Hydrogeologic Evidence of Preferential Pathways Near Municipal Supply Wells

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Why are preferential pathways important to consider?

Because human enteric viruses are detected in almost all groundwater wells tested.

How do the viruses reach deeply cased wells?

What are the impacts of leaky sewers on urban groundwater (quality and quantity)?

…understand problems associated with the nation's aging underground pipes and our drinking water quality

Waterborn Disease Outbreaks in the US

- *60% of 716 infectious disease outbreaks associated with drinking water were attributable to groundwater (1971 to 2002)*
- *Pathogen in more than 50% of outbreaks is unknown and assumed viral*
- *0.75 to 5.9 million illnesses/year in the US result from contaminated groundwater*
- *Three measures of virus contamination (mean, max, and %of positive samples) in wells are significantly associated with AGI*

Summarized from CDC reports, e.g., MMWR, 2004, 53(SS08);23-45

Door County

Log Den Goes High-Tech to End Water Trouble

June 18, 2007 06:31 PM

By *Elizabeth Ries*

The Log Den restaurant in Egg Harbor will reopen for business Saturday at 11 A.M., provided that last-minute water tests come back clear.

More than 200 people became ill after eating at the new restaurant late last month. Water tests confirmed the presence of norovirus in the restaurant's well. The virus can cause nausea, diarrhea, and fatigue.

> The Door County Sanitarian Department will begin digging holes to examine nine other septic systems in the area in the next two weeks.
>
> If none of those is shown to be the source of the norovirus

2006 Groundwater Rule: federal, risk-based approach to pathogen contamination

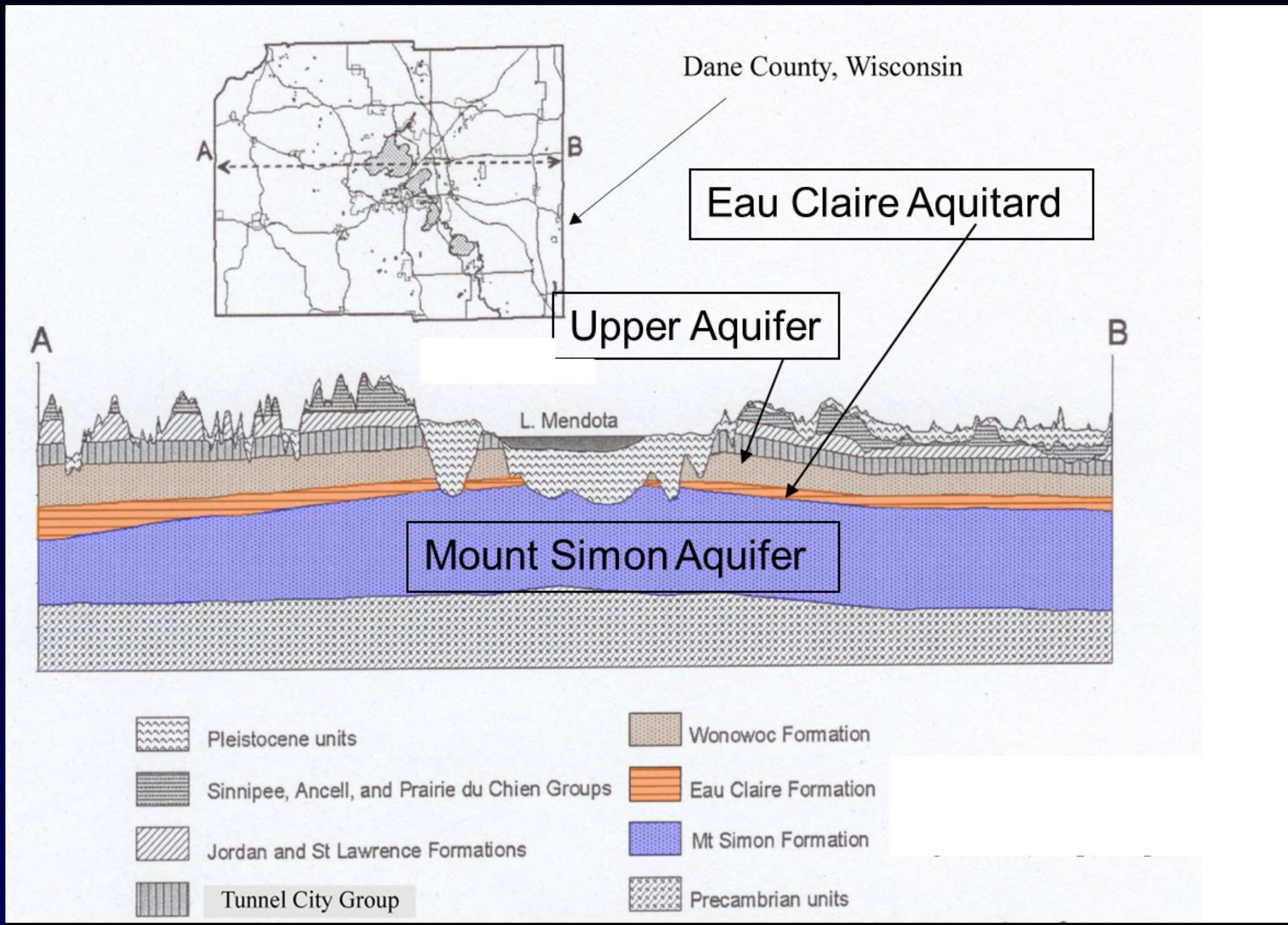
- Sanitary surveys of public systems: every 3 to 5 years, inspect well, well seal, storage, record keeping
- Test for total coliform throughout distribution system (Total Coliform Rule)
- Total coliform results do not have good correspondence with virus-positive tests (Choi and Jiang 2005; Hunt et al, 2010; Lambertini et al, 2011)

