Today’s agenda

- Aquifer Projects
- Review land subsidence
- Where water comes from
- Pump tests!
  - Basic assumptions
  - Pumping/hydraulic tests and analytical solutions for flow to a well

Group	Member 1 name	Member 2 name	Member 3 name	Aquifer Name	Presentation date (April 29 or May 1)
1	Maura Gould	Victoria Bettuelli	-	Ogallala	1-May
2	Kayla Gusikoff	Leidy Baxley	-	Nubian Sandstone aquifer	
3	Tyler Lagasse	Sarah Miller	-	New York & New England	
4	Kerry McNally	Lisa Lunchford	-	Upper Rhine Aquifer	
5	Jessica Berozsky <3	Ryan Knych <3	-	Gulf Coast Aquifer	
6	Emma Daly <3	Alexsia Khim	-	Guarani Aquifer	1-May
7	Erica Boudreau	Michael Turner	-	Sand Pass Divide Well, NV	
8	Christopher Leary	-	-	Basin & Range, AZ	1-May
9	Michael Mirakian	Patrick Hutchinson	Lisa Tuggle	Columbia platau aquifer	

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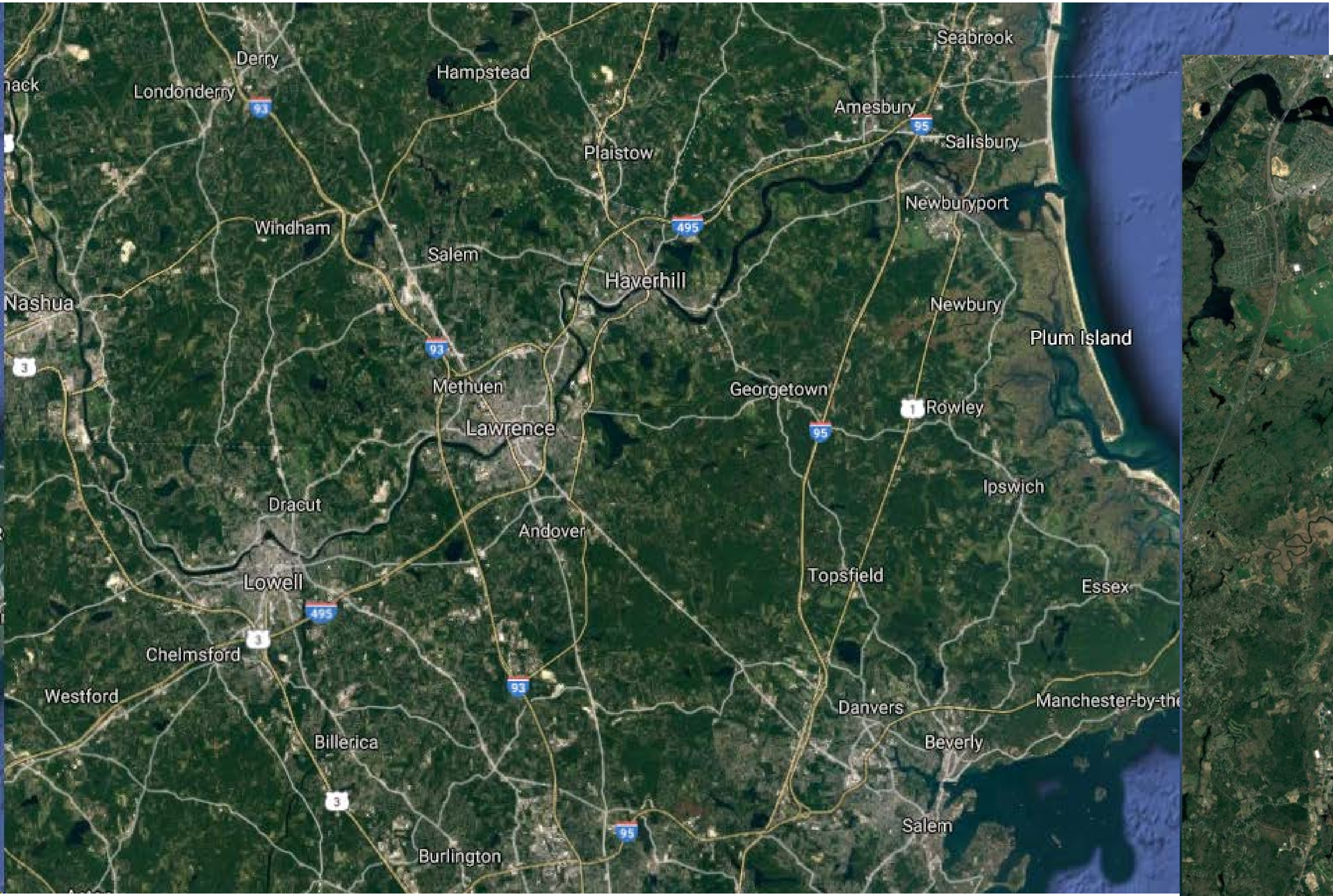
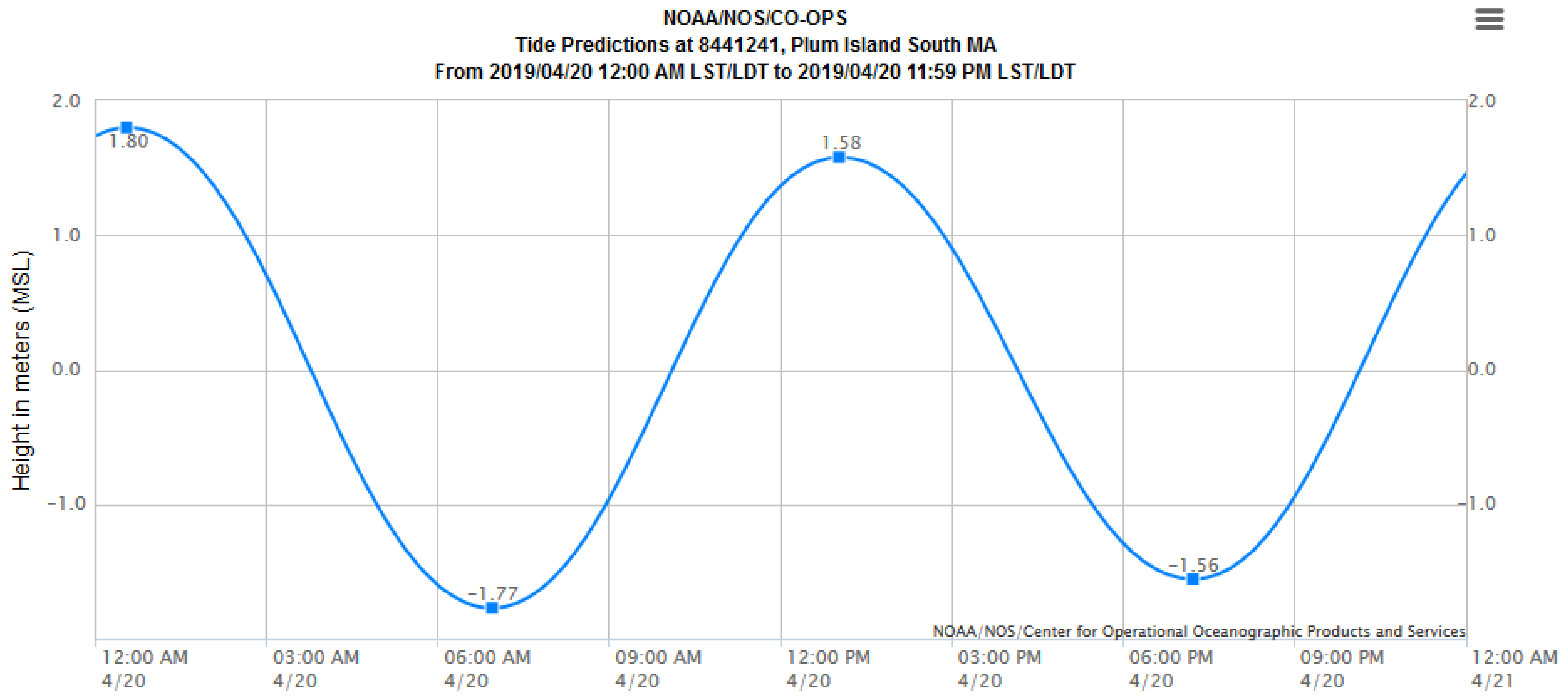
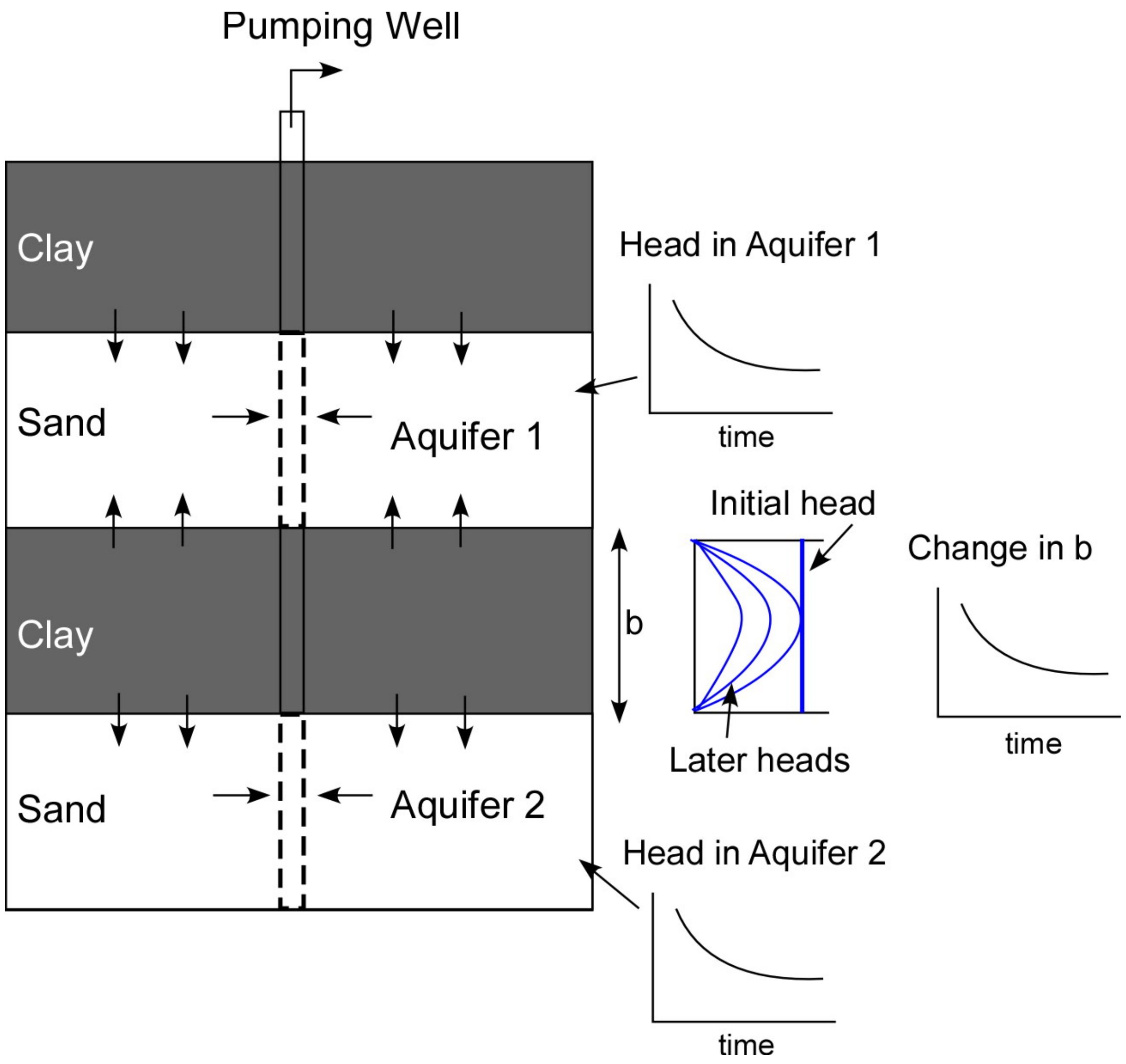

