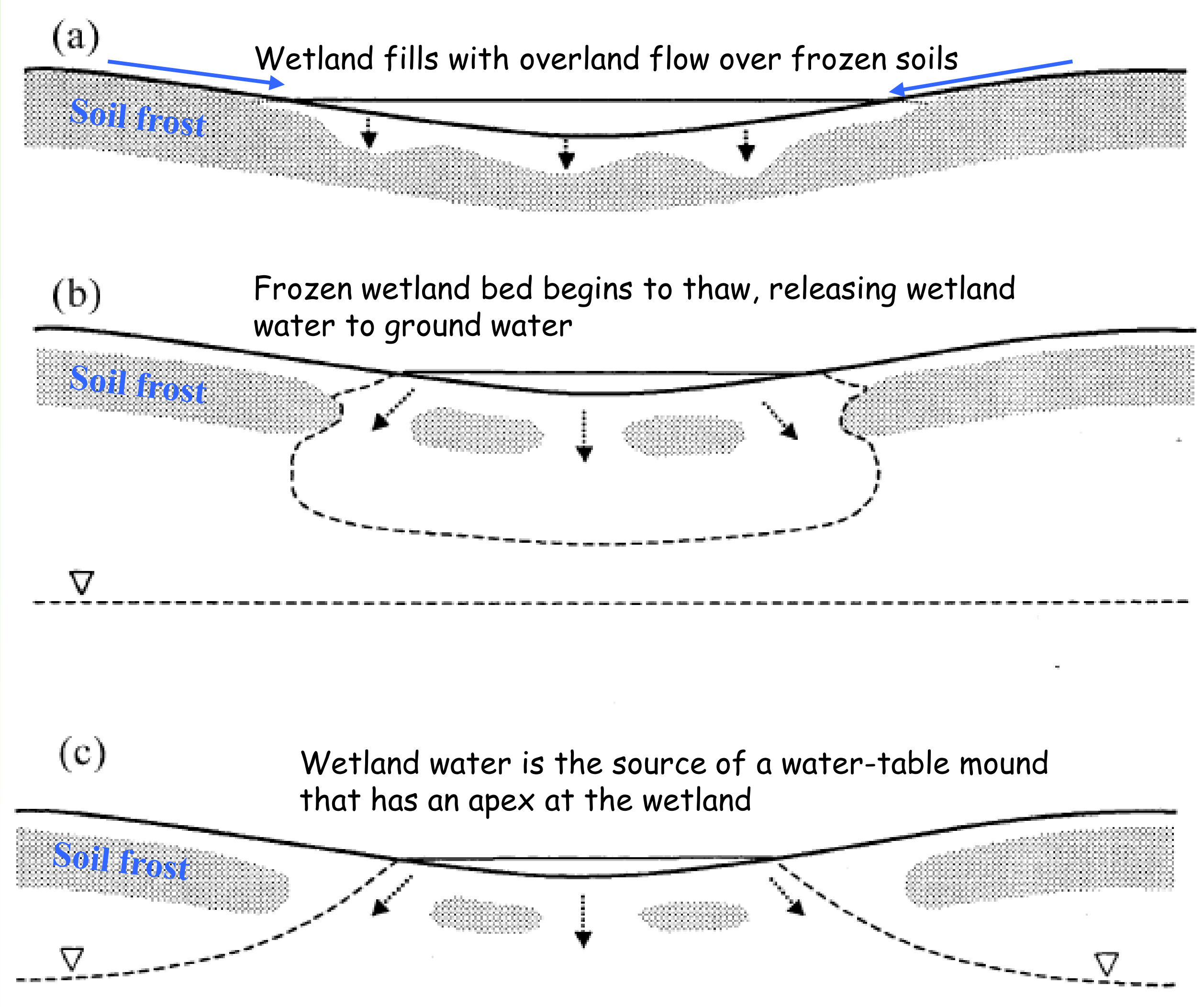


The source of water to wetlands can be . . .

C. from being adjacent to streams, especially slow moving streams in low-gradient settings,

D. from precipitation in cases where wetlands have no stream inflow and GW gradients slope away from the wetland,

This text is taken directly from Winter et al., 1998. We've added the words in dark red for additional clarity.

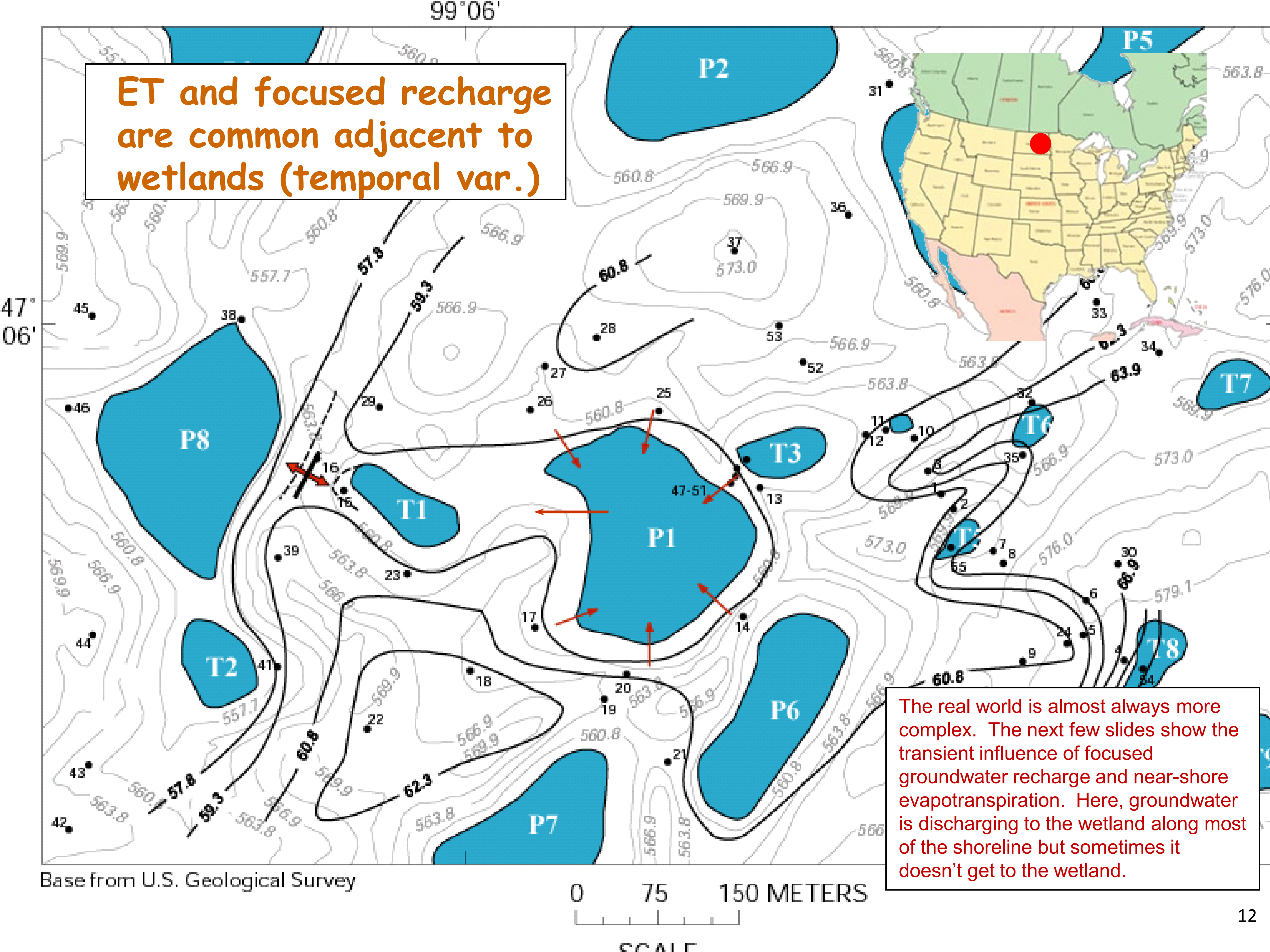


E. ***from runoff from the watershed*** ***(which can then become a source for ground water).***

The blue arrows indicate runoff that flows to the wetland; wetland water then recharges groundwater when the soil frost melts.

Hayashi et al., 2003, *JHydrol*

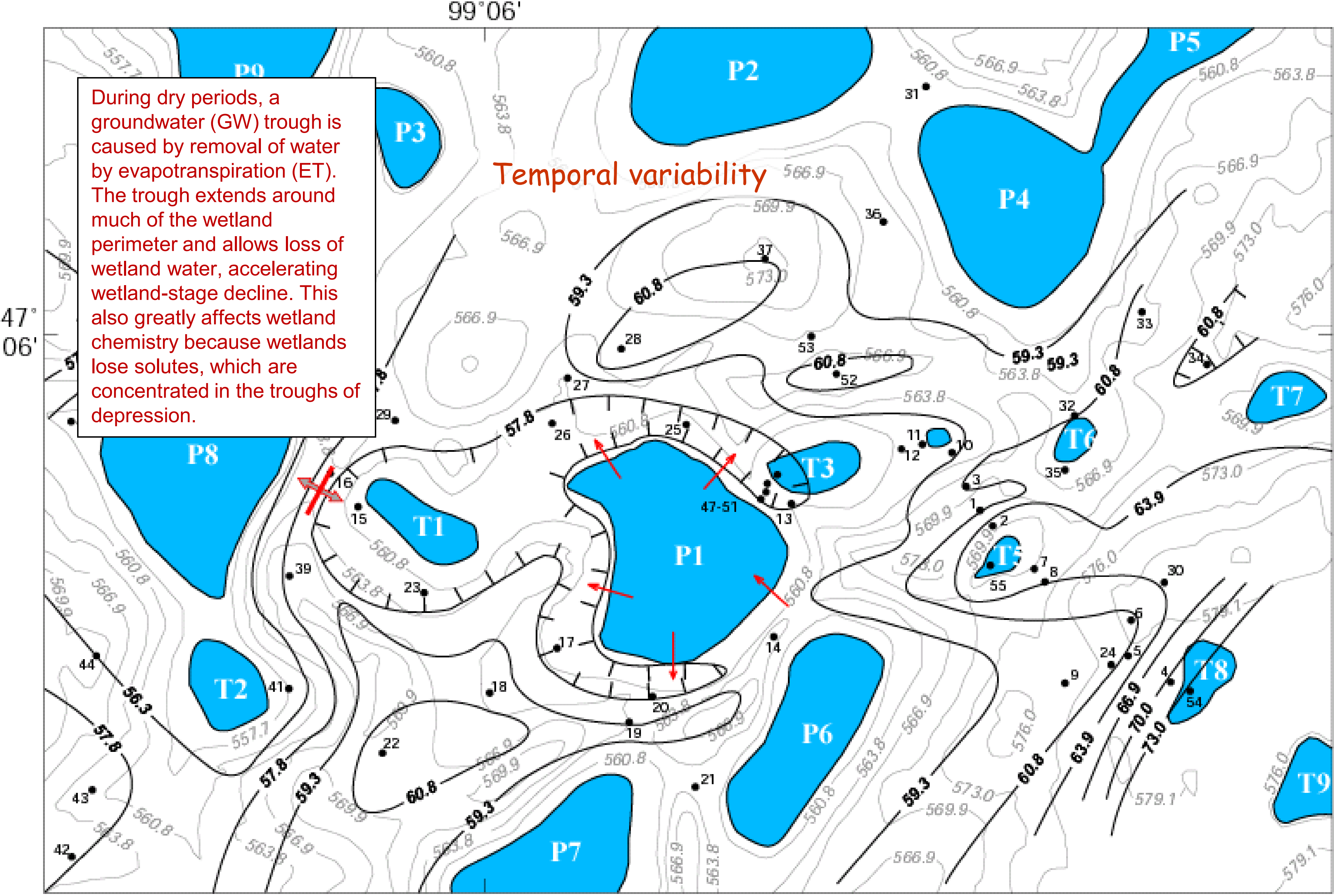
ET and focused recharge are common adjacent to wetlands (temporal var.)



The real world is almost always more complex. The next few slides show the transient influence of focused groundwater recharge and near-shore evapotranspiration. Here, groundwater is discharging to the wetland along most of the shoreline but sometimes it doesn't get to the wetland.

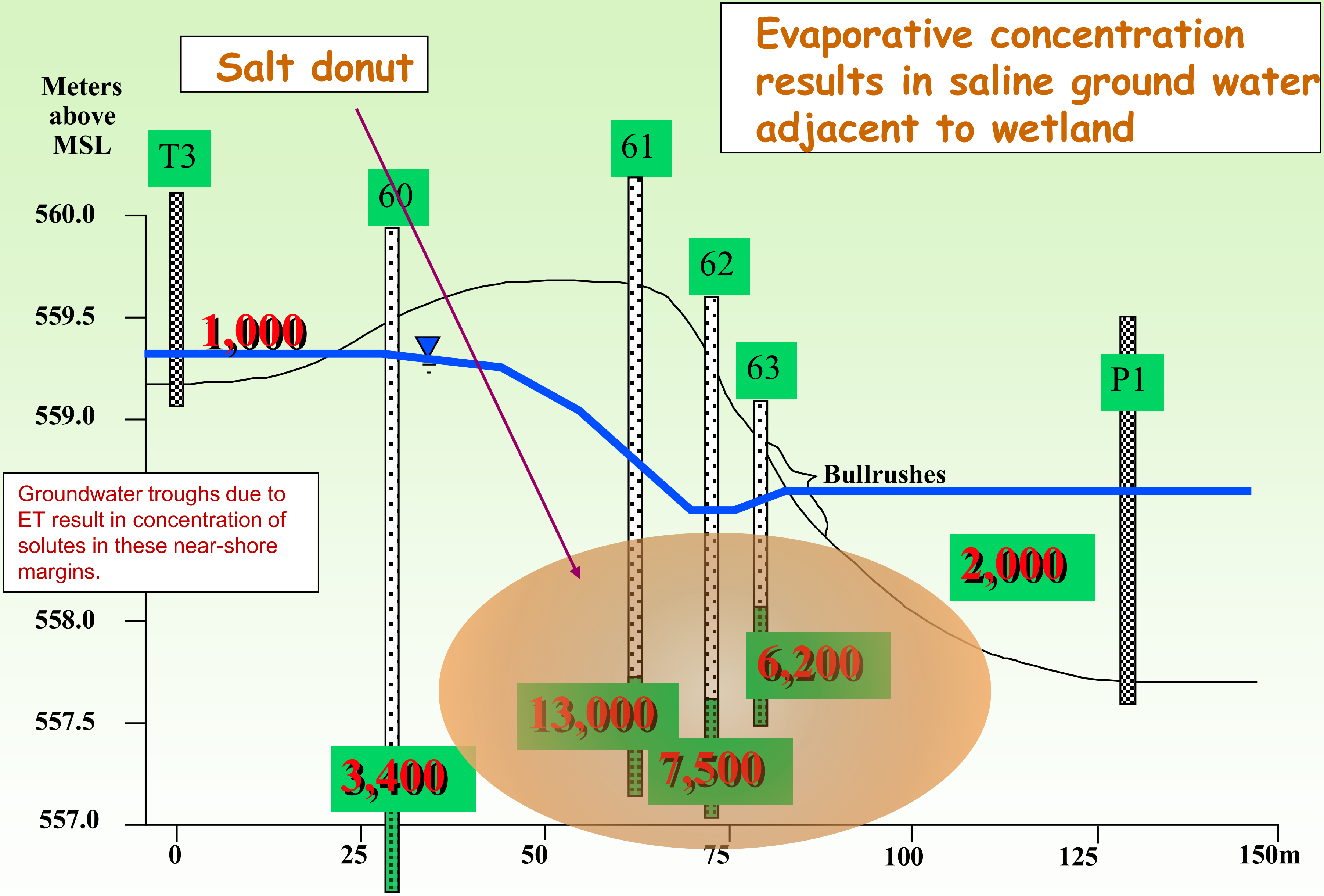
During dry periods, a groundwater (GW) trough is caused by removal of water by evapotranspiration (ET). The trough extends around much of the wetland perimeter and allows loss of wetland water, accelerating wetland-stage decline. This also greatly affects wetland chemistry because wetlands lose solutes, which are concentrated in the troughs of depression.