Groundwater-supplied public water systems are not required to disinfect

photo by Associated Press, 2/2011

December, 2010: Wisconsin DNR mandated that all public groundwater systems disinfect. About 12% , or 66, of such systems do not disinfect. Rescinded in May 2011 by the Wisconsin Legislature.

Virus occurrence in public supply wells



From Massie-Ferch 1997

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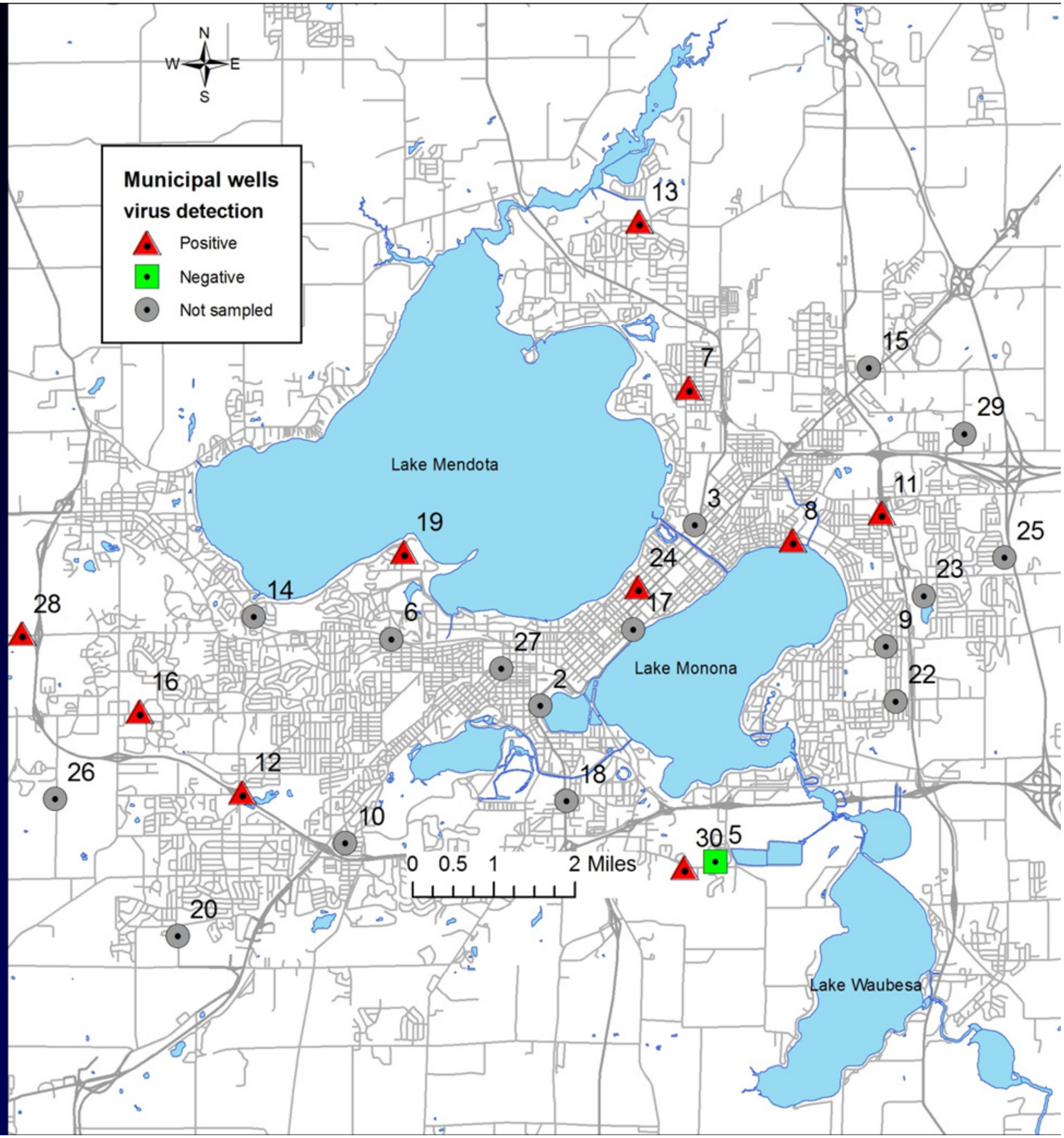
Initially sampled 10 wells, 3 lakes, and sewage