Seabrook
Derry
Hampstead
nack
Londonderry
93
Amesbury
95
Salisbury
Plaistow
Newburyport
495
Windham
Salem
Haverhill
Nashua
Newbury
Plum Island
93
3
Methuen
Georgetown
1
Rowley
Lawrence
95
Ipswich
Dracut
Andover
Topsfield
Lowell
Essex
495
3
Chelmsford
93
Westford
Danvers
Manchester-by-the
Billerica
Beverly
3
95
Salem
Burlington


NOAA/NOS/CO-OPS
Tide Predictions at 8441241, Plum Island South MA
From 2019/04/20 12:00 AM LST/LDT to 2019/04/20 11:59 PM LST/LDT
Height in meters (MSL)
2.0
1.0
0.0
-1.0
1.80
-1.77
1.58
-1.56
NOAA/NOS/Center for Operational Oceanographic Products and Services
12:00 AM 4/20
03:00 AM 4/20
06:00 AM 4/20
09:00 AM 4/20
12:00 PM 4/20
03:00 PM 4/20
06:00 PM 4/20
09:00 PM 4/20
12:00 AM 4/21

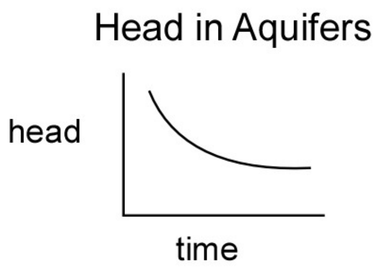
Basics of Land Subsidence:

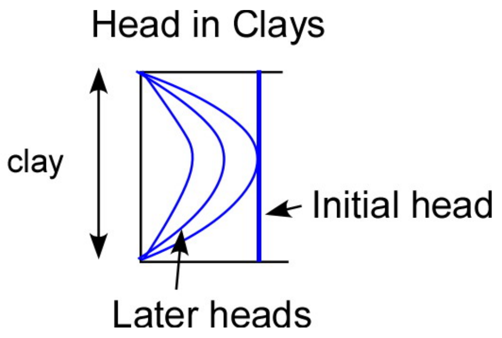


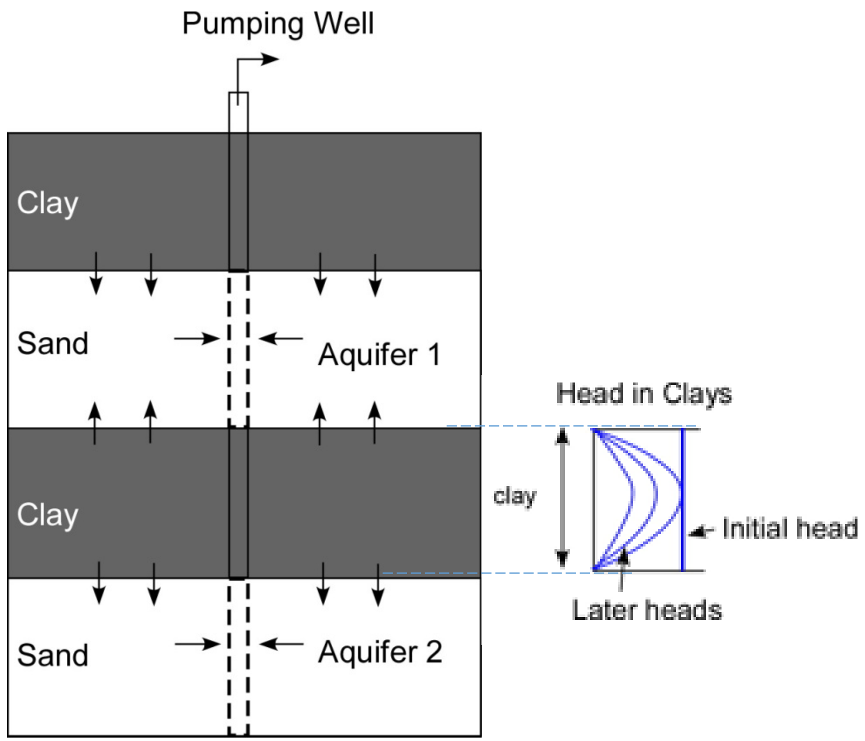
- Wells are screened in sand aquifers, extracting water lowers the heads in the sand
- Compressibility of clay is 1-2 orders of magnitude greater than that of sand. For a clay, $\alpha >> \eta\beta$
- K is much lower for clay than for sand, so drainage and compaction are much slower for confining units than for aquifers.
- **Aquifer drainage leads to compaction of aquitards.**

Basics of Land Subsidence:

When pumping occurs, there is a decrease in pressure in both the aquifer and the clay beds. The increase in effective stress acting on the clay can cause it to compact.