Temporal variability



Ground-water trough surrounds wetland P1

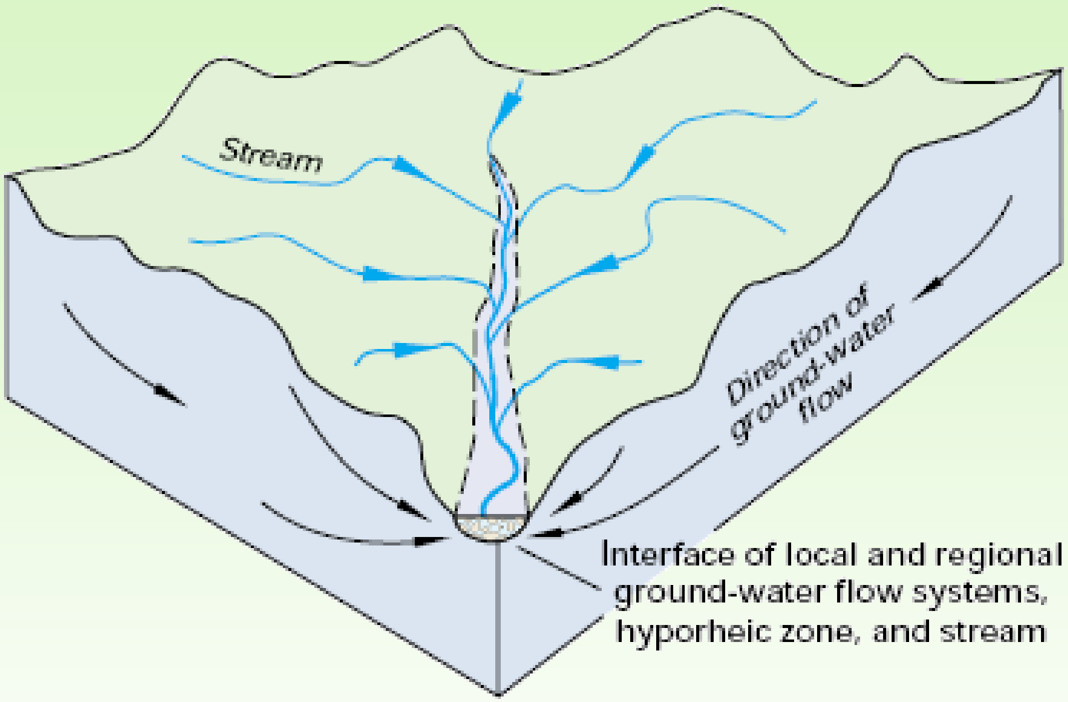
Winter and Rosenberry, 1995, *Wetlands*



Rosenberry and Winter, 1997

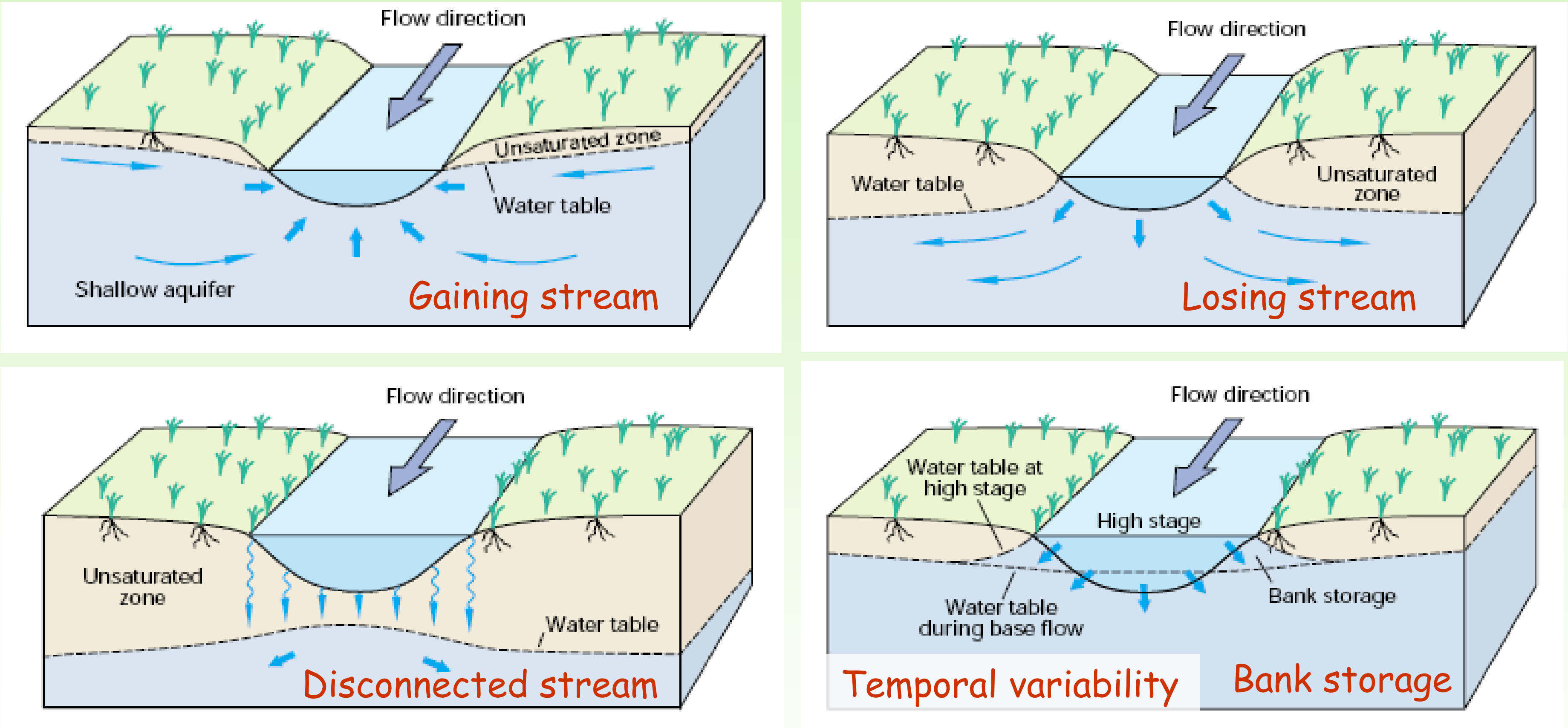
Interaction of ground water and <u>streams or rivers</u>

GW-SW exchange is particularly complex in highly dynamic fluvial settings. Several examples and some basic processes are presented in the next several slides. You'll see much more of this in a subsequent talk on hyporheic exchange.



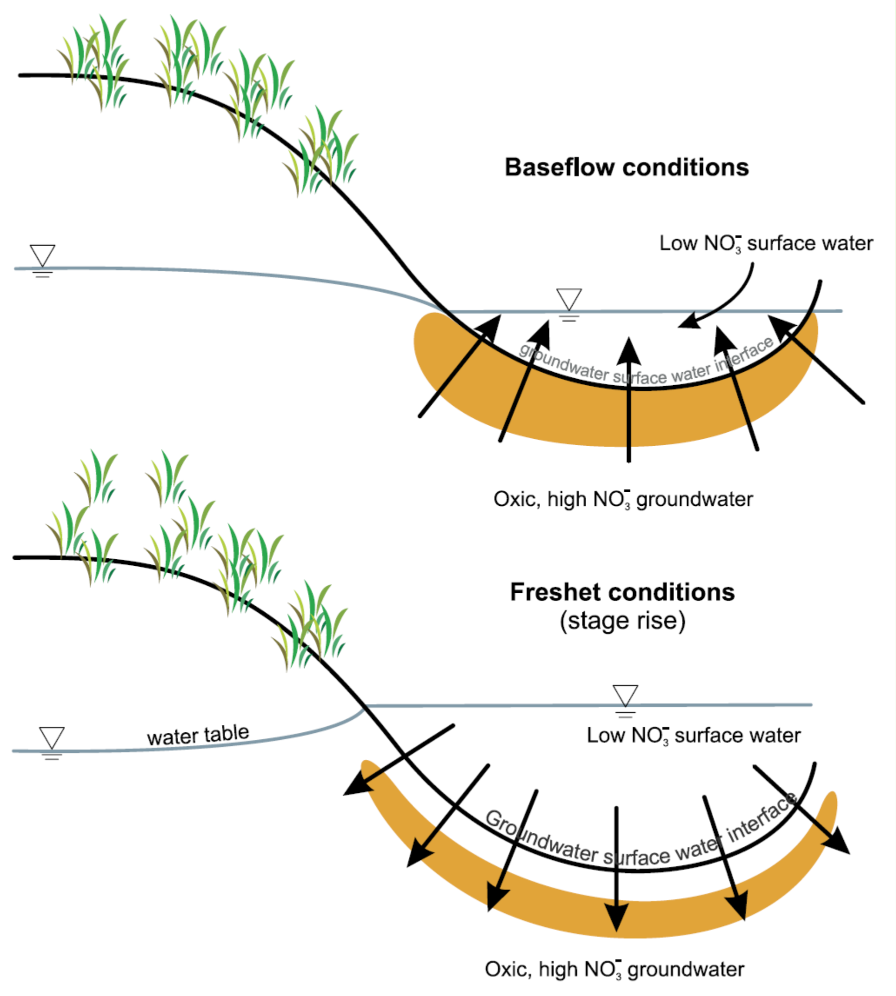
The movement of water between GW and SW provides a major pathway for chemical transfer between terrestrial and aquatic systems. GW discharge is often a mix of waters of different chemical composition resulting from (1) different land-use practices at different locations in a watershed, and (2) GW discharge from flowpaths of various lengths, sources, and travel times.

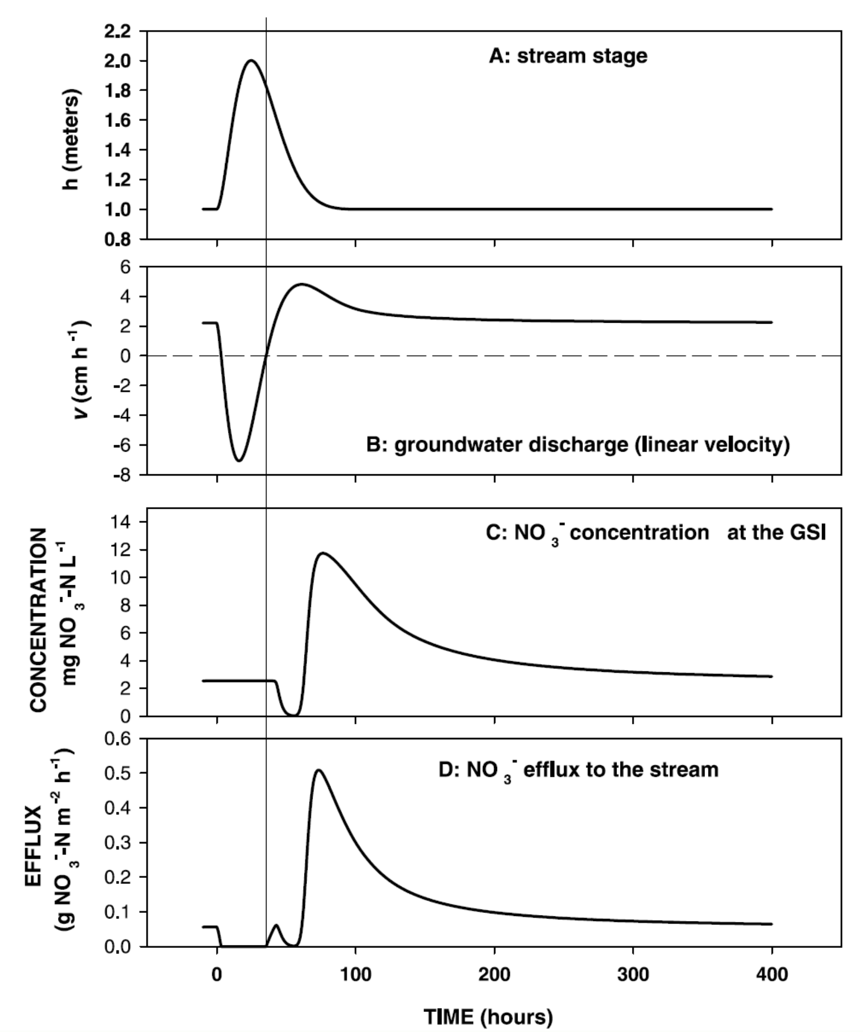
Interaction of Ground Water and Streams



Groundwater-stream exchange varies from place to place depending on climatic setting, physical setting, place in the landscape. It also varies over time.

Interaction of Ground Water and Streams

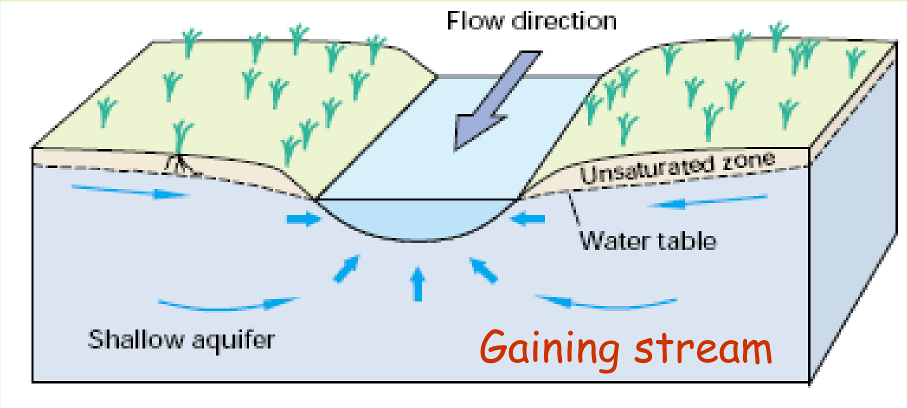


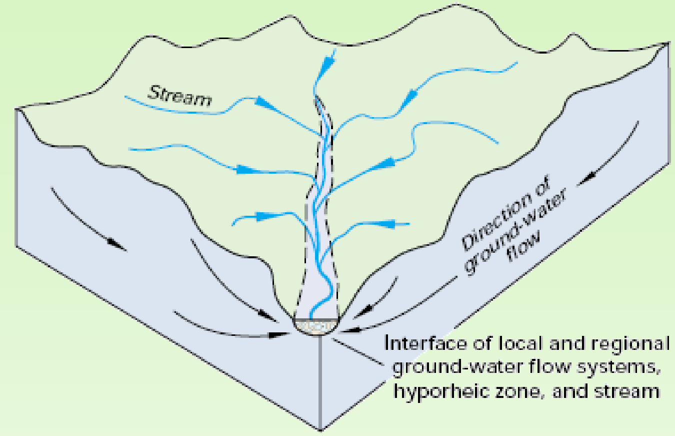


Bank storage can create temporal changes in water chemistry during and after the flood-flow event.

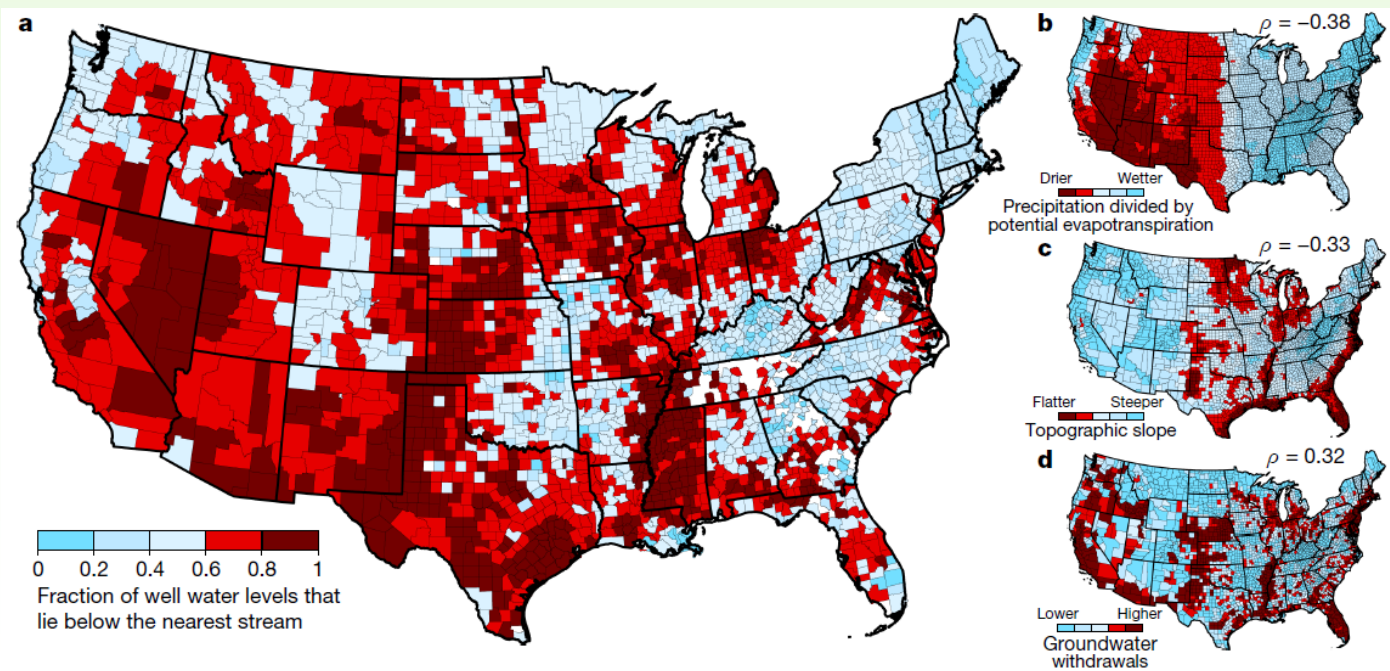
Gu et al., 2008, *WRR*

Many assume that GW almost always discharges to streams and rivers, particularly since they are the drains of the landscape





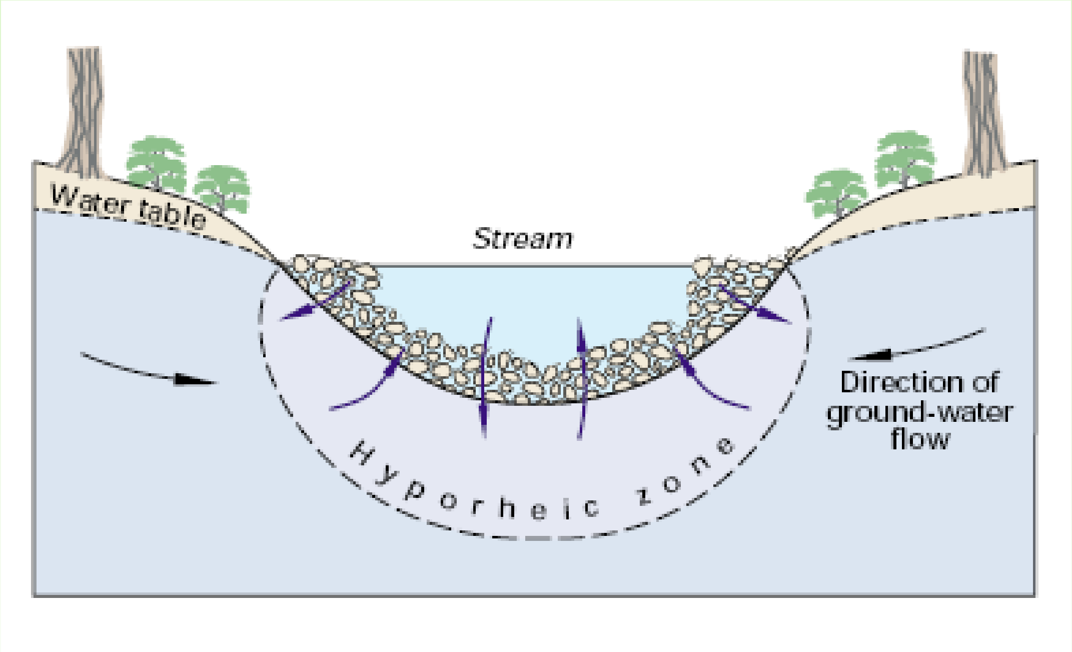
However, a recent study in USA indicates that 64 percent of streams and rivers actually lose water to groundwater



I remain a bit skeptical of these results, but the manuscript was vetted by Nature, so there's that.

Jasechko et al., 2021, *Nature*

The Hyporheic Zone:
In many stream settings, surface water flows through short segments of its adjacent bed and banks and then back into the stream. This subsurface zone is called the hyporheic zone.