Sampled 6 wells and sewage monthly for two years

Currently sampling 7 sites with three wells, twice a month for one year



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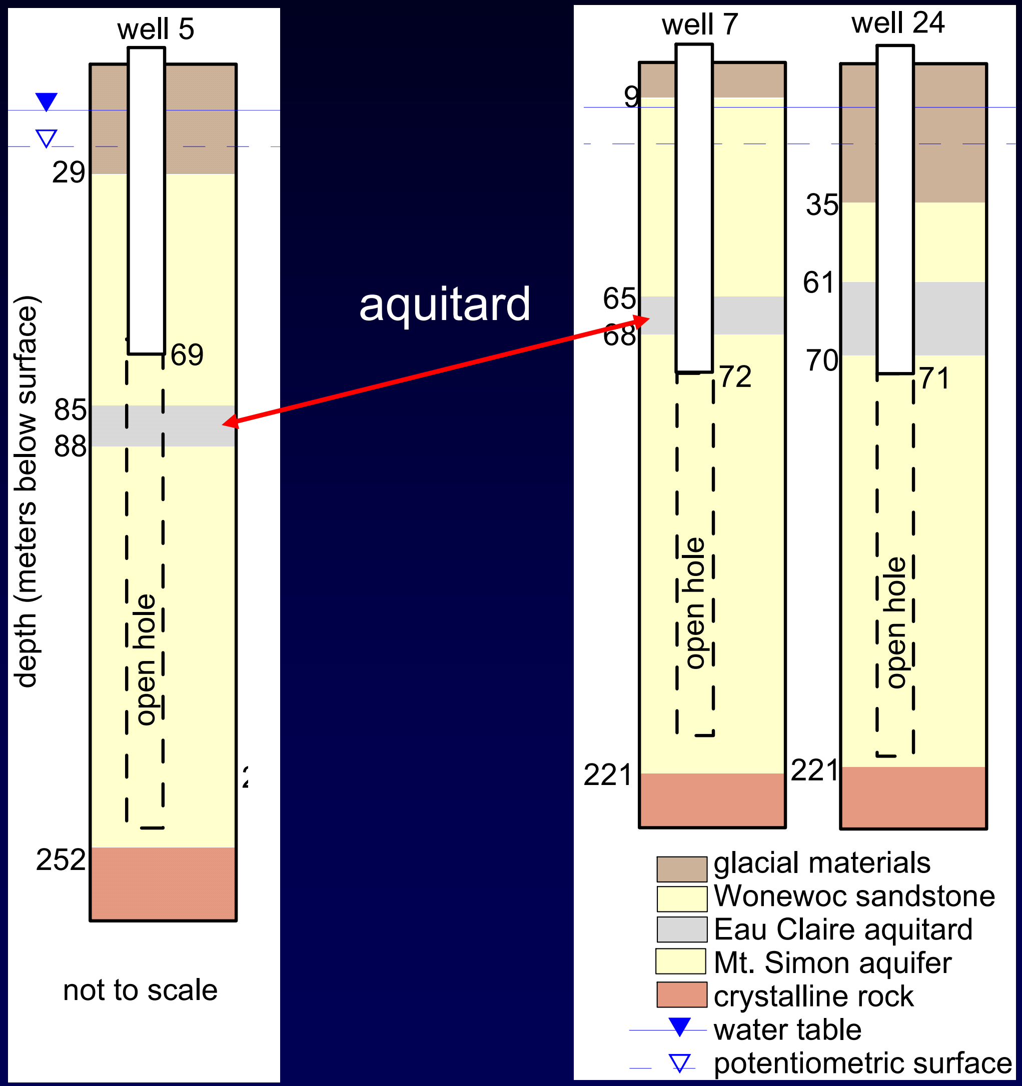
Well construction presumably protects water quality