In our example, the water produced IS the volume released from aquifer and clay compaction (ignoring water expansion). If all water comes completely from compression of the clay, the change in thickness of the system is related to our change in storage term (storativity):

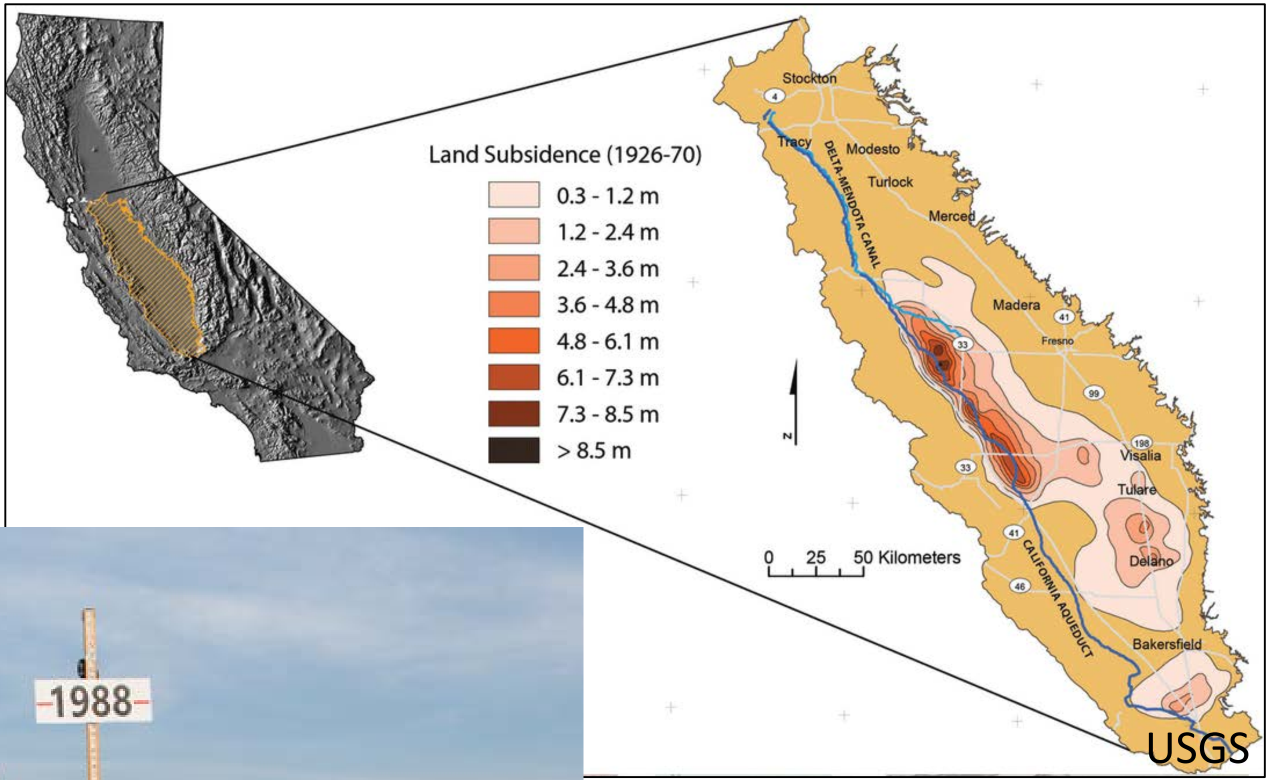
$$S_S = \underbrace{\rho g \alpha}_{\text{Aquifer Compaction}} + \underbrace{\cancel{\rho g \beta \eta}}_{\text{Expansion of Water}}$$

$$\Delta b = b \rho g \alpha \Delta h$$

Actually a function of time


1925
1955
SAN JOAQUIN VALLEY
CALIFORNIA
BM S661
SUBSIDENCE 9M
1925-1977
1977
USGS


1988
SAN JOAQUIN VALLEY, CA
SUBSIDENCE 6.2 ft
1988-2016
Benchmark
H1235
USGS
2004
2008
2016
H 1235
USGS


Land Subsidence (1926-70)
0.3 - 1.2 m
1.2 - 2.4 m
2.4 - 3.6 m
3.6 - 4.8 m
4.8 - 6.1 m
6.1 - 7.3 m
7.3 - 8.5 m
> 8.5 m
Stockton
Tracy
Modesto
Turlock
Merced
DELTA-MENDOTA CANAL
Madera
Fresno
Visalia
Tulare
Delano
Bakersfield
CALIFORNIA AQUEDUCT
N
0 25 50 Kilometers
USGS

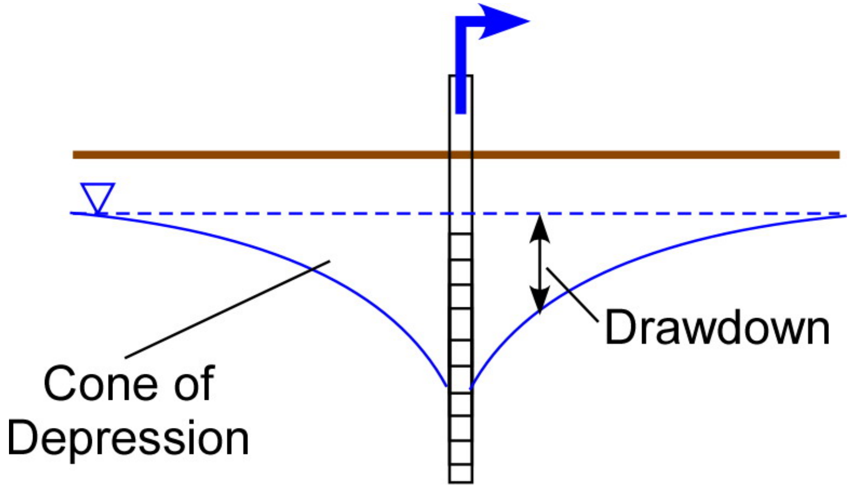
Flow to pumping wells: basic application of groundwater hydrology