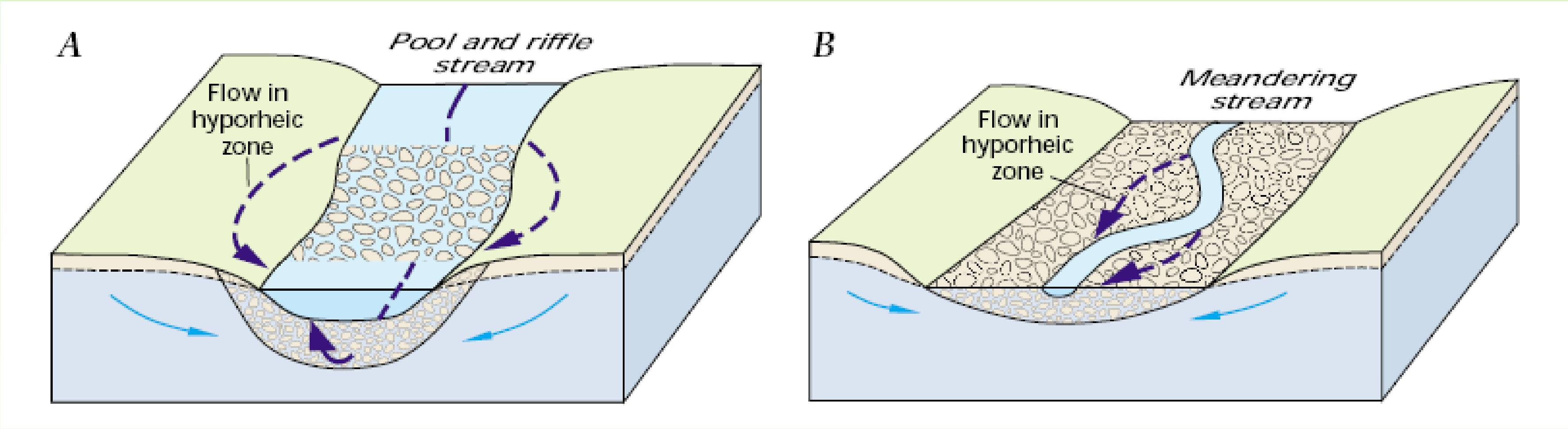


Hyporheic water is water in the sub-surface that originates as surface water. The hyporheic zone is a mix of this water and discharging groundwater.

Distinguishing hyporheic exchange from groundwater discharge can be very difficult in some settings. We will talk much more about this later.

The chemical and biological character of the hyporheic zone may differ markedly from adjacent surface and ground waters because of mixing of surface and ground waters within the zone.

Flow Within the Hyporheic Zone



Some gaining streams have short or intermittent reaches that lose water to the aquifer under normal conditions of streamflow; this is due to (A) abrupt changes in streambed slope or (B) stream meanders.

This will be discussed in greater detail in a talk on hyporheic processes

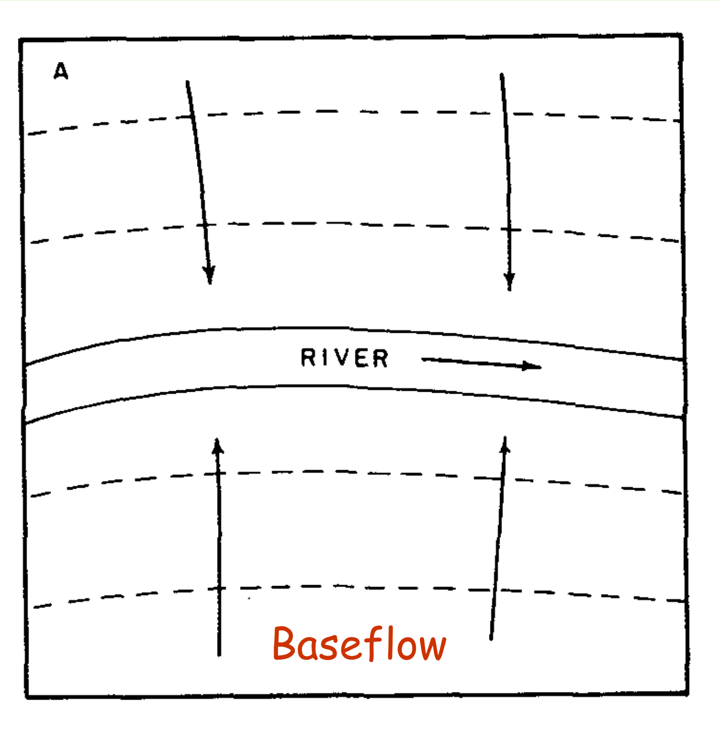
Base Flow—The Groundwater Component of Streamflow

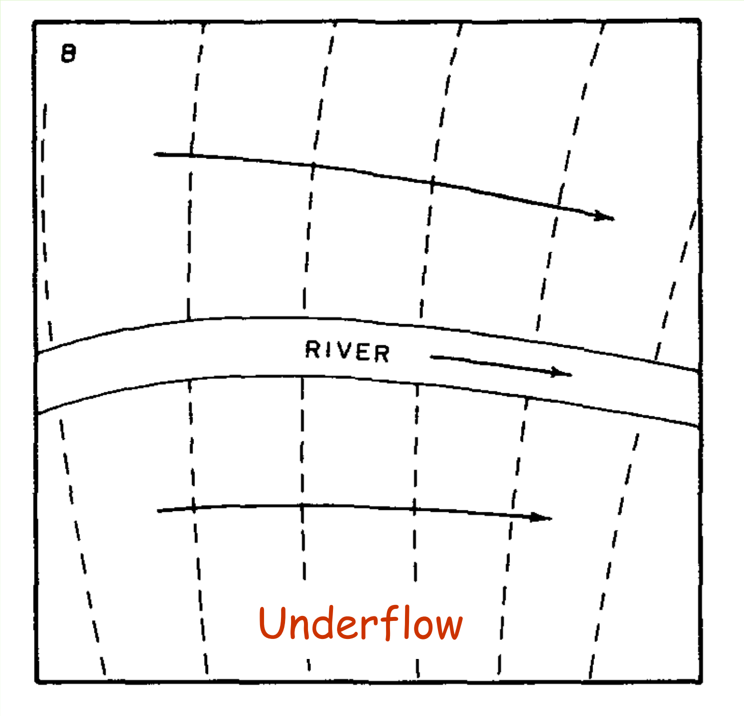
- **Groundwater contributes to streams in most physiographic and climatic settings, yet the proportion of stream water that is derived from groundwater inflow varies across these settings.**

- **Streamflow hydrograph-separation techniques can be used to estimate the amount of GW that contributes to streamflow; that is, the groundwater component, or <u>base flow</u>, of streamflow.**

Masaki will cover this in greater detail later in the course.

Baseflow and Underflow Components of Ground-Water Flow

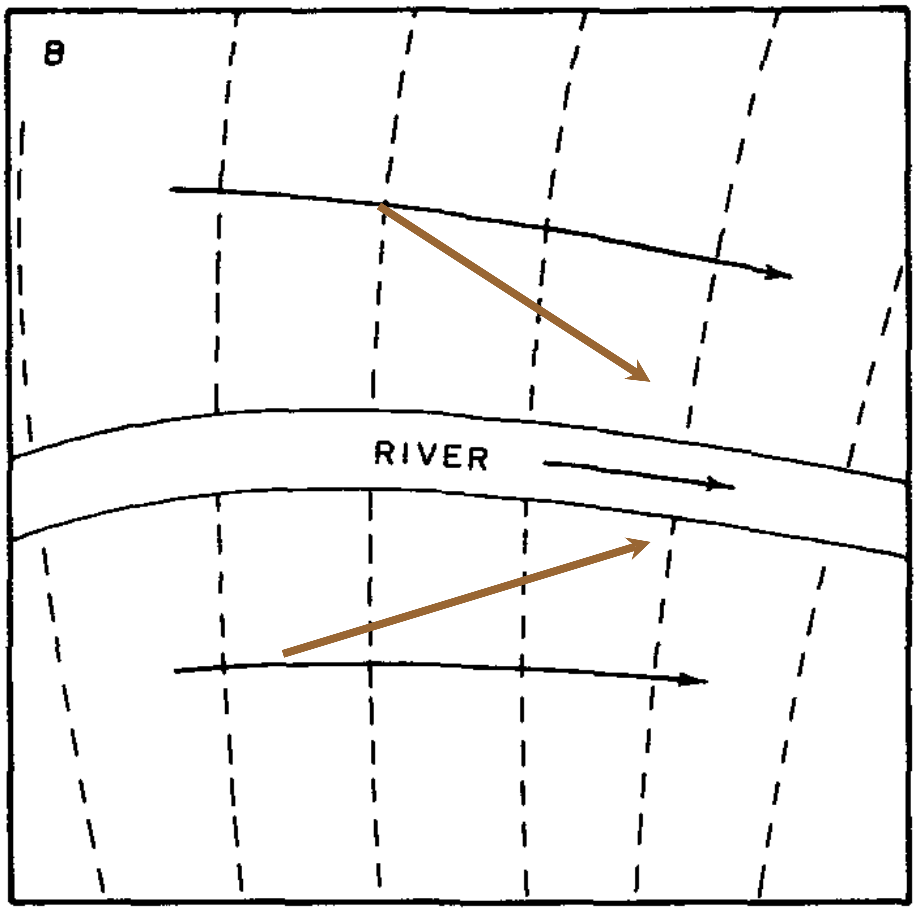




This is often how baseflow and underflow are depicted. Baseflow is the gain in streamflow due to net groundwater discharge along a stream reach. Underflow is flow through porous media adjacent and beneath the streambed that almost never is quantified or accounted for.

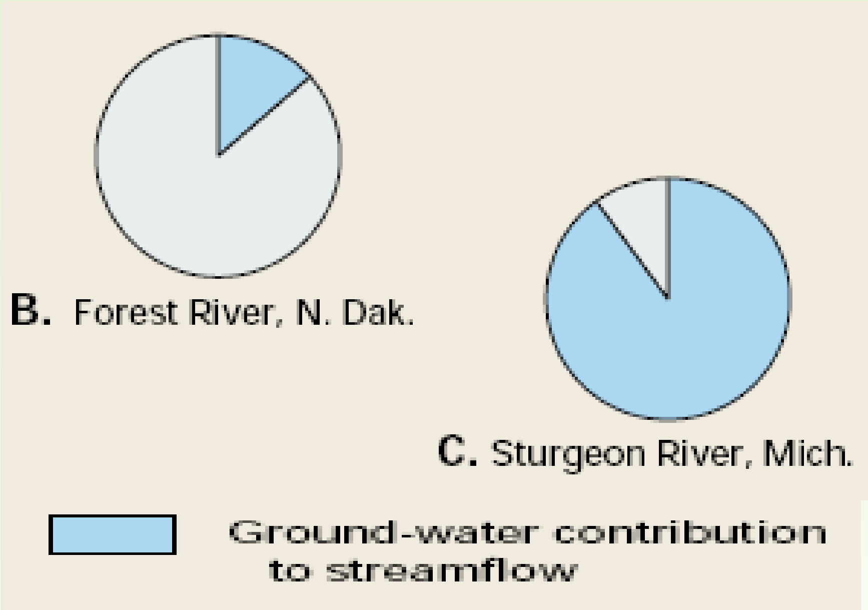
Larkin and Sharp, 1992, GSA Bulletin, v. 104, p. 1608-1620.

Baseflow and Underflow Components of Ground-Water Flow



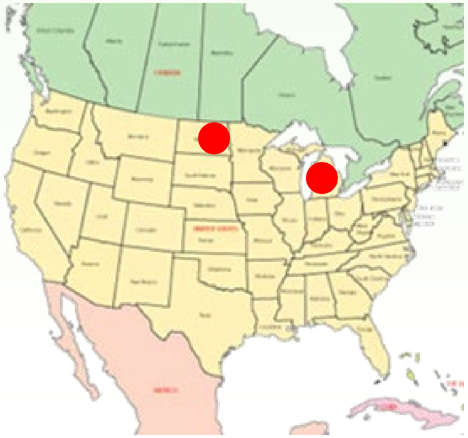
In most settings, the arrows are at an angle (brown arrows) and reflect a combination of both components of flow. The directions of the arrows and magnitudes of the associated flows are constantly changing, and even reversing in some settings. One example of a temporary reversal is bank storage.

The base-flow component of streamflow varies based on physiographic, geologic, and climatic settings.



The Forest River is underlain by poorly permeable silt and clay, with relatively little GW discharge to the river.

The Sturgeon River is underlain by highly permeable sand and gravel, with a large contribution of GW discharge to the river.



What do you think the baseflow component is for most streams and rivers in Spain?

Baseflow values can be artificially large when streamflow is influenced by upstream reservoirs or snowmelt

Water 2019, *11*, 1629 10

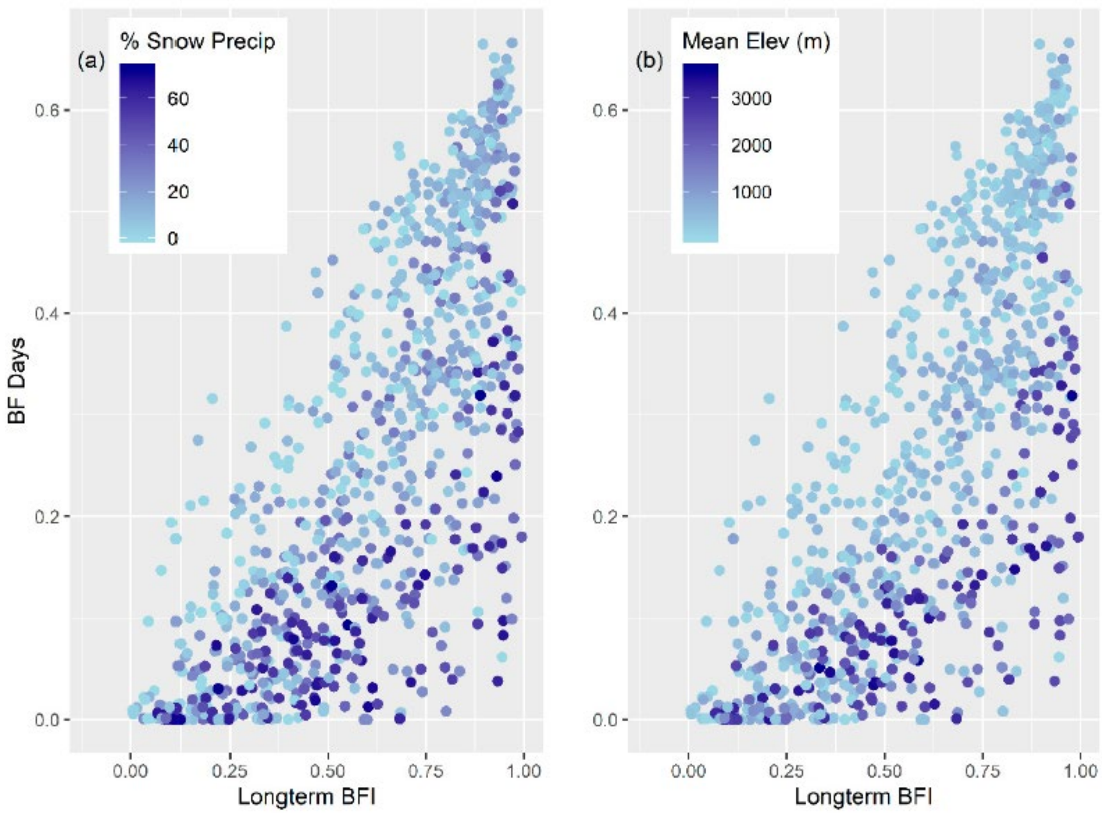


Figure 3. The long-term average base flow index (x-axis) compared to BF Days (y-axis). Sites are colored by the (a) average percent of snow that contributes to total annual precipitation and (b) the mean elevation within the watershed. Watershed slope is not displayed here, but mimics patterns like mean elevation in the watershed.

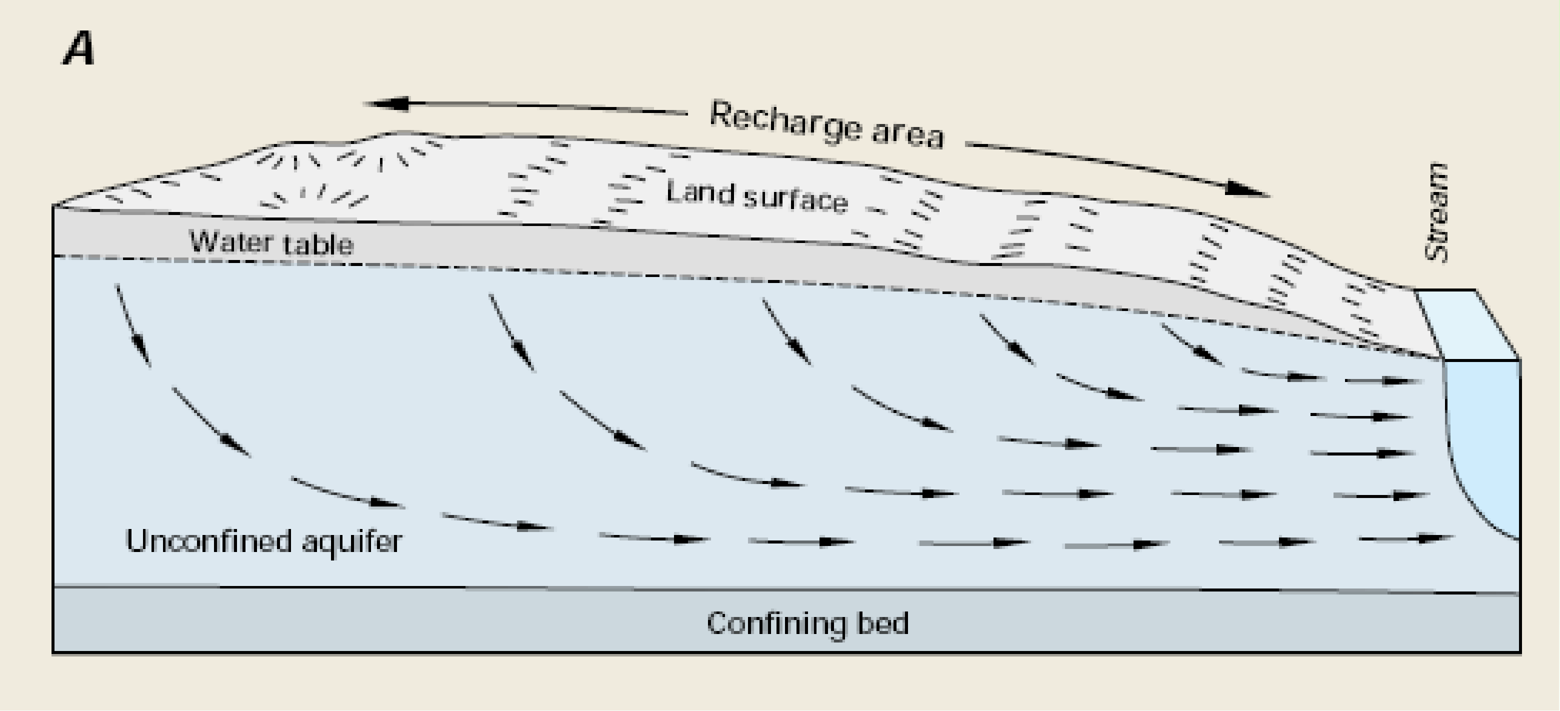
The authors applied optimal hydrograph separation, using used both specific conductance and streamflow discharge, at 825 streamflow sites distributed across USA, for the years 1983 to 2016. These graphs show the extent to which snowmelt (darker-blue dots) contributed to the baseflow index number.