multi-aquifer well

confined aquifer well



Pumping induces large (>> 1) vertical gradients across the aquitard

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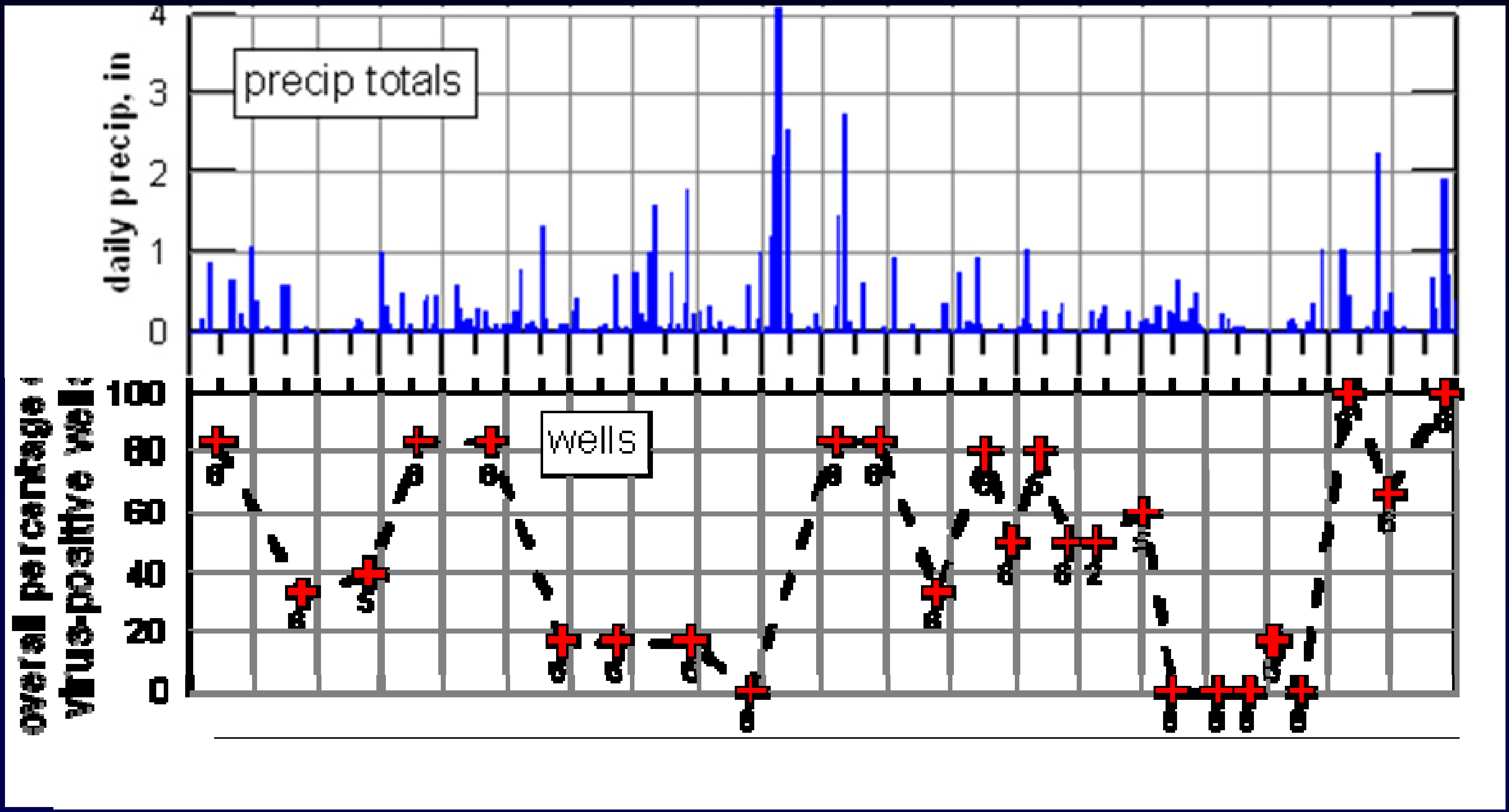
Virus Detections by Source

		virus detection (gc/l)			
water source	number of samples	percent positive	min	max	mean
wells	147	46.6	0.00	6.27	0.65
Lake Mendota	18	82	0.00	532*	44*
sewage influent	26	100.0	12,900	36,310,000	2,010,000