Pumping occurs for:

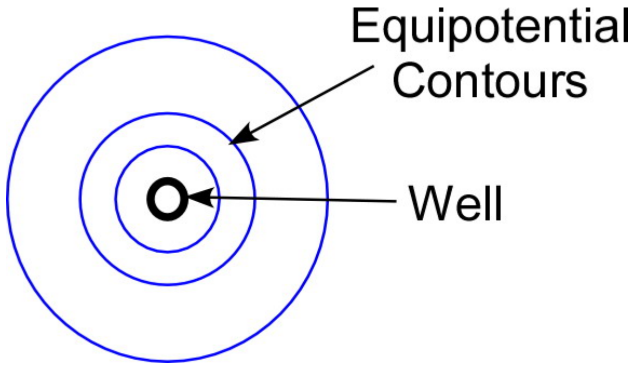
- Water supply (domestic, community, industrial)
- Irrigation
- Removal of contaminated water (pump-and-treat)
- Lowering water table for construction and mining (dewatering)
- Relieving pressure under dams
- Draining farmland
- Hydraulic tests
- Control of saltwater intrusion - injection (hydraulic barriers)
- Wastewater injection
- Artificial recharge of aquifers during wet seasons

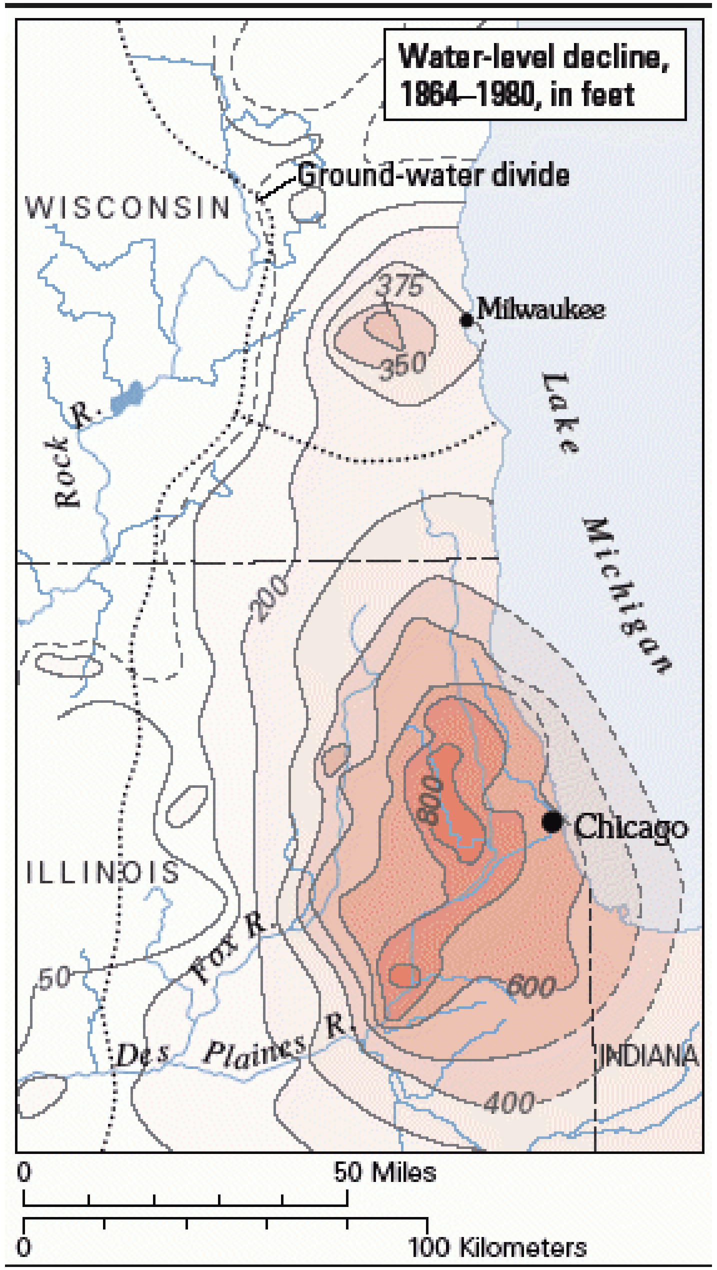
What happens when you pump?