BF Days is the fraction of days with streamflow equal to baseflow.

Mountainous areas have fewer BF days.

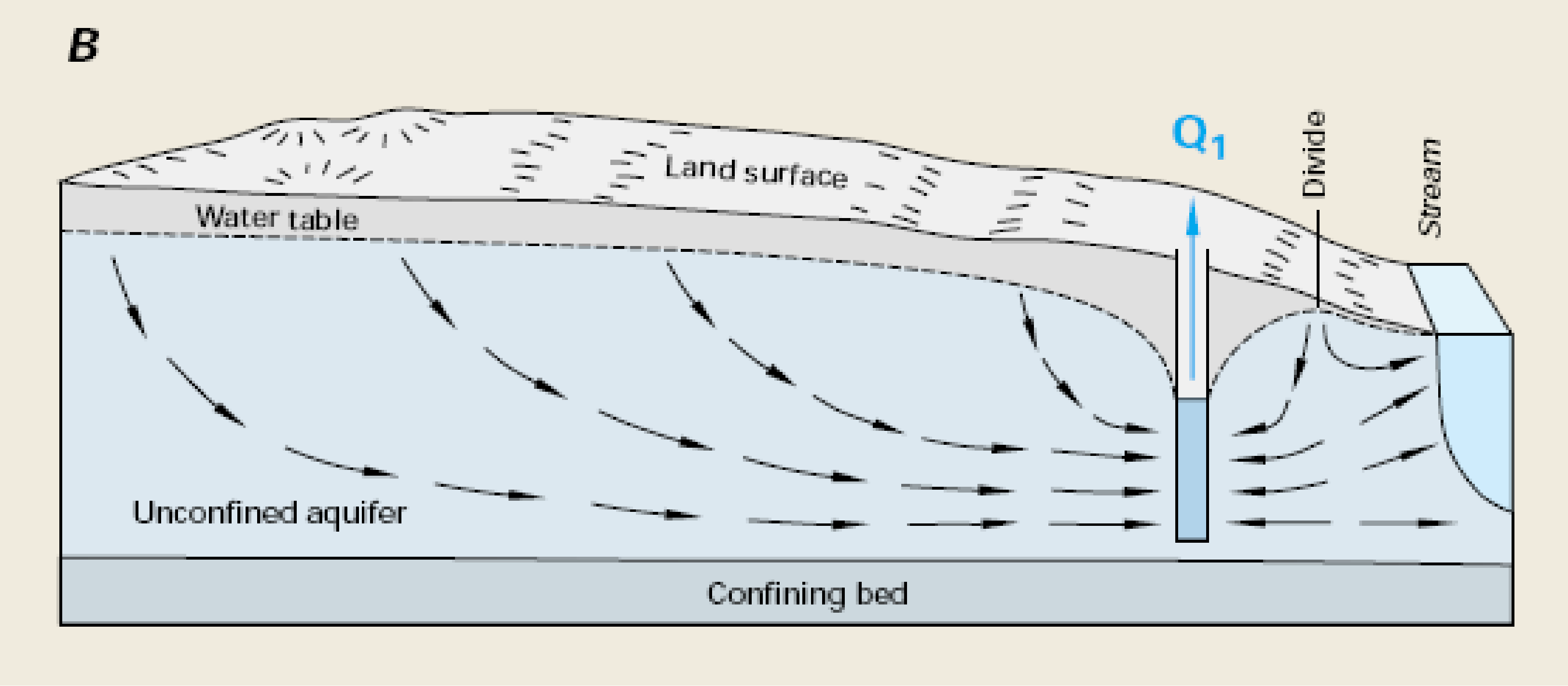
Foks et al., 2019, *Water*

Effects of Ground-Water Pumping on Streamflow



Here, groundwater discharges to a stream under natural conditions.

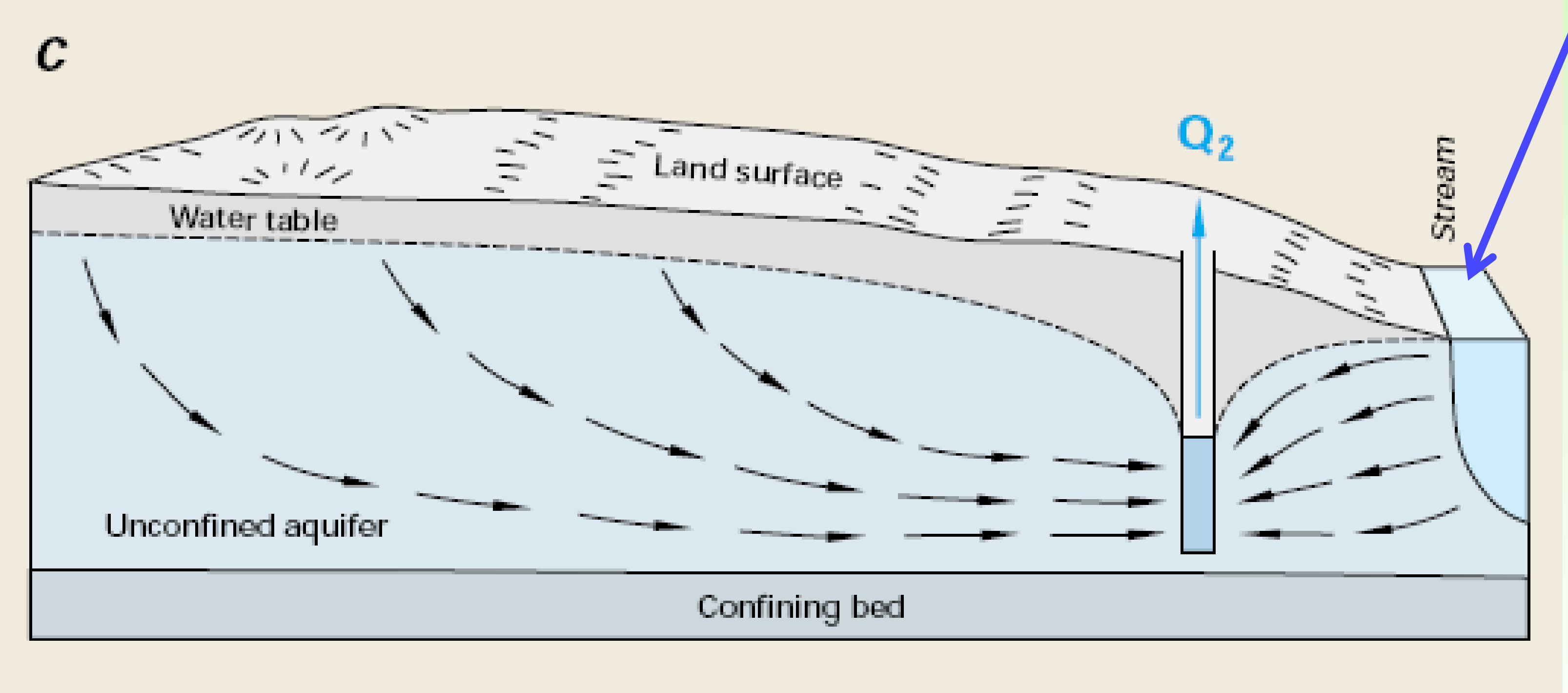
Effects of Ground-Water Pumping on Streamflow



At lower pumping rates, removing water from a well captures ground water that would otherwise have discharged to the stream.

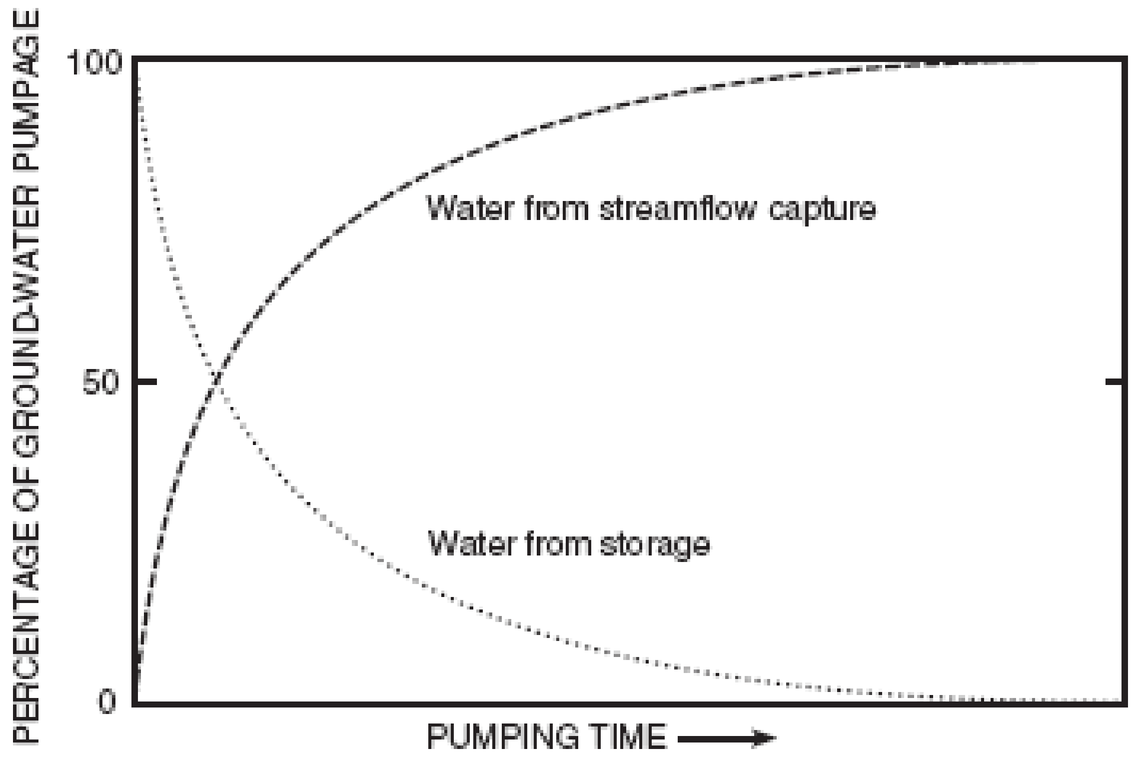
Effects of Ground-Water Pumping on Streamflow

This could also be a lake or wetland or coastline



At increased pumping rates, the well captures (1) ground water that would otherwise have discharged to the stream and (2) induced infiltration of streamflow into aquifer

Sources of Water to a Well as a Function of Time



The process shown in the previous two slides is displayed graphically here.

What happens when water from storage is all used up?

Ground-water withdrawals deplete streamflow and stress aquatic communities in the Ipswich River, Massachusetts

There are many examples where drawdown of groundwater heads pulls so much water from the stream that it ceases to flow. What happens to fish, benthic animals, plants, when this occurs?

Temporal variability

This report discusses streamflow depletion in substantial detail and is a good resource for anyone interested in this topic.

Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow

By Paul M. Barlow and Stanley A. Leake

Photograph by Robert F. Breault, U.S. Geological Survey

Wyoming Pond on the Wood River, Pawcatuck River Basin, Rhode Island.

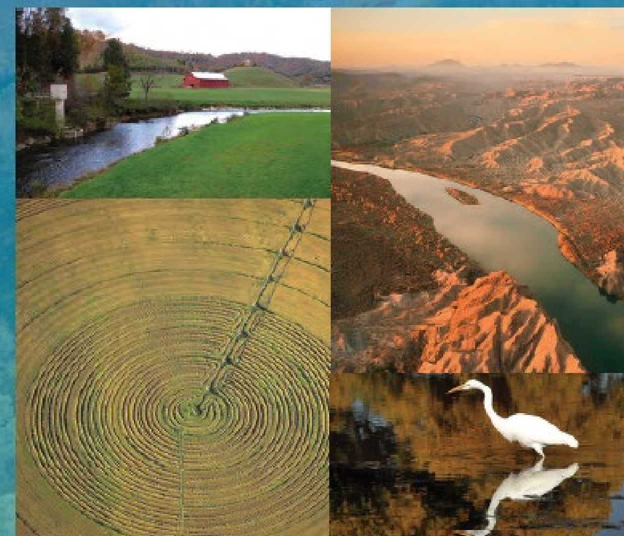
Groundwater Resources Program

Circular 1376, 2012

USGS
science for a changing world

Groundwater Resources Program

Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow



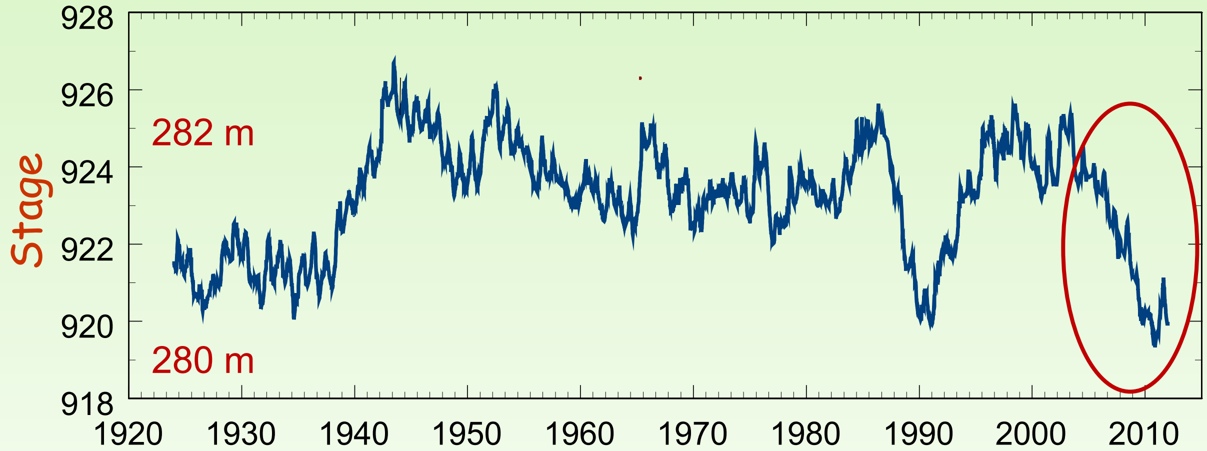
Circular 1376

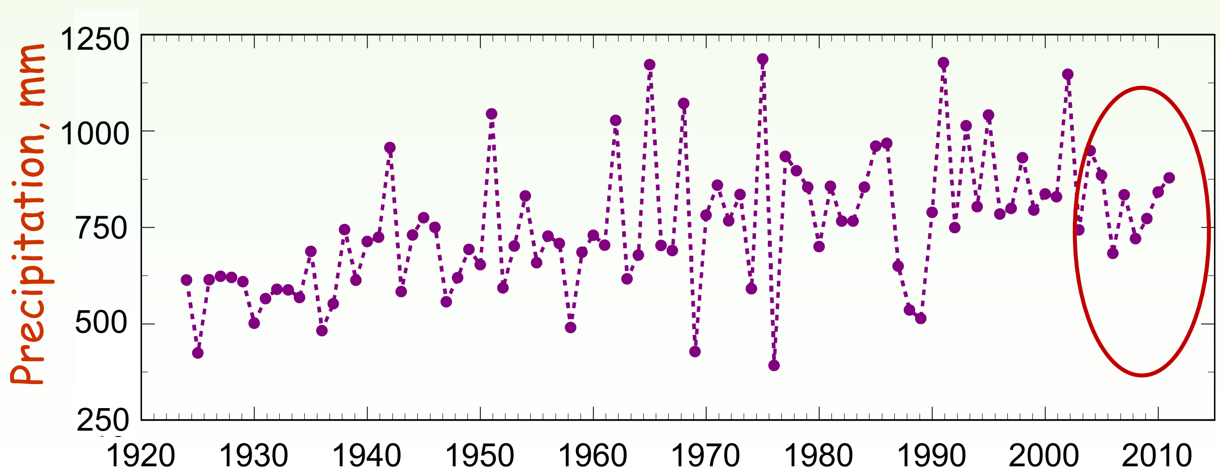
U.S. Department of the Interior
U.S. Geological Survey

An example from a lake in Minnesota, north-central USA

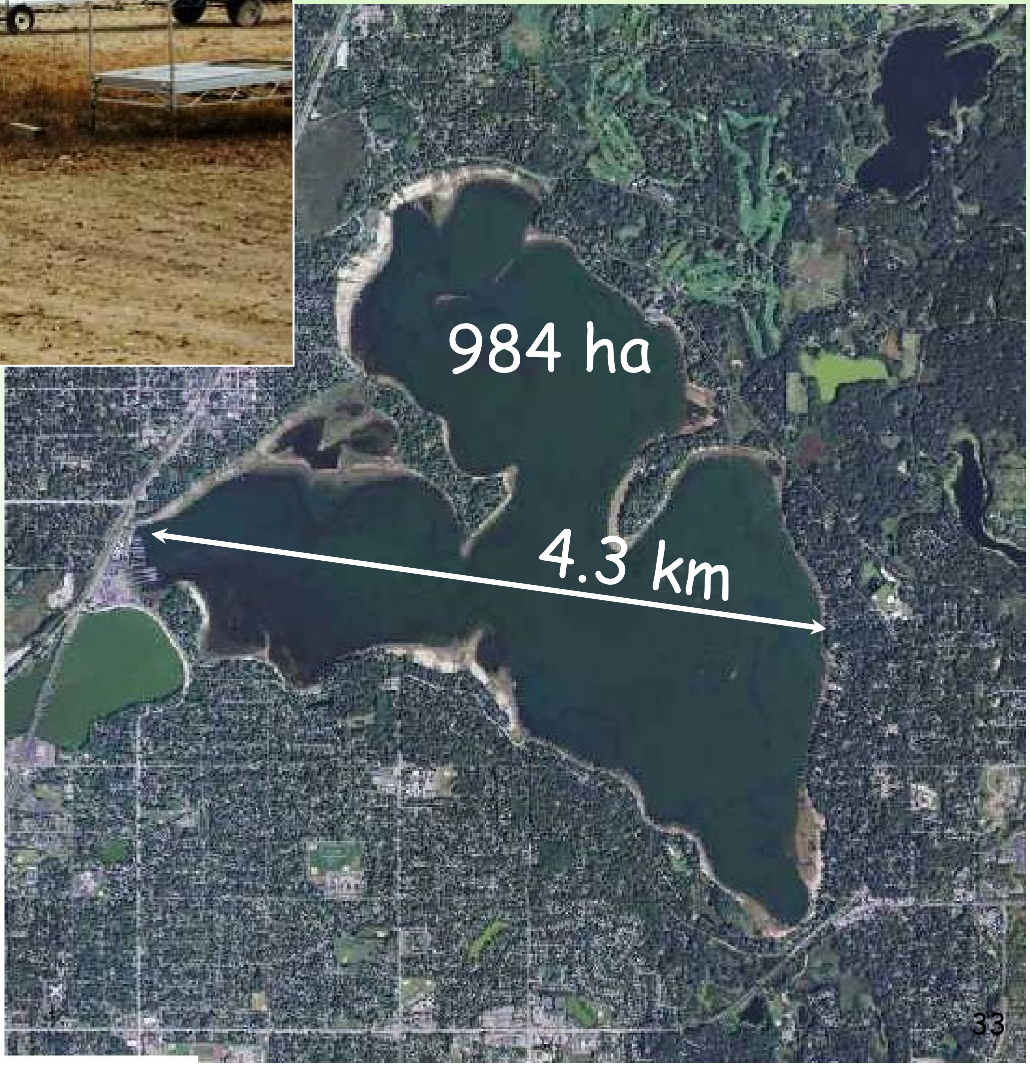
Here we show an example of how pumping an aquifer can also affect a lake.