Bradbury, et al., 2010

Wells tend to be virus positive at the same time



Bradbury, et al., 2010

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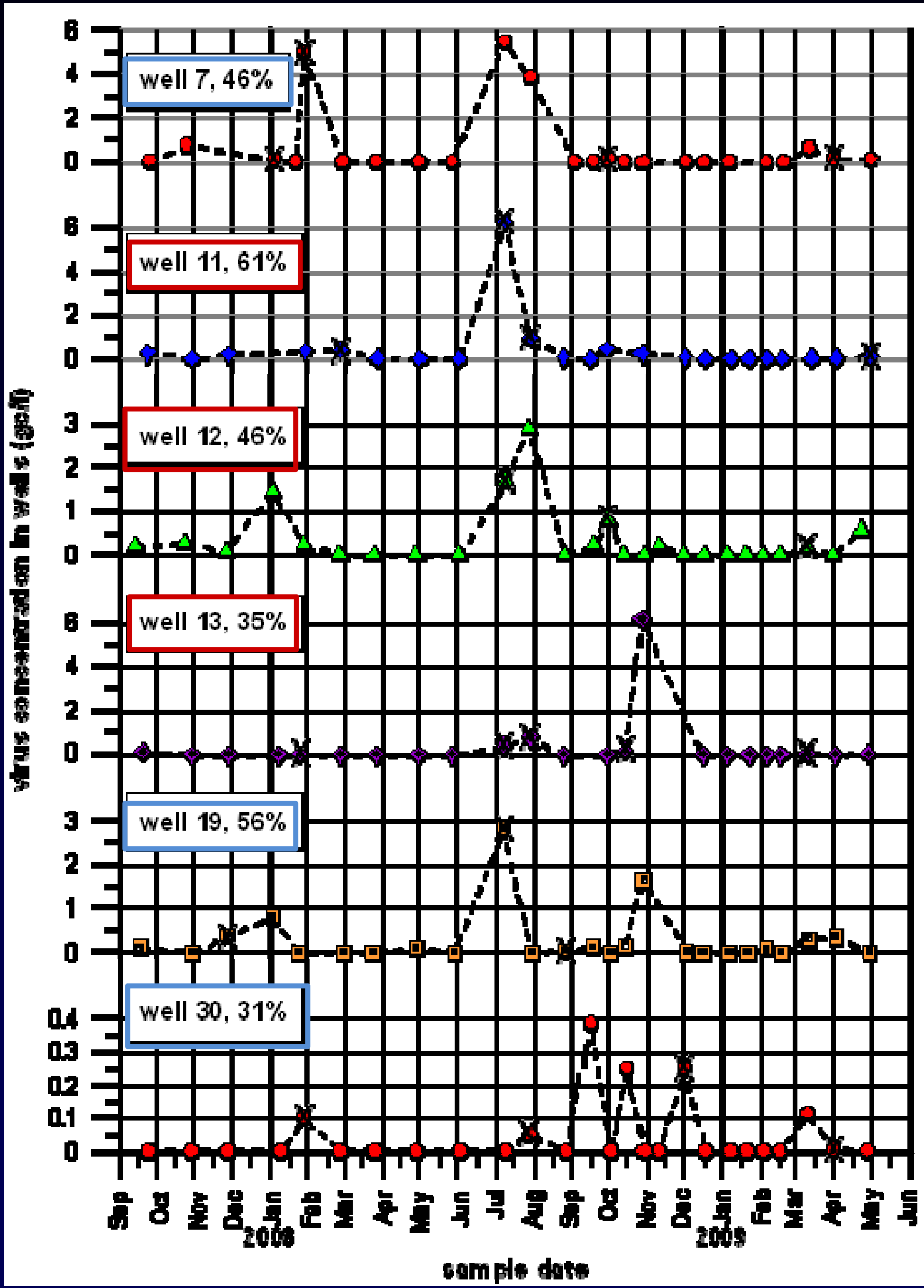
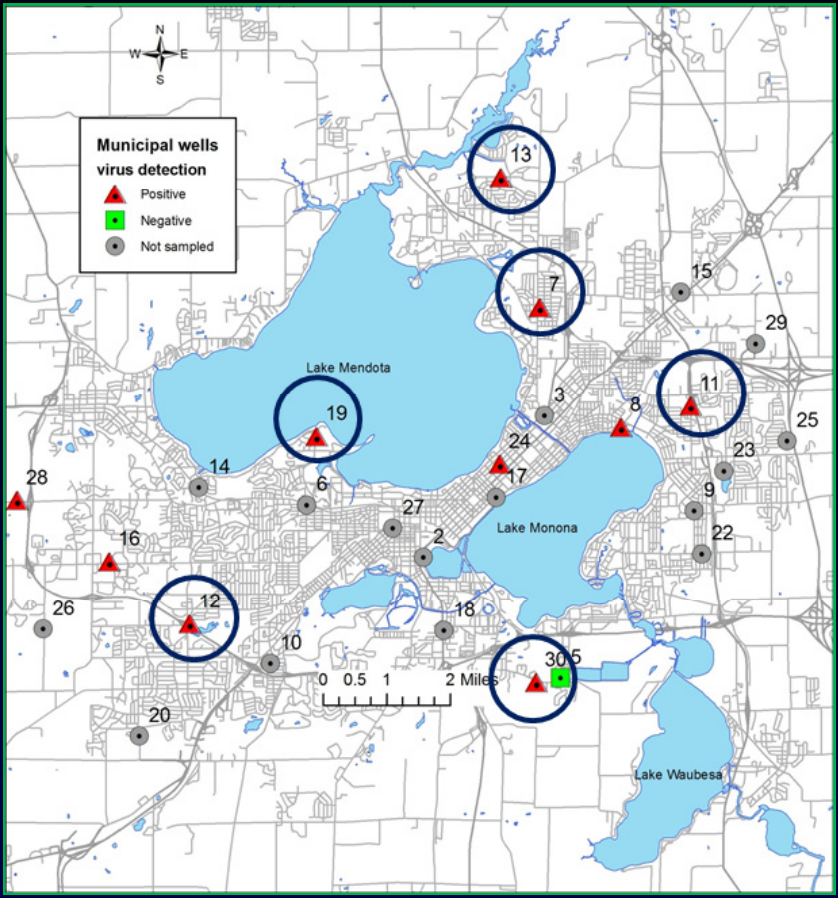
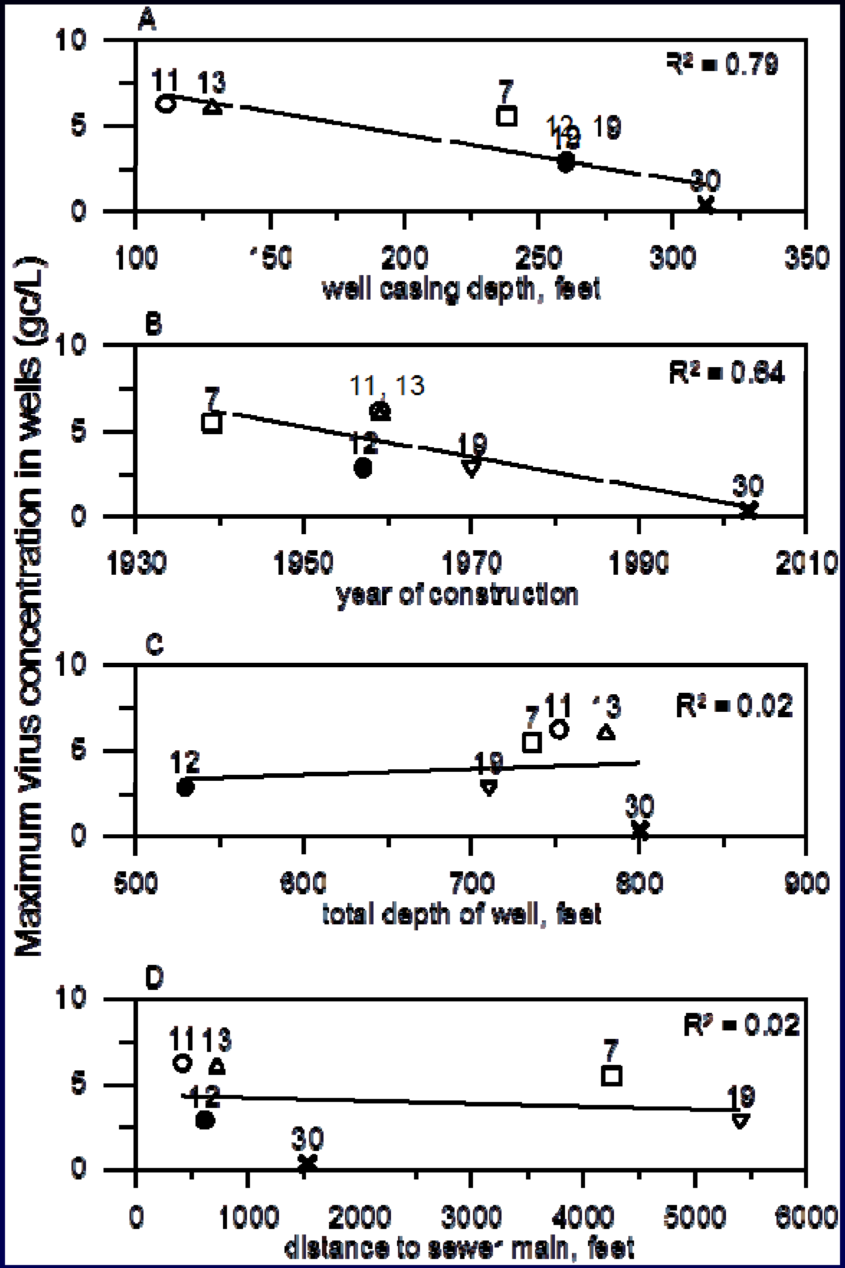