Side View

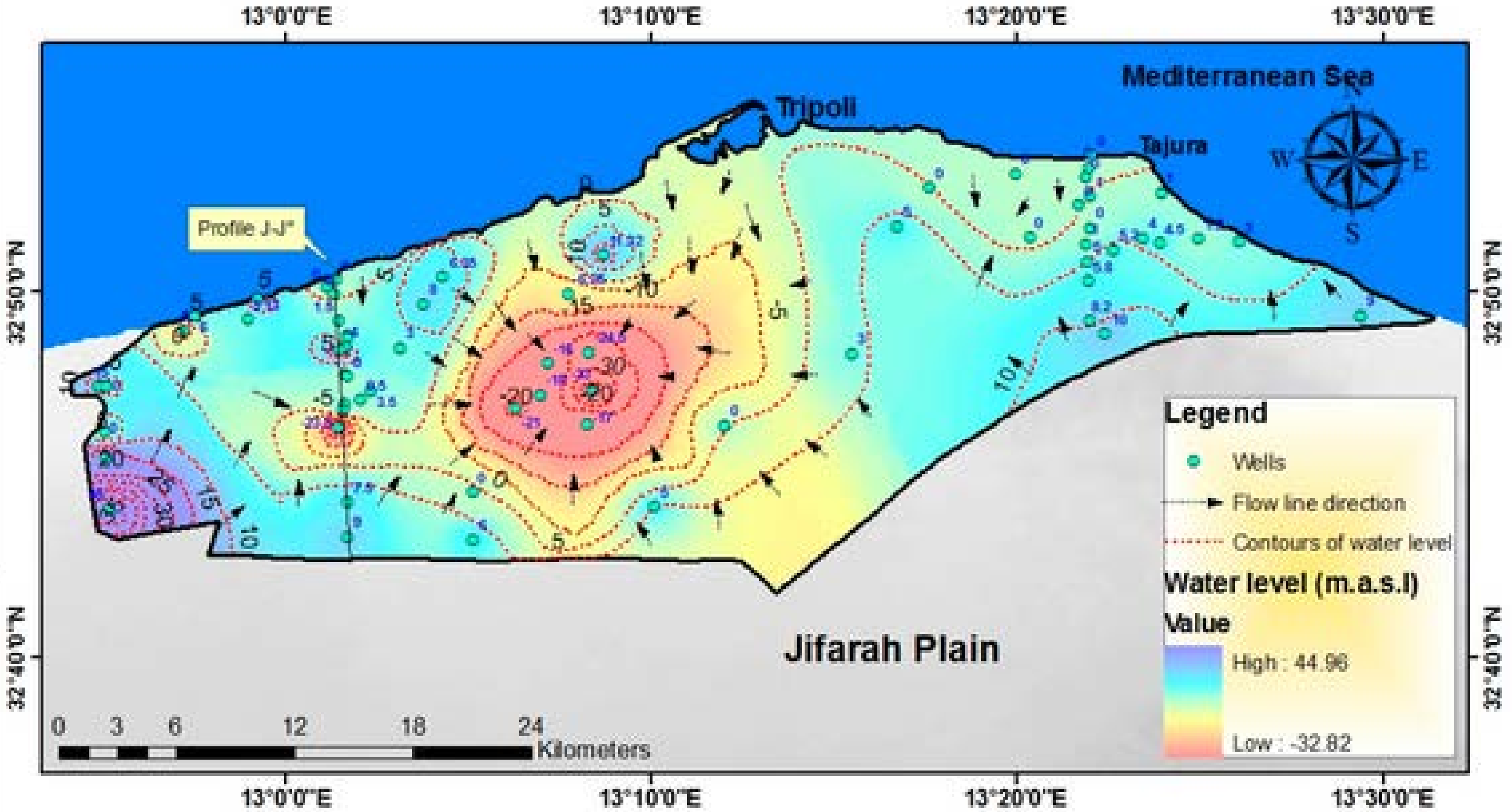


Top View





USGS



AlFarrah et al. 2018, Water

What water can be captured?

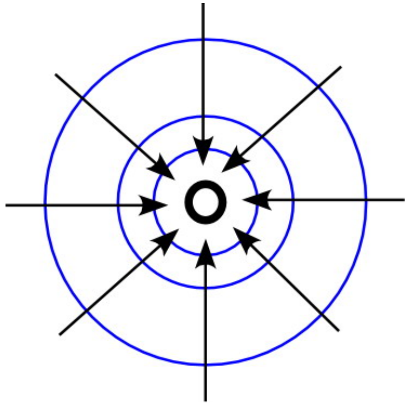
- rainwater recharge
- water from a surface water body (stream, lake, ocean, river)
- water from an adjacent aquifer
- water in an adjacent confining unit
- water from ‘storage’ (elastic (Ss) or lowered water table(Sy))
- water ‘not lost’ to drains or evapotranspiration-ET (lower water table stops these from functioning)
- water that ‘would have’ discharged elsewhere

Flow to wells can be complex. For simplicity, the following discussion makes some basic assumptions.

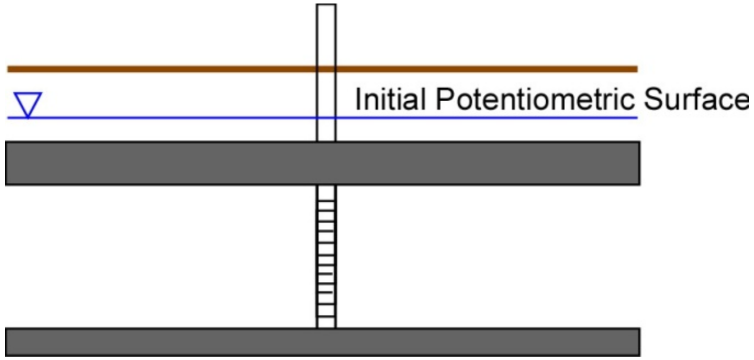
Assumptions:

1. The aquifer is bounded below by a confining (no-flow) unit
2. Geologic formations (aquifers and confining units) are horizontal and have infinite extent
3. Potentiometric surface is flat (no flow)
4. The potentiometric surface is not changing with time (steady-state prior to pumping)
5. All changes to potentiometric surface are due to pumping alone
6. Aquifers are homogeneous and isotropic
7. Groundwater flow is horizontal
8. Darcy's Law is valid (can be tricky very close to wells, but we'll ignore that)
9. Fluid density and viscosity is constant
10. Pumping and observation wells are fully penetrating – screened over entire aquifer thickness
11. Pumping wells have ~0 diameter and are 100% efficient

Under these conditions, all flow will be toward (or away) from a well in 2 dimensions.