White Bear Lake level has lowered 2 m in 10 years while annual precipitation stayed about normal





White Bear Lake is one of the most popular and developed lakes in the Minneapolis - St. Paul metro area, the largest population center in Minnesota



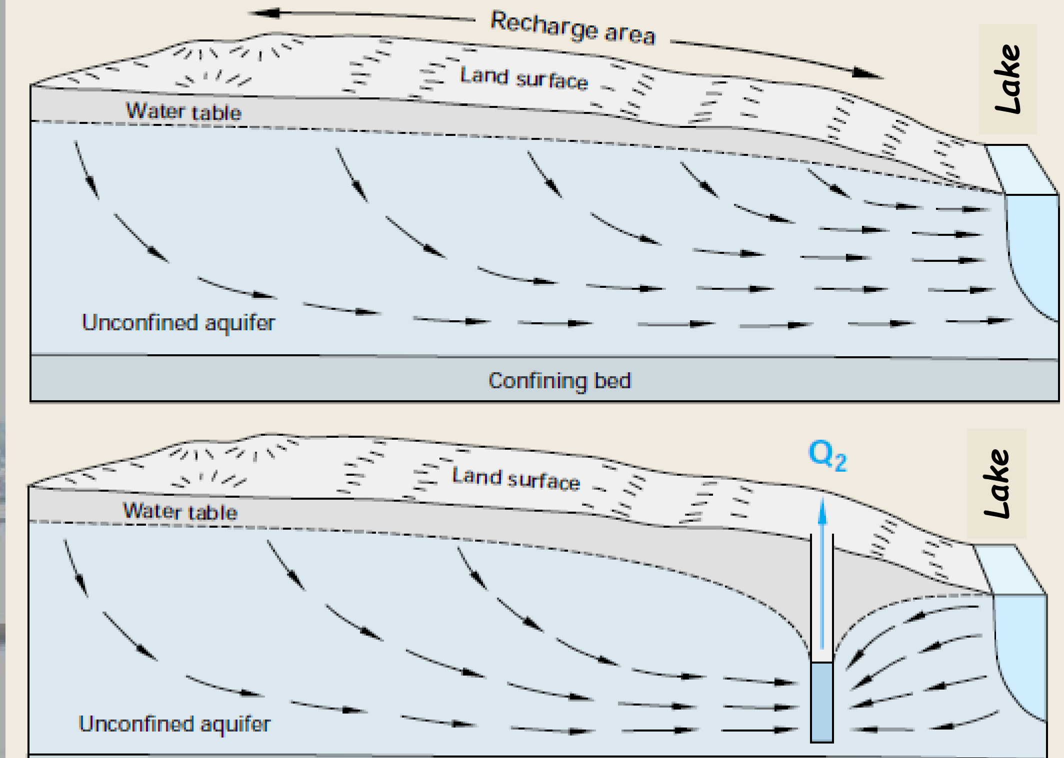
The truck is driving on what normally is the lake. The shoreline has retreated 100 m in places.

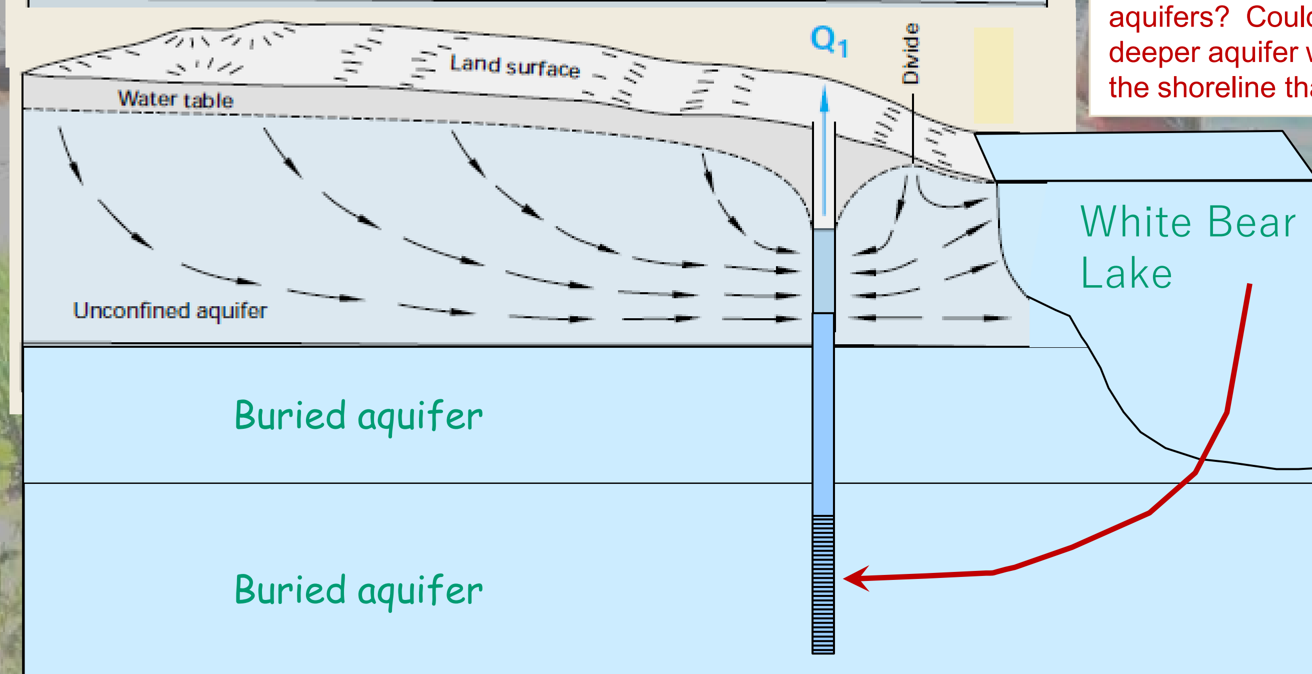
A few images from Google

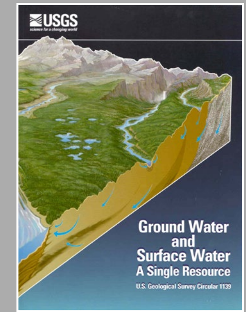
These docks are at the marina in the town, where people dock their boats when they motor or sail across the lake to have dinner and drinks in the evening.

The public beaches were closed because of dense aquatic growth at the new shoreline.

A few images from Google







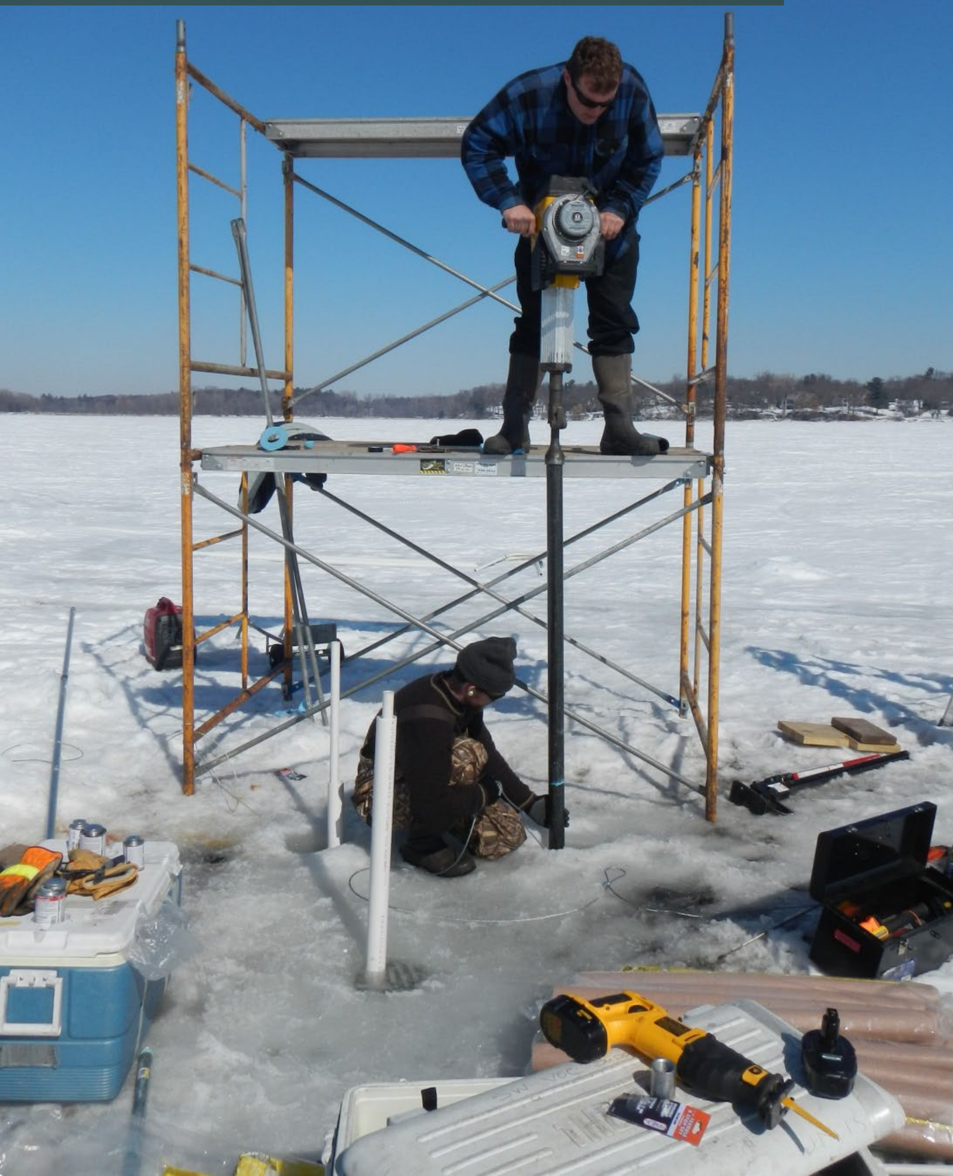
If municipal pumping wells near the lake were shallow, all gradients would be away from the lake. But what if municipal pumping was from deeper aquifers? Could we have loss of lake water to the deeper aquifer while still maintaining gradients near the shoreline that indicated flow to the lake?

Seepage was upward, to the lake, along the entire shoreline
Mie Andreasen took this course in 2010.
These data from in-lake piezometers and seepage meters all indicated gradients near the shoreline were all toward the lake.
USGS
Johnson

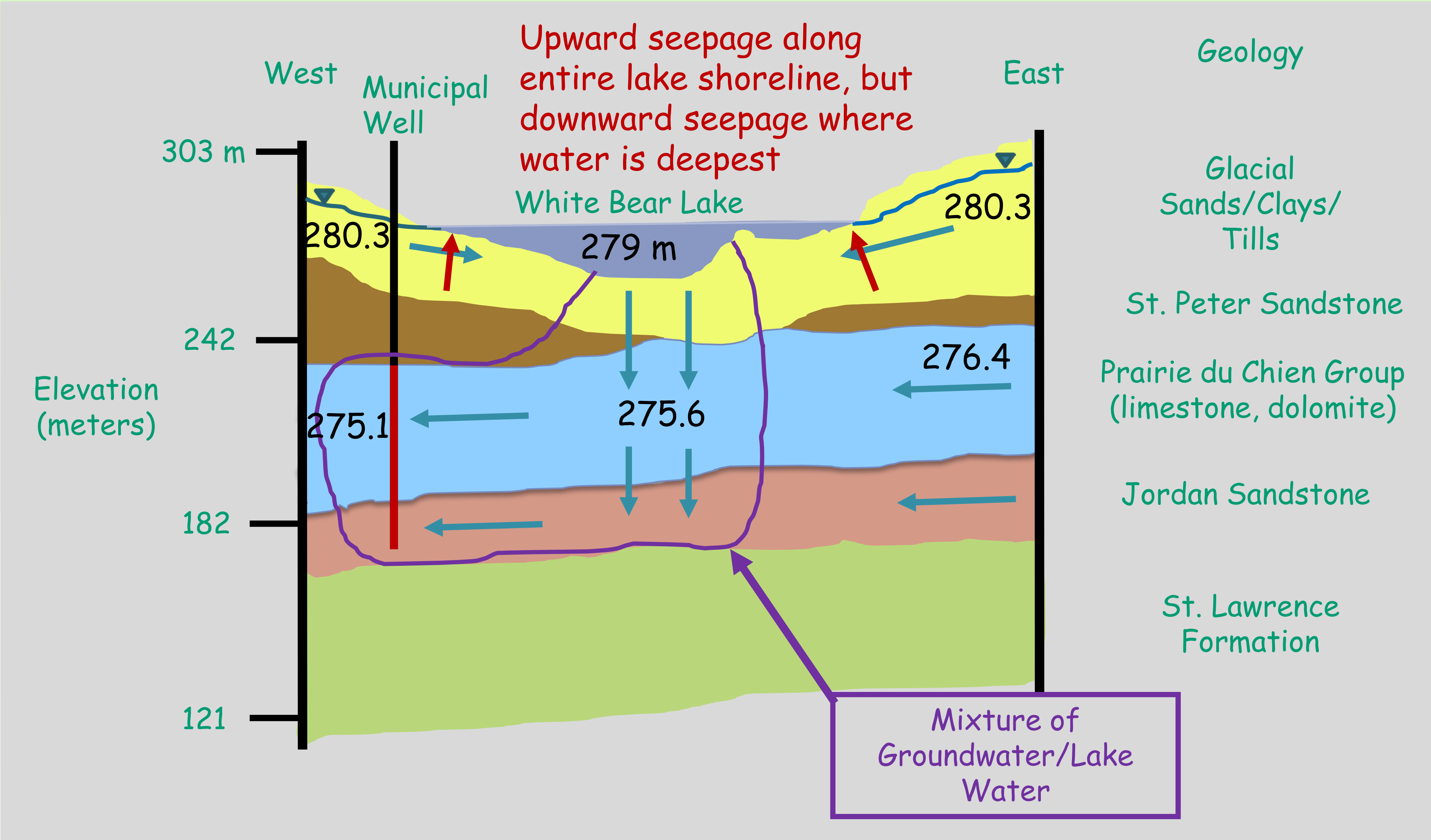

We installed seepage meters in the center of the lake where water was 10 to 22 m deep.
Karoline Edelvang and . . .
. . . Christina Jensen took this course in 2013.
Measuring seepage in the deep, central portion of the lake

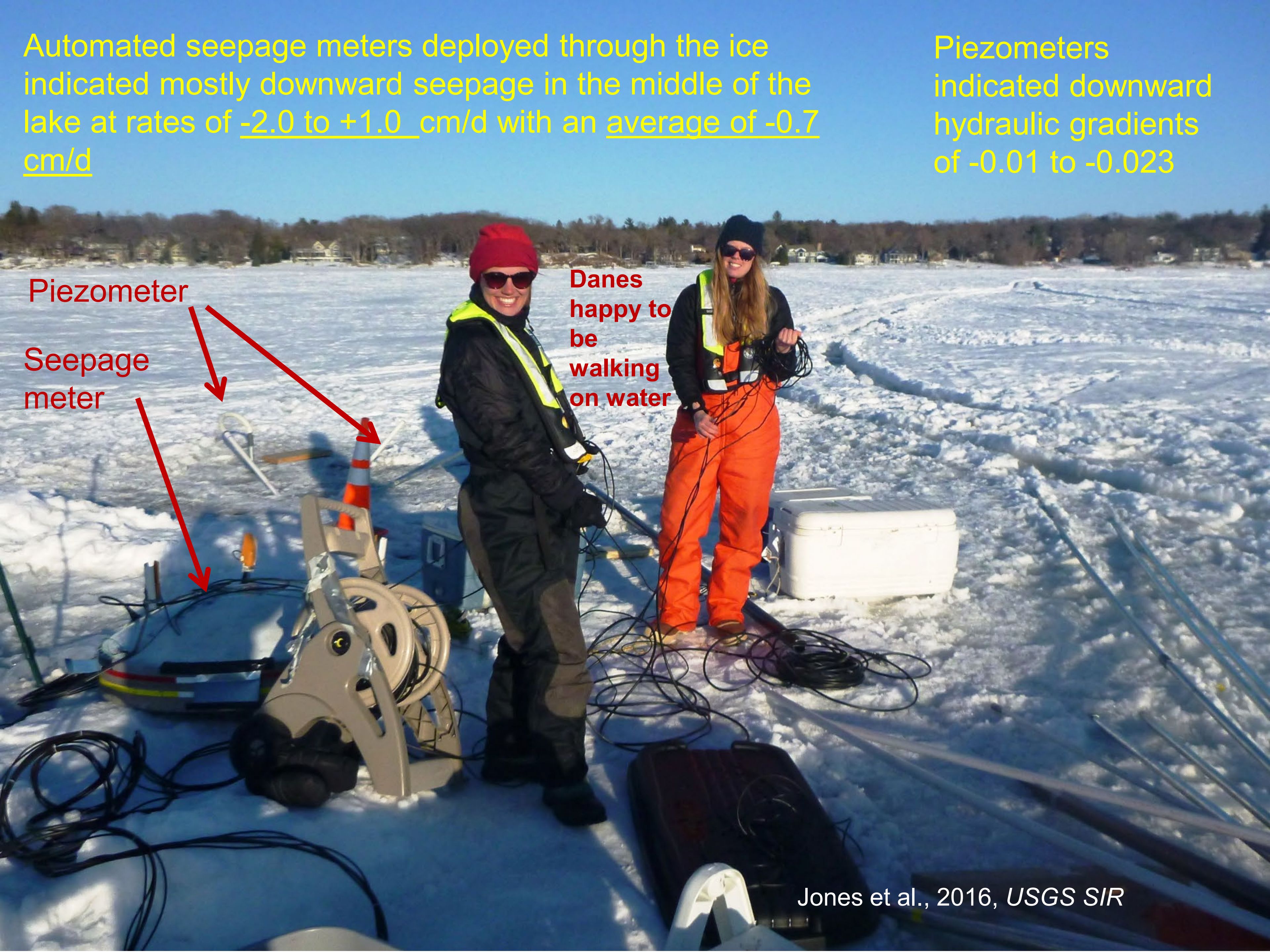
Installing monitoring wells in the deep water

We also installed piezometers in the middle of the lake at the same locations, driving the piezometers into the sediment with a vibrating hammer.