"X" indicates positive for infectious enterovirus or adenovirus or both

Bradbury, et al., 2010



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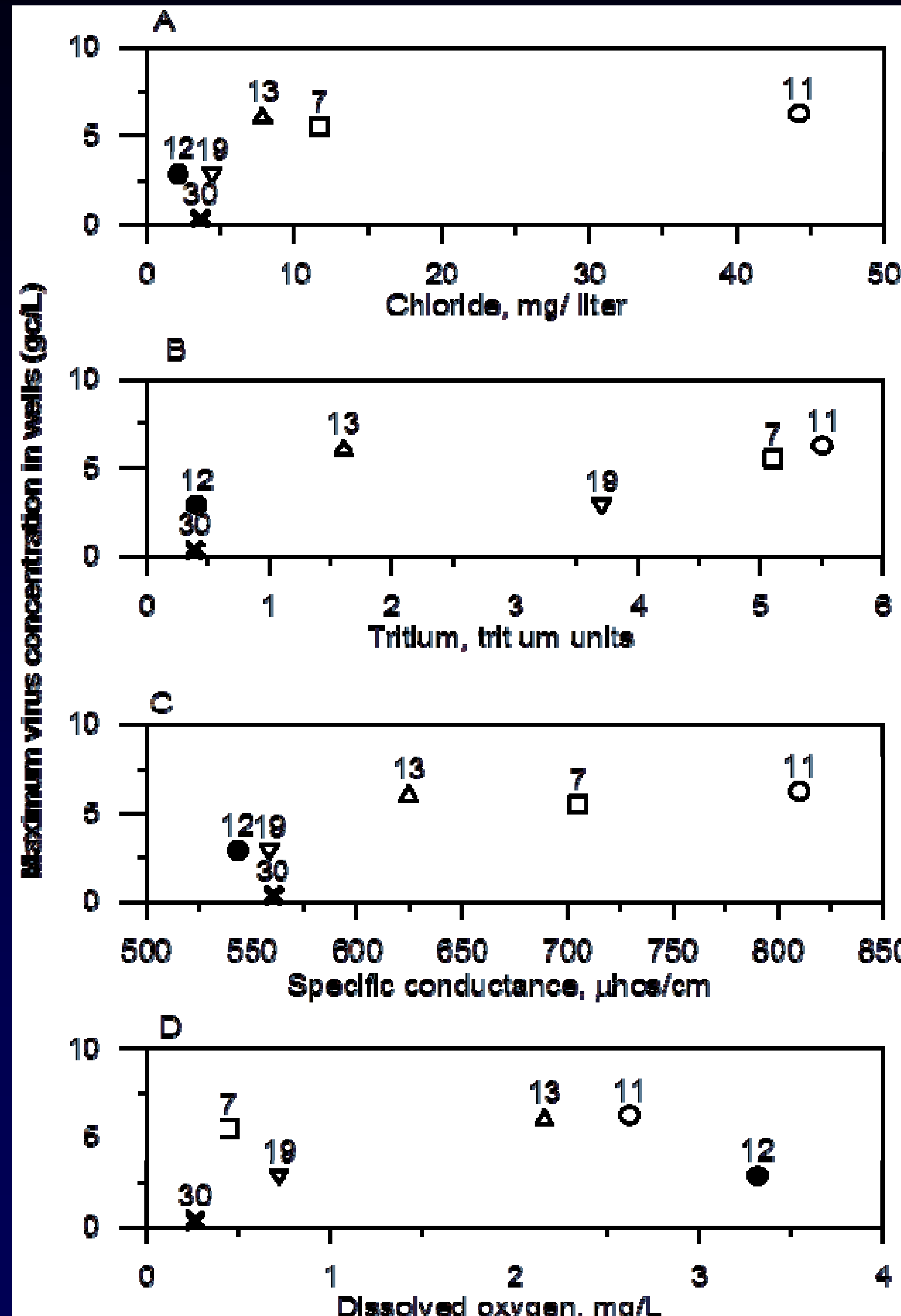