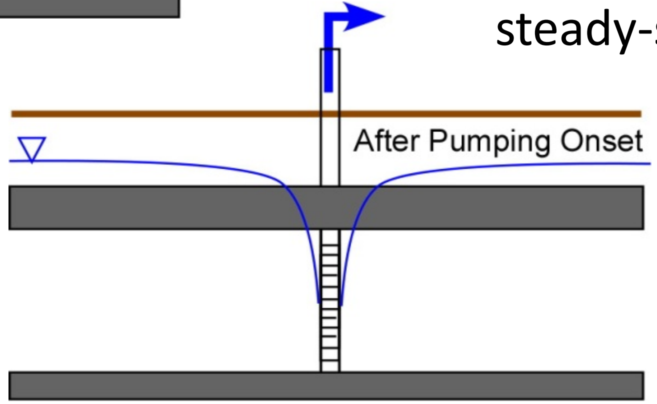


This means that flow is 1D, radially (there is radial symmetry)

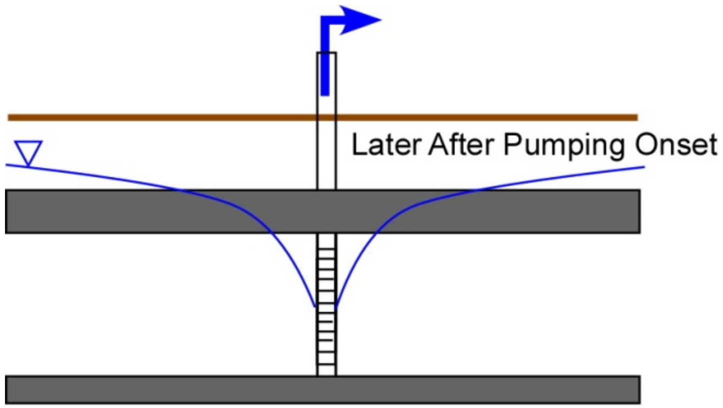


- Drawdown cone spreads and deepens over time until it reaches a steady state where the gradient can sustain the pumping rate (w)

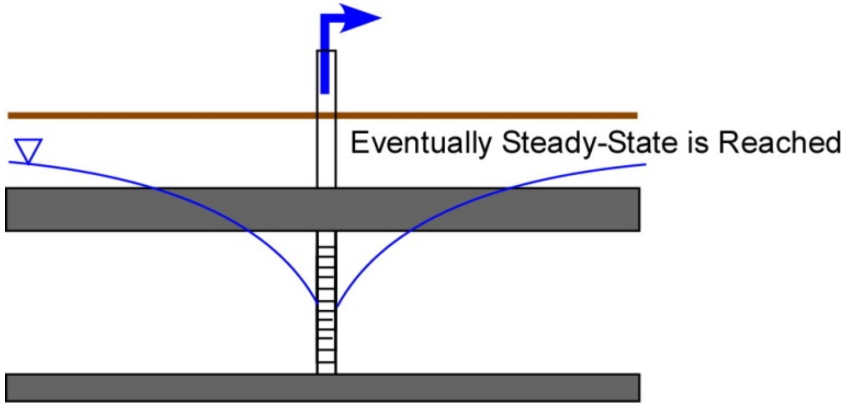
- Shape of the cone (depth, width) and time to reach steady-state depend on T and S



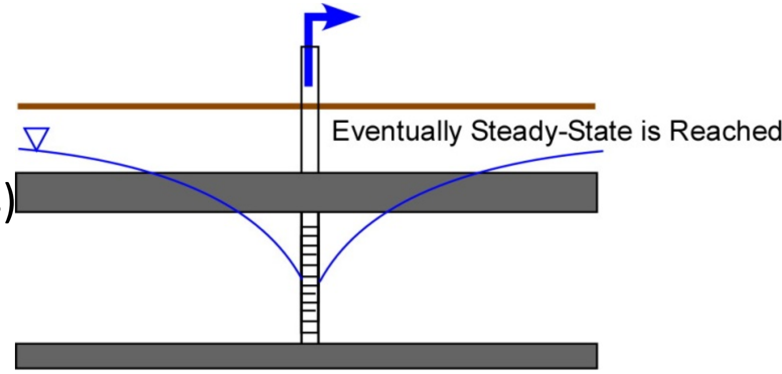
Steady-state flow: heads are constant in time



Unsteady flow: heads change with time



Where does pumped water come from?



Note that:

- Prior to development, the aquifer is in equilibrium (no change in flow or heads)
- When pumping occurs, water comes from storage (Ss or Sy) *until* a new equilibrium (Steady State) is reached
- At steady-state flow, pumped water comes from recharge or nearby lakes or rivers, *not* from Sy or Ss

Essential factors that determine response of an aquifer to well development:

- Distance to, and amount of, recharge (rainfall vs lake)
- Distance to, and amount of, natural discharge
- Character of cone of depression (function of T and S)

Where does pumped water come from?

Some water must always be mined (taken from storage) to create groundwater development. This rearranges hydraulic gradients in the aquifer so that water flows toward the well.

Estimates of capture (where the water to the well is coming from, and how much) are fundamentally important to long-term planning of groundwater development

- Important for supply
- Important for quality

Single Well Test
Slug Test

Multiple Well Test
Pump Test (multiple types)

To the board..

Theim Example: Determining T for a confined aquifer with a steady-state pumping test:

A well in a confined aquifer is pumped at a rate of 100 m3/d for a long time at a steady rate (the system is in ~equilibrium). Observed heads in two wells located 25m and 85m from the pumping well are 124m and 130m, respectively (above mean sea level). Estimate the value of aquifer transmissivity.

If the aquifer is 200m thick, what is K?