Water isotopes indicated that more than 50 percent of the water removed from the municipal well originated as surface water




Automated seepage meters deployed through the ice indicated mostly downward seepage in the middle of the lake at rates of -2.0 to +1.0 cm/d with an average of -0.7 cm/d
Piezometers indicated downward hydraulic gradients of -0.01 to -0.023
Piezometer
Seepage meter
Danes happy to be walking on water
Jones et al., 2016, *USGS SIR*

Interaction of Ground Water and Marine settings

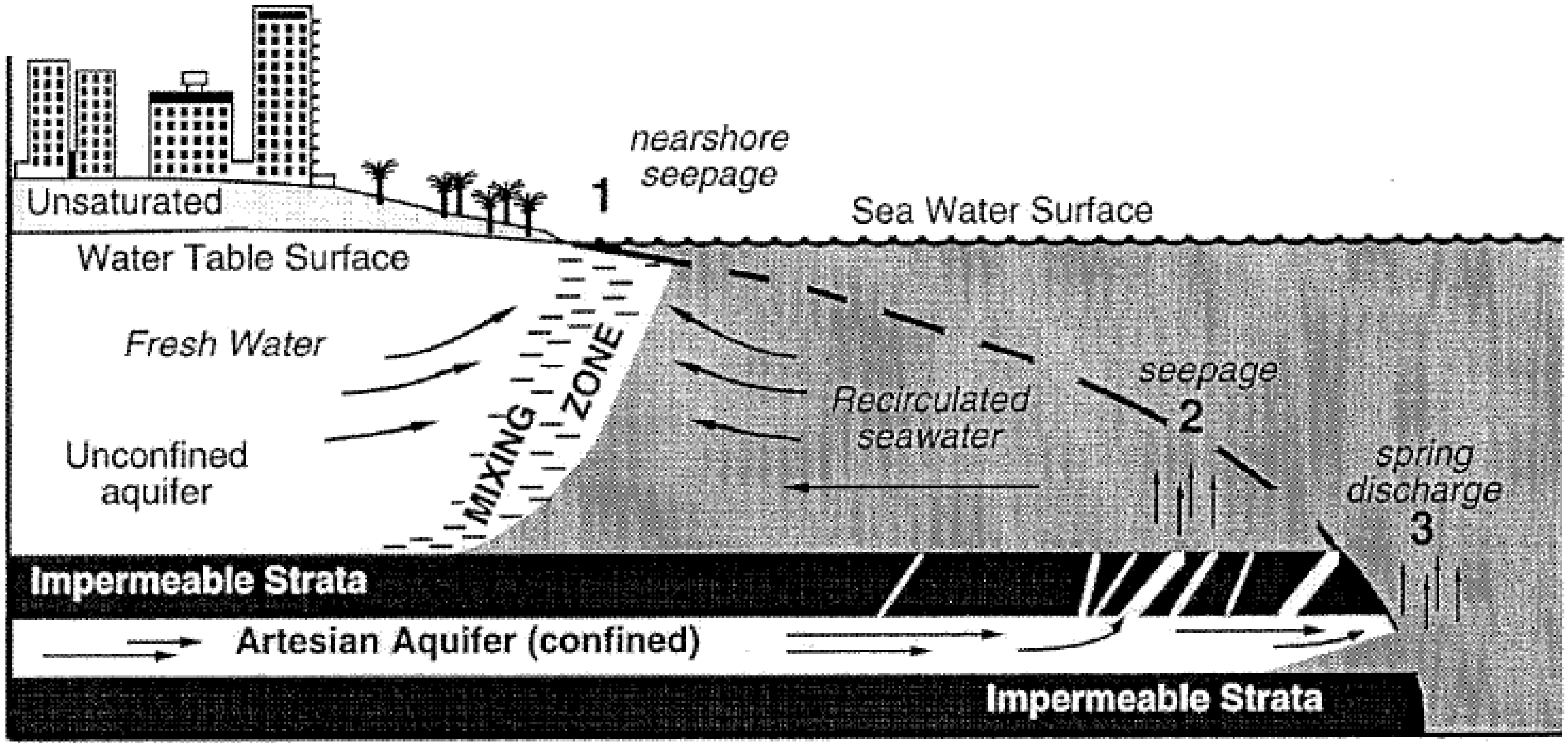


Fig. 1. Diagrammatic view of the relationships between coastal aquifers, seawater, and groundwater discharge. Three types of submarine groundwater discharge are illustrated: (1) nearshore seepage; (2) offshore seepage; and (3) submarine springs.

Coastal settings can be more complex because now water is flowing not only in response to hydraulic gradients but also to salinity and density gradients.

Burnett et al., 2001, *Journ. Sea Res.*

Interaction of Ground Water and Marine settings

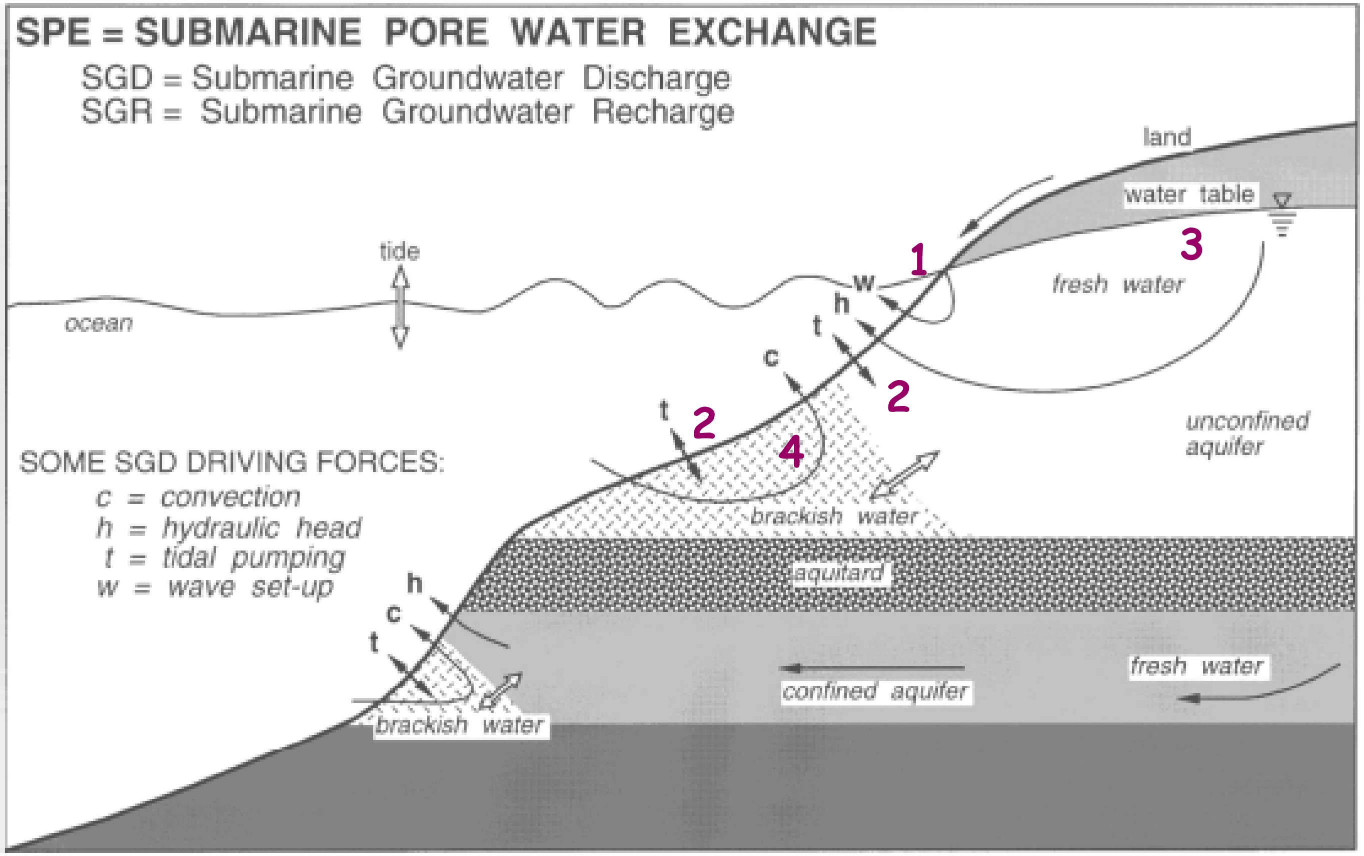
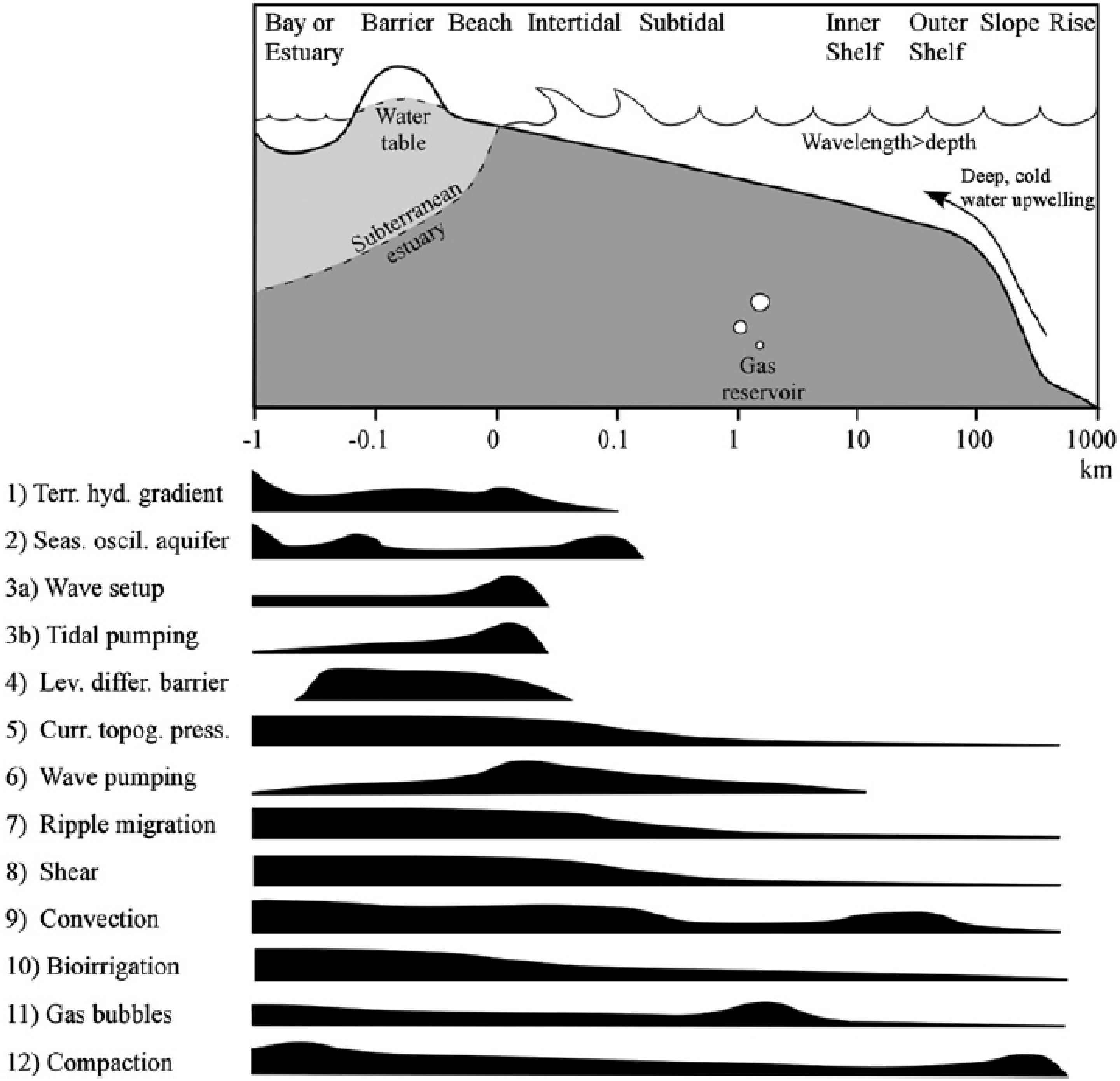


Figure 1. Nomenclature of fluid exchange and schematic depiction (no scale) of processes associated with submarine groundwater discharge and recharge. Arrows indicate fluid movement. Modified from Thibodeaux and Boyle (1987)

1. Wave setup
2. Tidal pumping
3. Topographic gradients
4. Salinity-driven convection
5. Geothermal convection

Burnett et al., 2003, *Biogeochemistry* special issue

There are many processes in coastal settings that affect GW-SW exchange as much as or more than near-shore hydraulic gradients. Santos et al. describe each of these 12 processes in considerable detail.

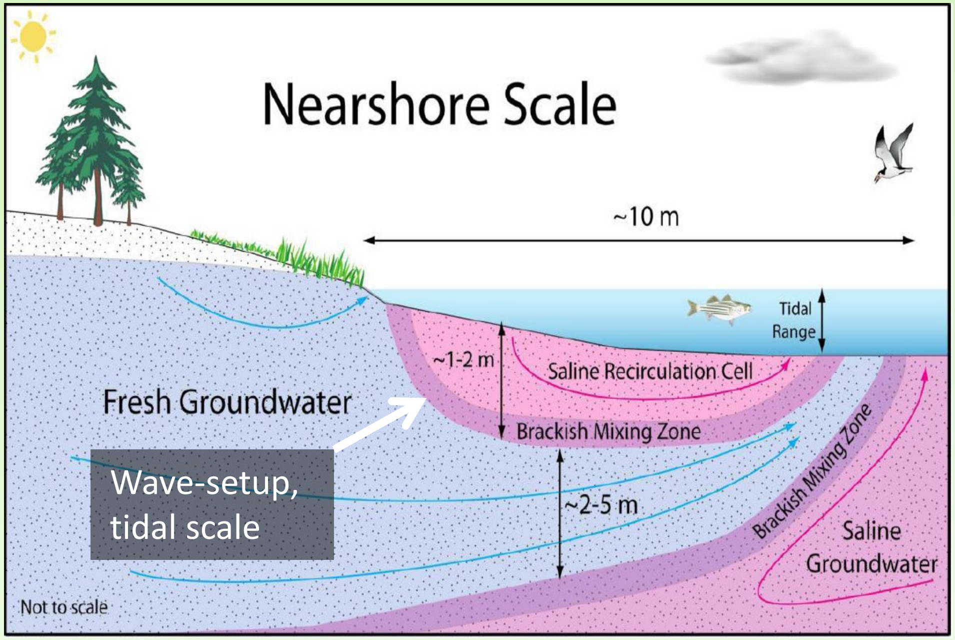


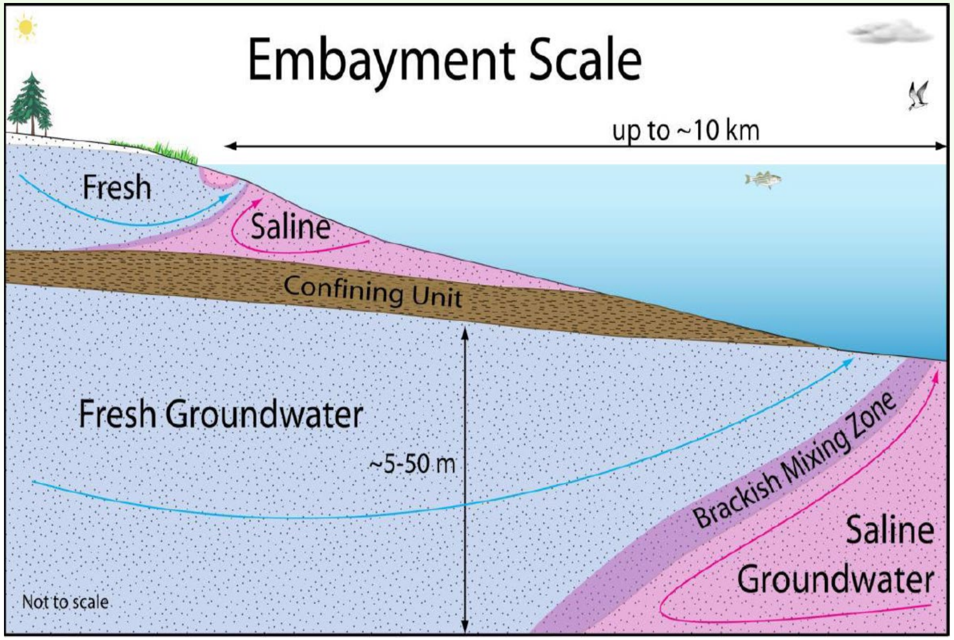
Santos et al., 2012, *Est. Coast. Shelf. Sci.*

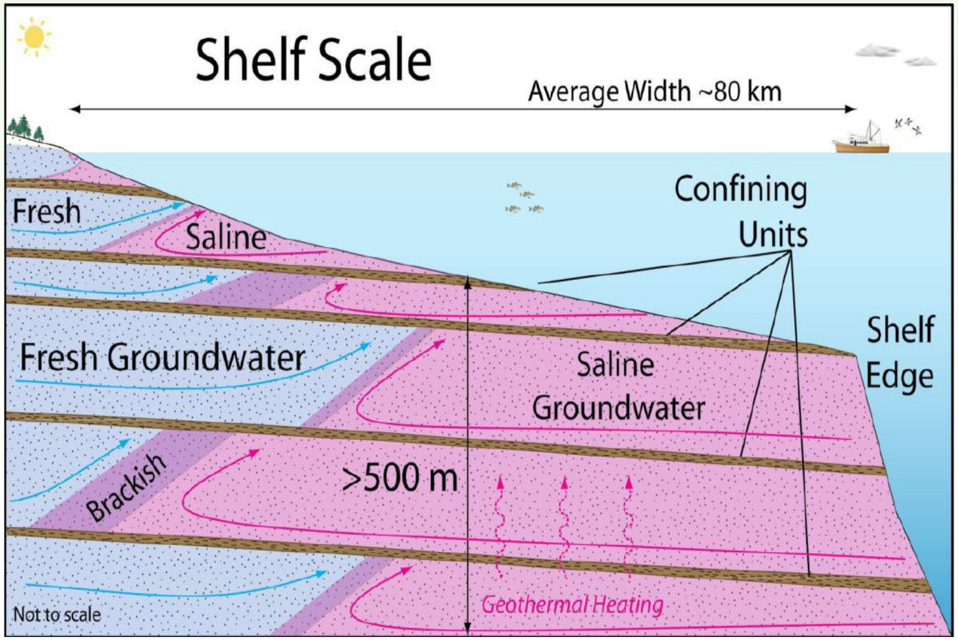
Three scales of SGD: Nearshore scale, Embayment scale, Shelf scale

Bratton, Geology, 2010

And processes vary depending on the shape or configuration of the shoreline, the scale of the study or the physical setting, in addition to distance from shore.