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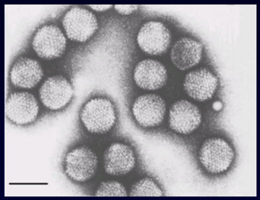
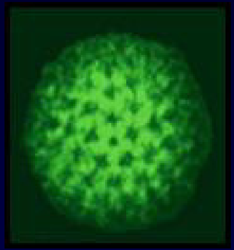
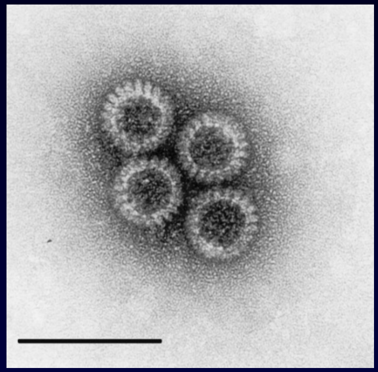
Virus characteristics

- *Particulates and common diameters*
  - *Colloids (<0.2 um)*
  - *Bacteria (~.2 – 20 um)*
  - *Viruses (~50 nm, or 0.050 um)*
- *For comparison*
  - *Human hair (~50-100 um)*
  - *Rock fracture (1 um to > 1 mm)*

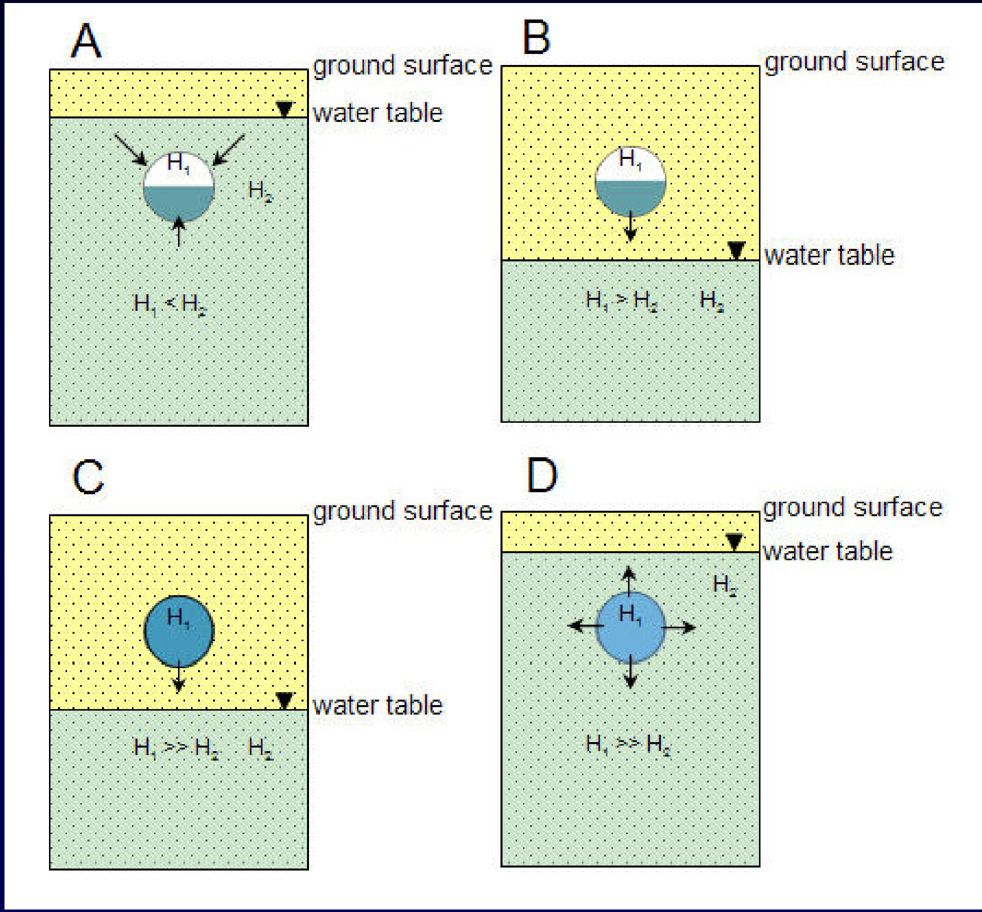
Viruses (e.g., adenovirus, enterovirus, rotavirus)