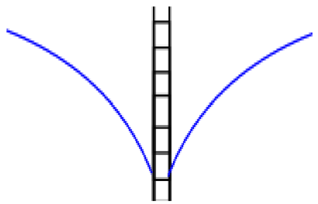
Pumping Test Analysis: Theis Equation

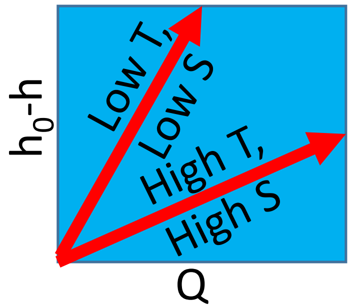
Predict drawdown at a particular point in space and time (r, t), knowing the hydraulic properties of the system (S, T)

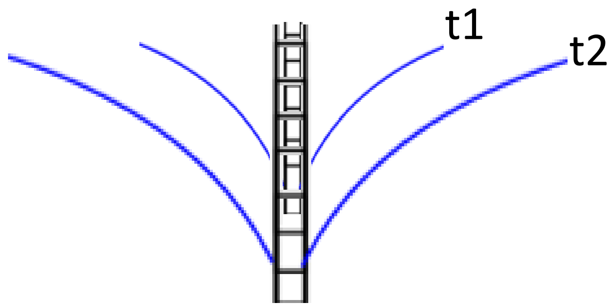
$$h_o - h(r,t) = \frac{Q}{4\pi T} W(u) \qquad \text{where } u = \frac{r^2 S}{4Tt}$$

The analytical solution:

- Describes geometric characteristics of the cone of depression: steepening toward the well
- $h\text{-}h_0$ increases linearly with pumping rate
- Drawdown at a time and location is greater for lower T & lower S
- Quantifies changes in the cone of depression -> increases in depth and extent with time for given aquifer properties







A well screened in a confined aquifer is pumped for 10 days at a rate of 5000 ft^3/d. The aquifer is 50 ft thick, with a hydraulic conductivity of 10 ft/d. Aquifer specific storage is $1x10^{-4}$ ft^{-1}. What are drawdowns 10 ft and 100 ft from the well?

$$h_o - h(r,t) = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Table 1. Values of the Well Function W(u) for Values of u

u	$W(u)$	u	$W(u)$	u	$W(u)$	u	$W(u)$
1×10^{-10}	22.45	7×10^{-8}	15.90	4×10^{-5}	9.55	1×10^{-2}	4.04
2	21.76	8	15.76	5	9.33	2	3.35
3	21.35	9	15.65	6	9.14	3	2.96
4	21.06	1×10^{-7}	15.54	7	8.99	4	2.68
5	20.84	2	14.85	8	8.86	5	2.47
6	20.66	3	14.44	9	8.74	6	2.30
7	20.50	4	14.15	1×10^{-4}	8.63	7	2.15
8	20.37	5	13.93	2	7.94	8	2.03
9	20.25	6	13.75	3	7.53	9	1.92
1×10^{-9}	20.15	7	13.60	4	7.25	1×10^{-1}	1.823
2	19.45	8	13.46	5	7.02	2	1.223
3	19.05	9	13.34	6	6.84	3	0.906
4	18.76	1×10^{-6}	13.24	7	6.69	4	0.702
5	18.54	2	12.55	8	6.55	5	0.560
6	18.35	3	12.14	9	6.44	6	0.454
7	18.20	4	11.85	1×10^{-3}	6.33	7	0.374
8	18.07	5	11.63	2	5.64	8	0.311
9	17.95	6	11.45	3	5.23	9	0.260
1×10^{-8}	17.84	7	11.29	4	4.95	1×10^{0}	0.219
2	17.15	8	11.16	5	4.73	2	0.049
3	16.74	9	11.04	6	4.54	3	0.013
4	16.46	1×10^{-5}	10.94	7	4.39	4	0.004
5	16.23	2	10.24	8	4.26	5	0.001
6	16.05	3	9.84	9	4.14		

Source: Adapted from L. K. Wenzel, *Methods for Determining Permeability of Water-Bearing Materials with Special Reference to Discharging Well Methods*. U.S. Geological Survey Water-Supply Paper 887, 1942.

A well screened in a confined aquifer is pumped for 10 days at a rate of 5000 ft^3/d. The aquifer is 50 ft thick, with a hydraulic conductivity of 10 ft/d. Aquifer specific storage is 1x10^{-4} ft^{-1}. What are drawdowns 10 ft and 100 ft from the well?

$$h_o - h(r,t) = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

$$u = \frac{(100 ft)^2 \text{ x } 1\text{x}10{-}4 ft^{-1}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{ x } 10d} = 5e-4$$

$$u = \frac{(10 ft)^2 \text{ x } 1\text{x}10{-}4 ft^{-1}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{ x } 10d} = 5e-6$$

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1×10^{-10}	22.45	7×10^{-8}	15.90	4×10^{-5}	9.55	1×10^{-2}	4.04
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3	21.35	9	15.65	6	9.14	3	2.96
4	21.06	1×10^{-7}	15.54	7	8.99	4	2.68
5	20.84	2	14.85	8	8.86	5	2.47
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7	18.20	4	11.85	1×10^{-3}	6.33	7	0.374
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5	16.23	2	10.24	8	4.26	5	0.001
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Source: Adapted from L. K. Wenzel, *Methods for Determining Permeability of Water-Bearing Materials with Special Reference to Discharging Well Methods*. U.S. Geological Survey Water-Supply Paper 887, 1942.

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$$u = \frac{r^2 S}{4Tt}$$

$$h_o - h(r,t) = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{(100 ft)^2 \text{ x } 1x10{-}4 ft^{-1}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{ x } 10d} = 5e-4$$

$$ho - h = \frac{5000 \frac{ft^3}{d}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{x } \pi} \text{x} 7.02 = 5.58'$$

$$u = \frac{(10 ft)^2 \text{ x } 1x10{-}4 ft^{-1}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{ x } 10d} = 5e-6$$

$$ho - h = \frac{5000 \frac{ft^3}{d}}{4 \text{ x } 50 ft \text{ x } 10 \frac{ft}{d} \text{x } \pi} \text{x} 11.63 = 9.25'$$