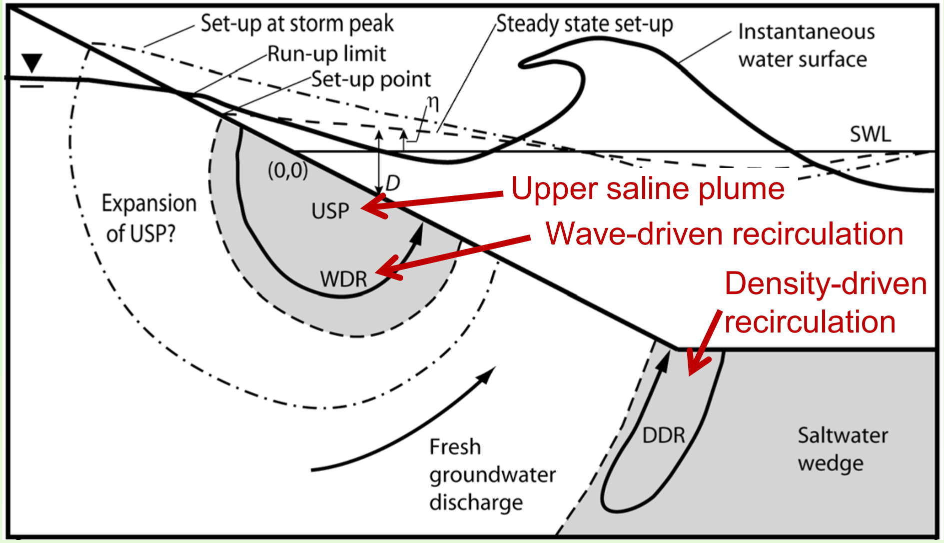




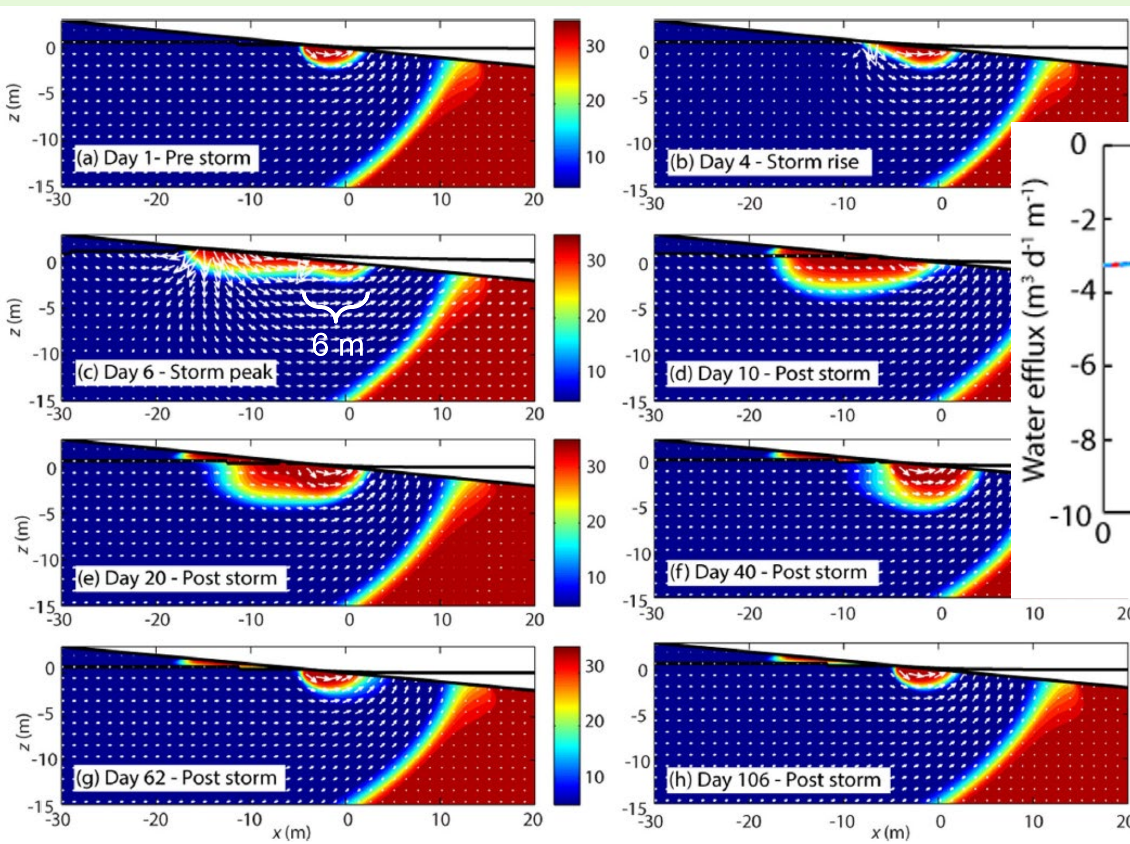


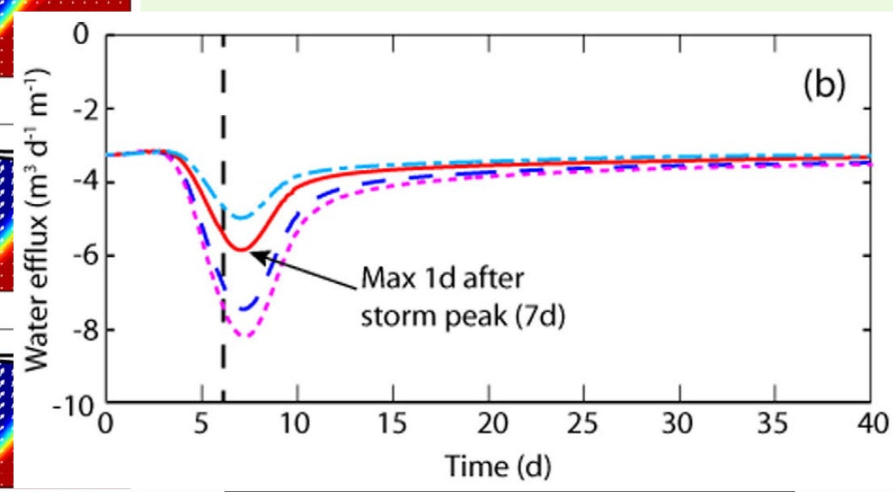
Extent of wave setup is substantial and long-lasting

Robinson et al., WRR, 2014



SUTRA was used to simulate storm-driven salt introduced into fresh GW discharge with a bed slope of 0.1 and *K* of 10 m/d. A 3-m max wave height has about a 0.5-year recurrence interval. Salt blob introduced by storm reached 5 m maximum depth, was still evident 106 days later, and moved about 15 m toward the regular shoreline



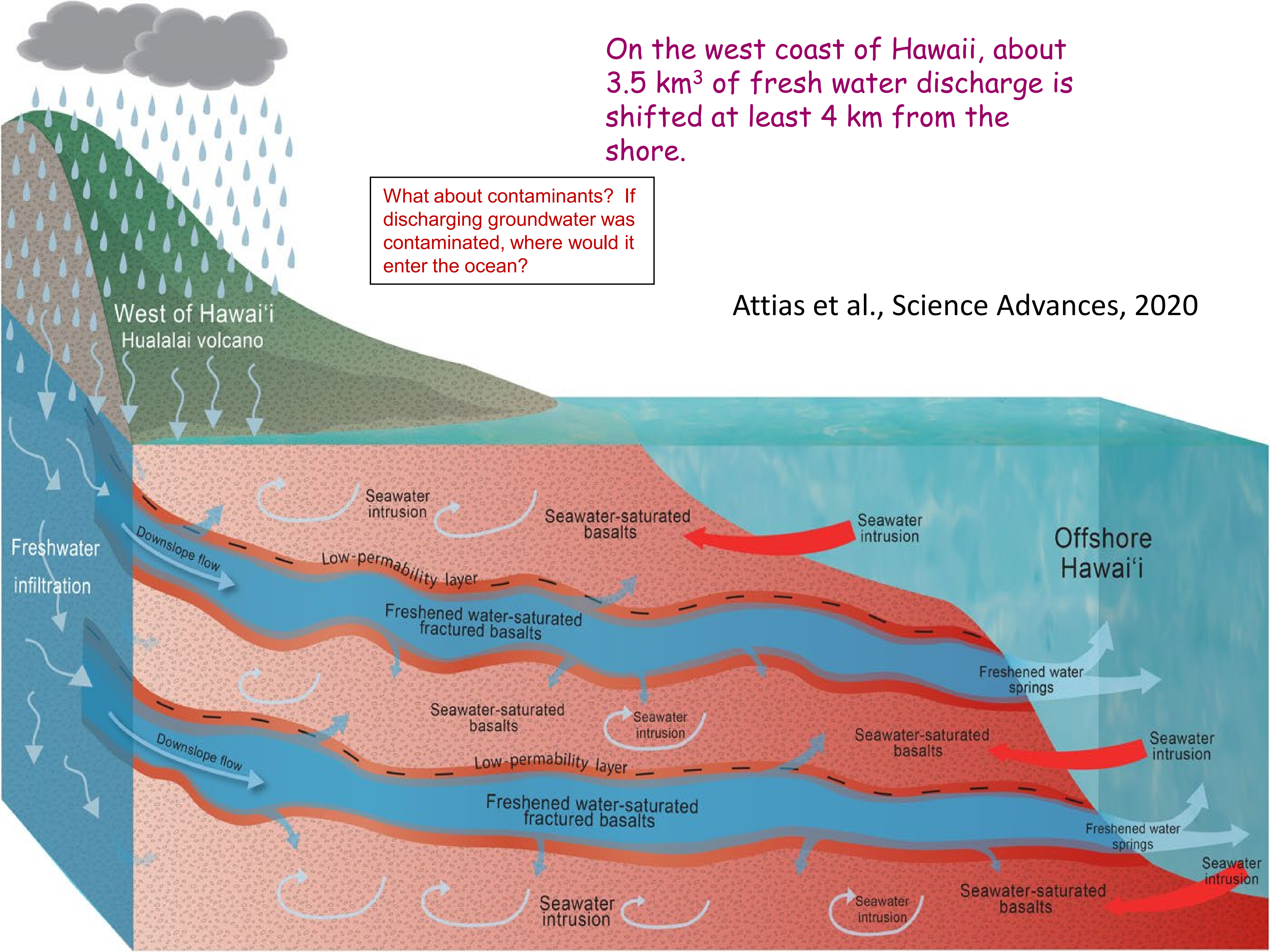


If the wave efflux zone is about 6 m wide, a maximum efflux rate of 6 $m^3\ d^{-1}\ m^{-1}$ would equate to a seepage flux of about 1 m/d.

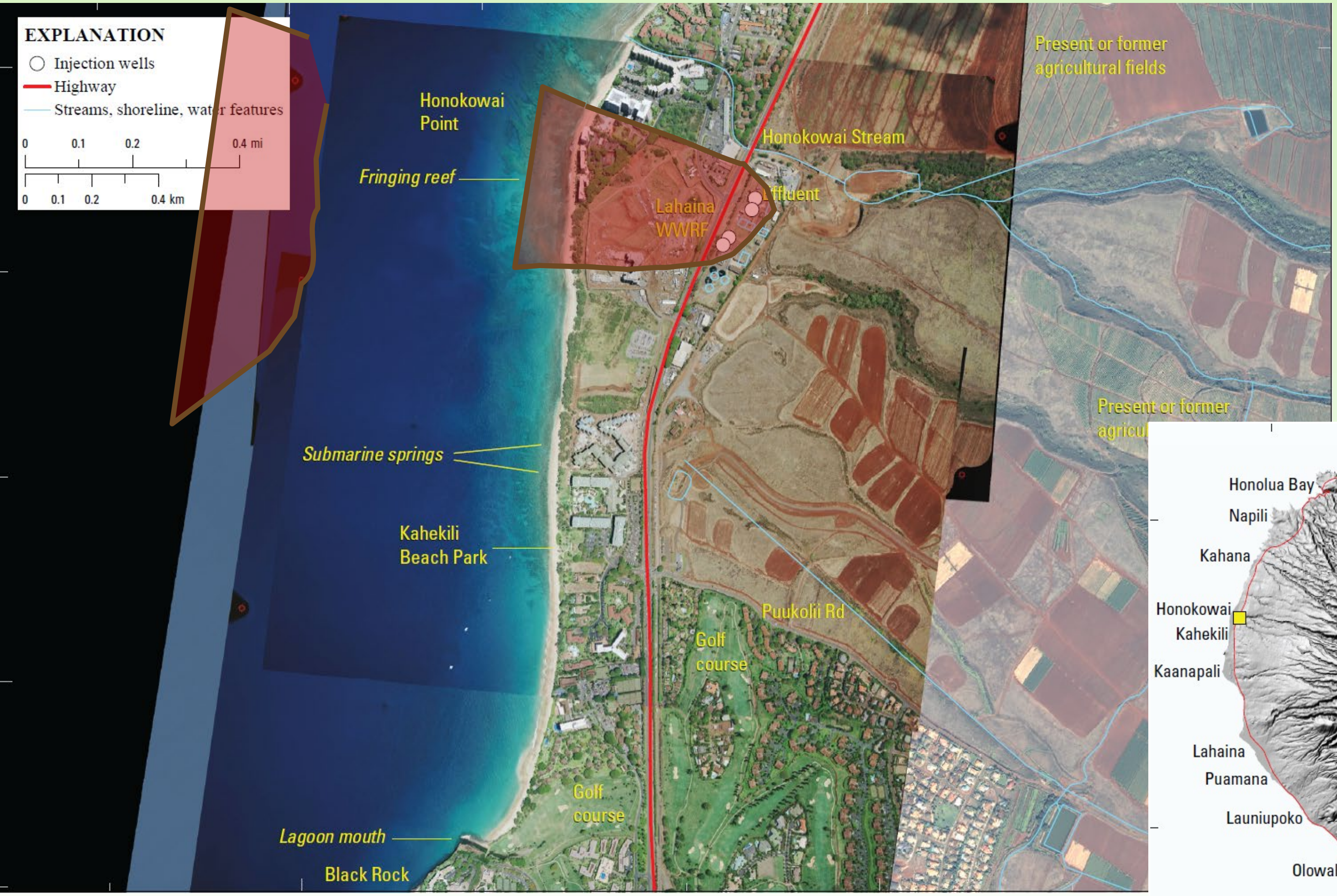
On the west coast of Hawaii, about 3.5 km^3 of fresh water discharge is shifted at least 4 km from the shore.

What about contaminants? If discharging groundwater was contaminated, where would it enter the ocean?

Attias et al., Science Advances, 2020

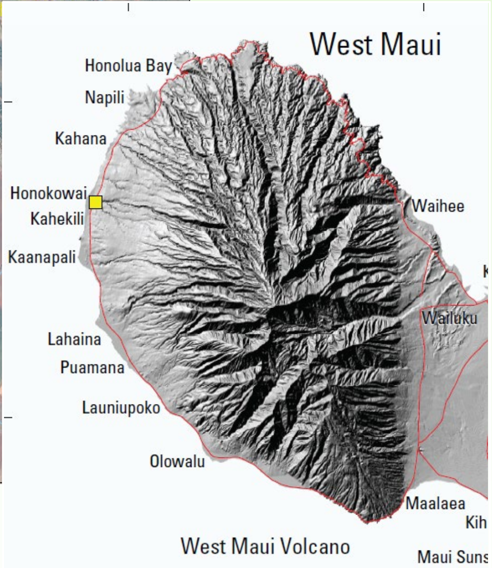


Relevant to a U.S. Supreme Court case about connectivity of contaminants to navigable waters

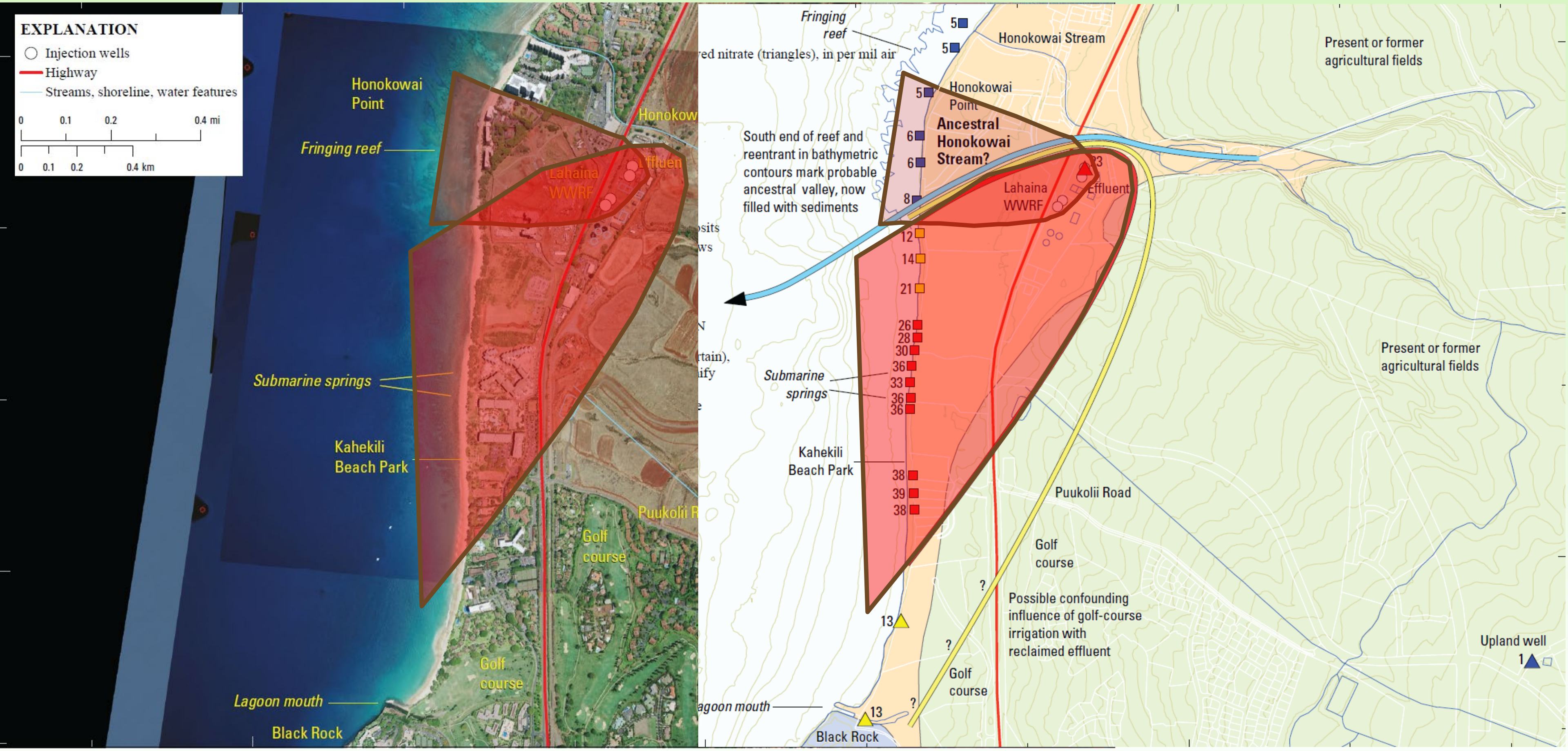


If we knew the geology, point-source connectivity could be based on logic

. . . If only we knew the geology



This is a slide from a talk that I am giving in December about GW-SW connectivity related to this U.S. Supreme Court decision on contaminants from a wastewater injection well. Where do the contaminants go? What methods are there for quantifying and identifying the flows? The methods you are learning have societal relevance in many ways.

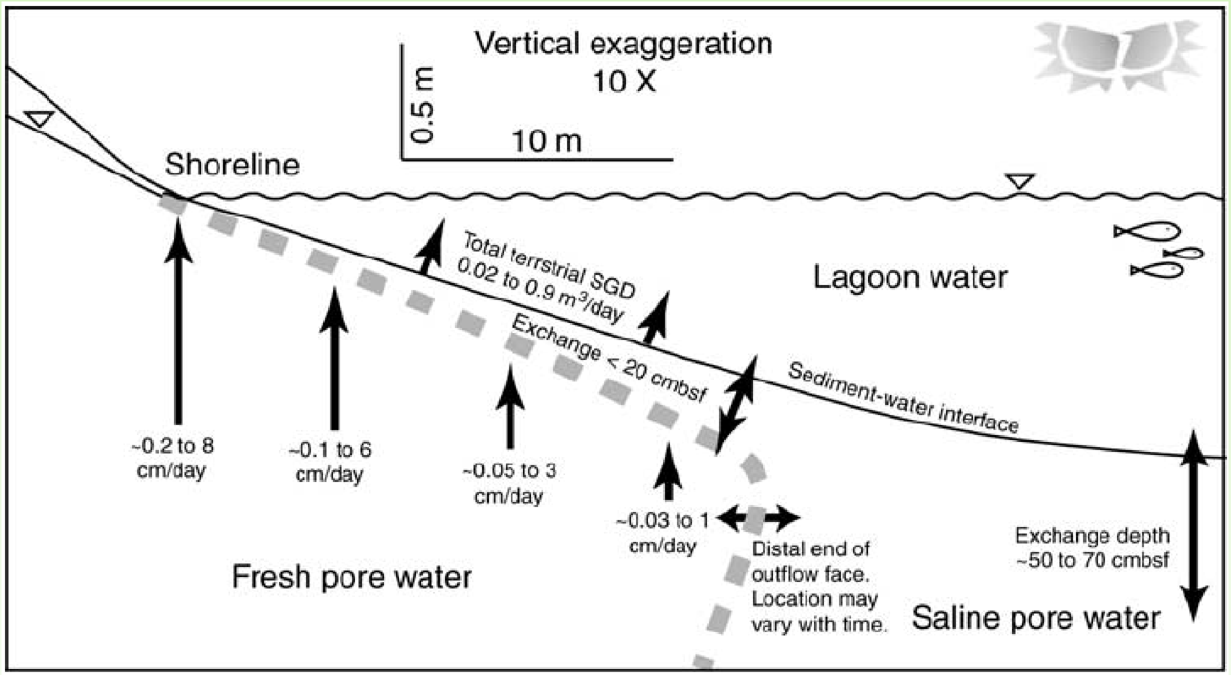


Hunt & Rosa, 2009, USGS SIR

"... Diverted south by a probable buried ancestral valley at Lahaina, Hawaii"

The data showed that the contaminants were discharging near the shoreline (near the break in slope) but not where they first looked. Geology was altering the contaminant distribution.

GW-SW caused by Bioirrigation



Martin et al., 2007,
Water Resour. Res.

Animals can create their own seepage rates. In a setting where seepage ranges between 0 and 8 cm/day, shrimp and worms that filter water to generate seepage on the order of 0.2 to 5 cm/day can greatly confound interpretations of hydraulically driven seepage rages.

Bioirrigating organism		Irrigation rates, mL h^{-1}	Number of burrows, m^{-2}	Volume exchanged, $m^3\ m^{-2}\ day^{-1}$	Linear velocity, cm day^{-1}
Common name	Species				
Ghost shrimp[1]	*Callianassa sp.*	30	3	0.002	0.2
Mud shrimp[2]	*Upogebia affinis* (?)	300	3	0.022	2.2
Lugworm[3]	*Arenicola marina*	96	7	0.016	1.6
Plumed worm[4]	*Diopatra cuprea*	60	9	0.013	1.3
			Total	0.1	5

Cable et al., 2006, *L&O-Methods*

Freshwater bioirrigation

- Rusty crayfish
- Lakes in Minnesota
- ~25 cm/d
- Watch for holes in bed beneath and adjacent to seepage meter

This shrimp altered measured seepage by about 10 cm/d in 2017 at a study in the East River in New York City.

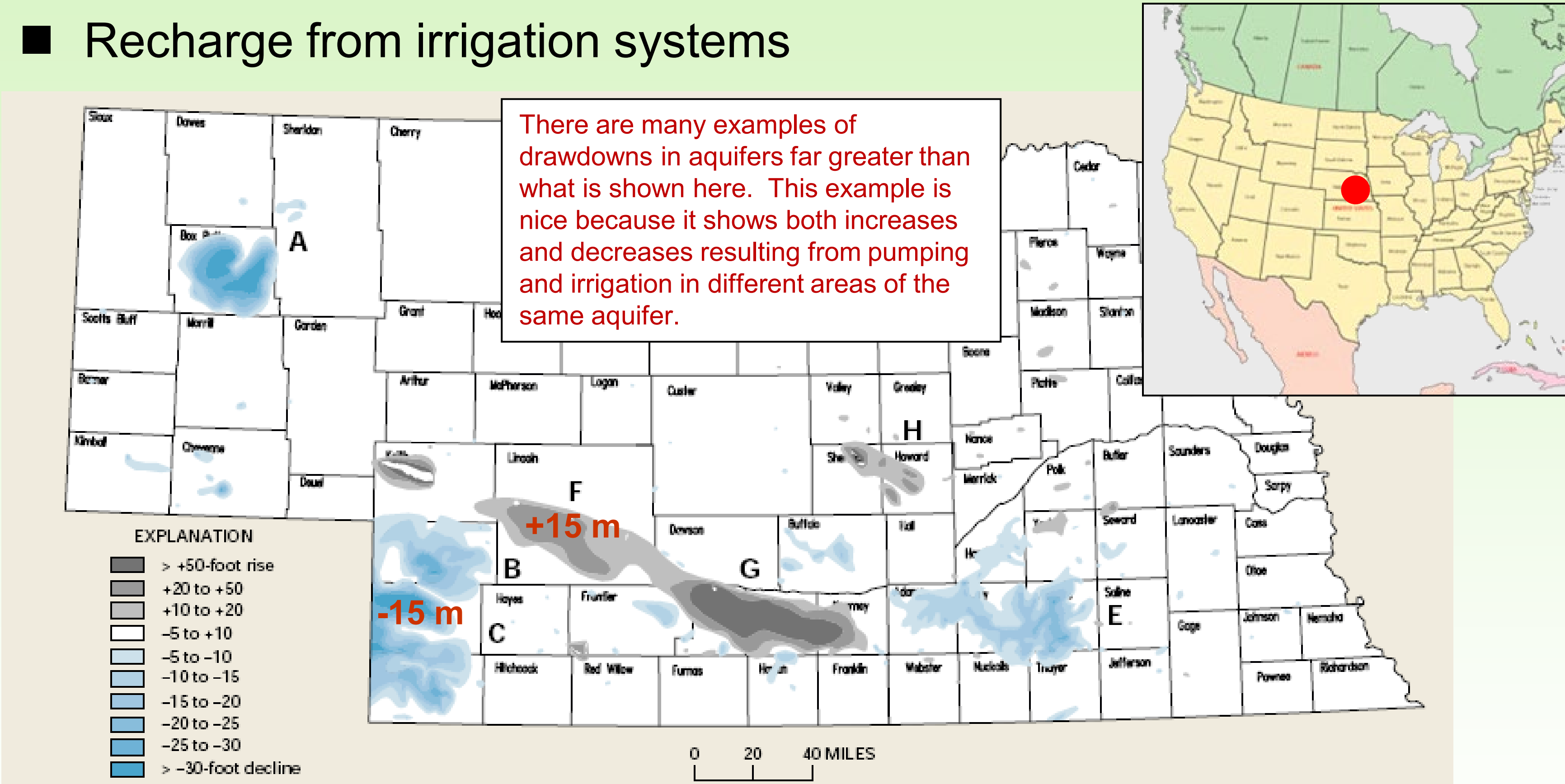
Human Effects on GW/SW Interactions

- Contamination of ground-water and surface-water systems by agricultural chemicals, chemicals used in urban and industrial settings, and so forth
- Drainage of landscapes for agricultural and urban development, which can change the distribution of GW recharge and discharge
- Changes to GW recharge and discharge patterns due to the construction of levees and reservoirs and removal of natural vegetation

What about Spain? Are there any concerns about aquifers or the public water supply?

Human Effects on GW/SW Interactions

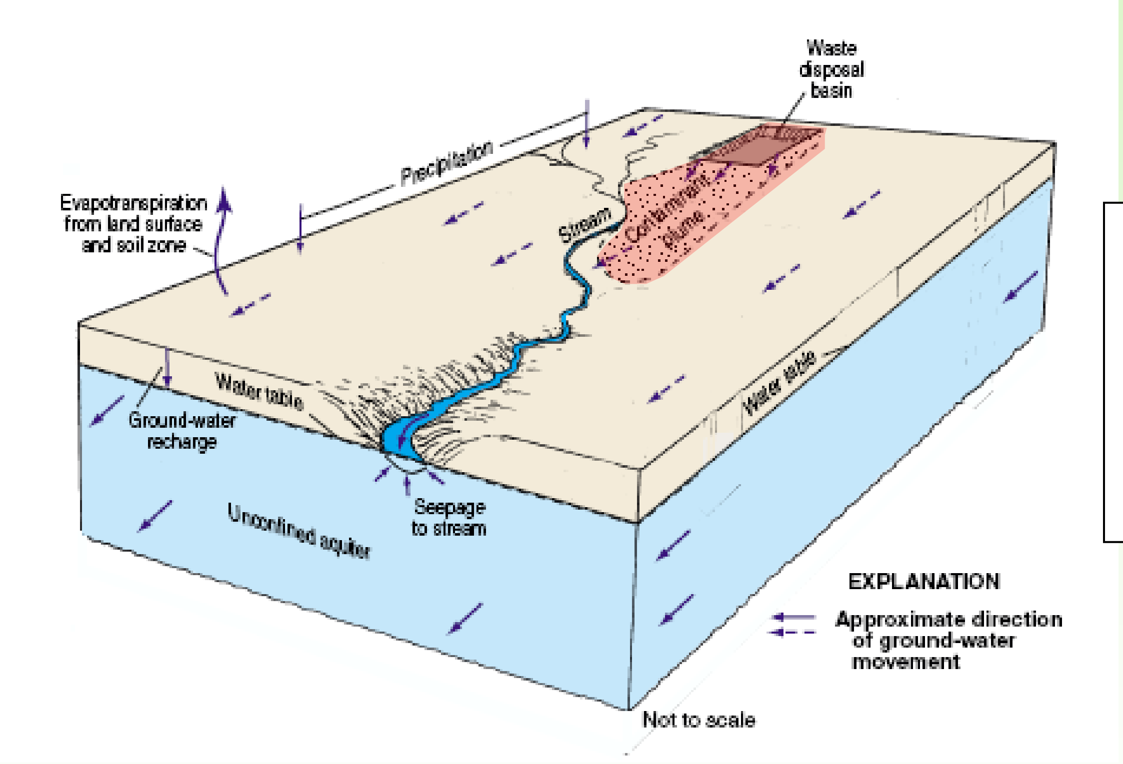
- Ground-water pumping for water supply, irrigation
- Recharge from irrigation systems



There are many examples of drawdowns in aquifers far greater than what is shown here. This example is nice because it shows both increases and decreases resulting from pumping and irrigation in different areas of the same aquifer.

The use of both gw and sw for irrigation has resulted in significant rises and declines in gw levels in different parts of Nebraska.

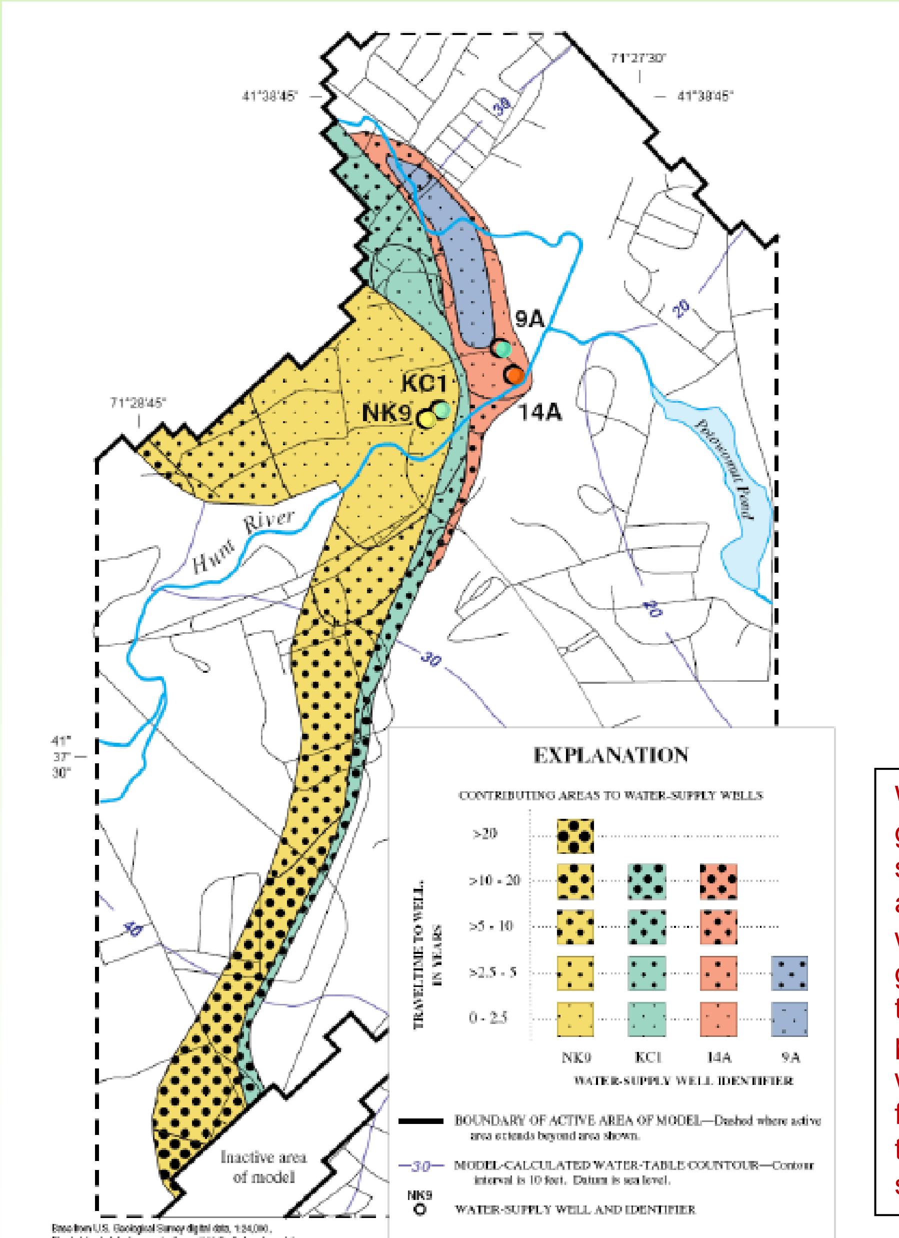
The Quality of Discharging Ground Water Can Affect the Quality of the Receiving Stream



Exchange between GW and SW affects exchange of water chemistry also. Any contaminants present in groundwater or surface water also are transported along with the water across the sediment-water interface.

Simplified representation of a contaminant plume in ground water.

Conversely, the quality of streamflow seeping into an aquifer, perhaps due to induced infiltration caused by pumping, can affect the quality of the receiving aquifer and wells



Induced infiltration from the Hunt River, RI, is a source of water to wells 14A, KC1, and NK9, as shown by the contributing areas to the wells, which overlie the river.

We usually think of groundwater contaminating surface water, but here's an example of surface water contaminating groundwater. In this case, the source area for a pumping well for public water supply is inducing flow from the Hunt River that contains contaminated sediments.

What are Some of the Current Scientific and Management Issues in GW/SW Interactions?

- The role of GW discharge in sustaining low flows, instream flows, and environmental flows
- Physical, chemical, and biological processes in the hyporheic zone
- Continued interest in the mechanics and timing of streamflow depletion by wells (and accretion by irrigation return flows)
- Advanced methods for coupled GW-SW models, such as GSFLOW
- Improved methods for conjunctive-management of GW-SW systems, including optimization techniques
- Changes in GW-SW exchange in the face of a changing climate

This is an incomplete list. What other concerns or issues would you add?

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