- *Viruses are much smaller than bacterial pathogens*
- *Virus survivability favored by low temp, moisture, absence of UV light*
- *Generally thought to survive for up to ~ 2 years in groundwater systems*
- *Virus retention in sediment and fractures influenced by flow rate, gradient, aperture size, surface chemistry of colloid and sediments*

Sanitary sewers are a concentrated source of viruses widespread across urban areas

Sewage exfiltration rates:
0.3 to 300 gallons/hr/mile

Chisala and Lerner, 2008.

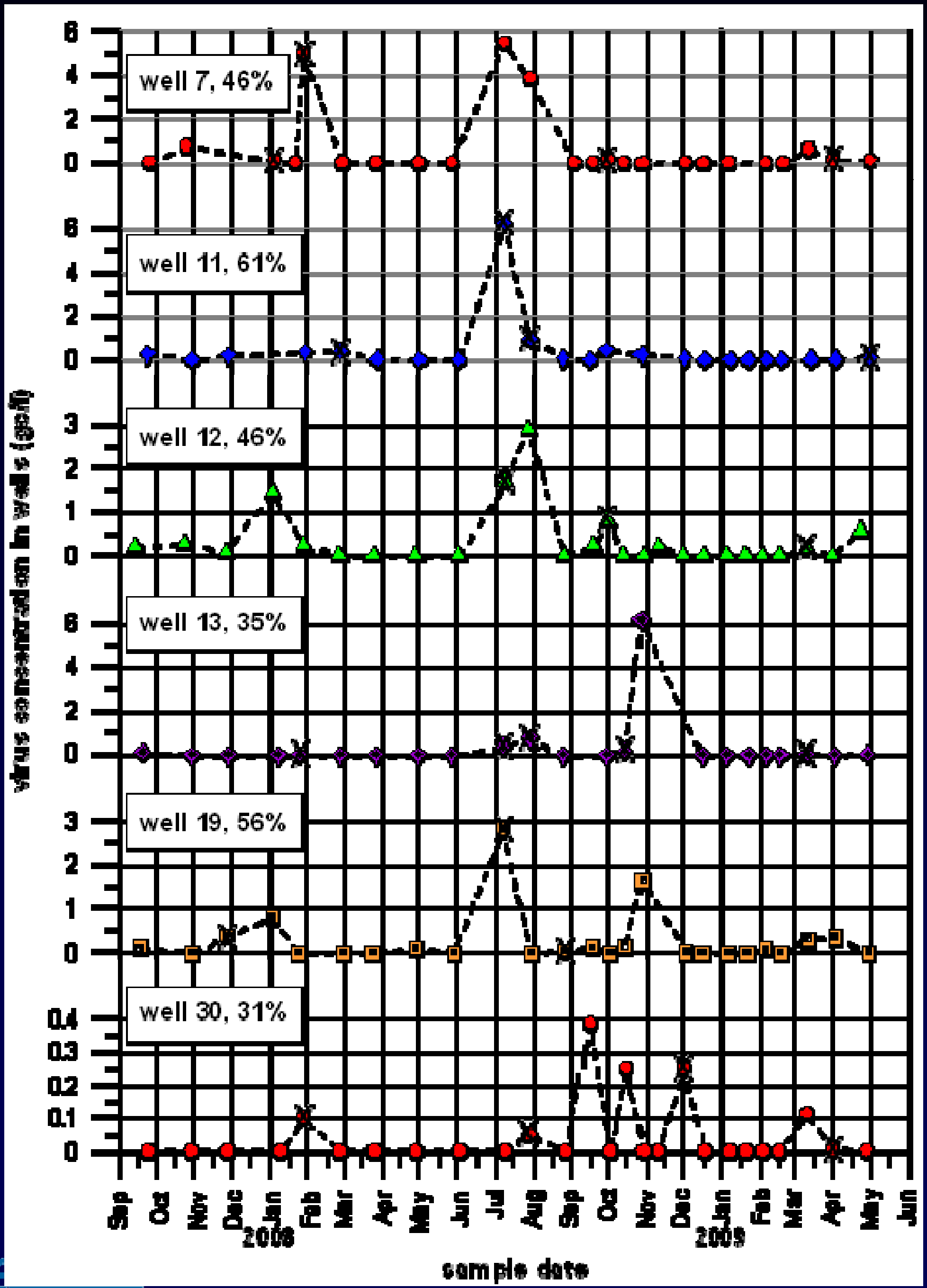


Hydraulic relationships between sewer and water table

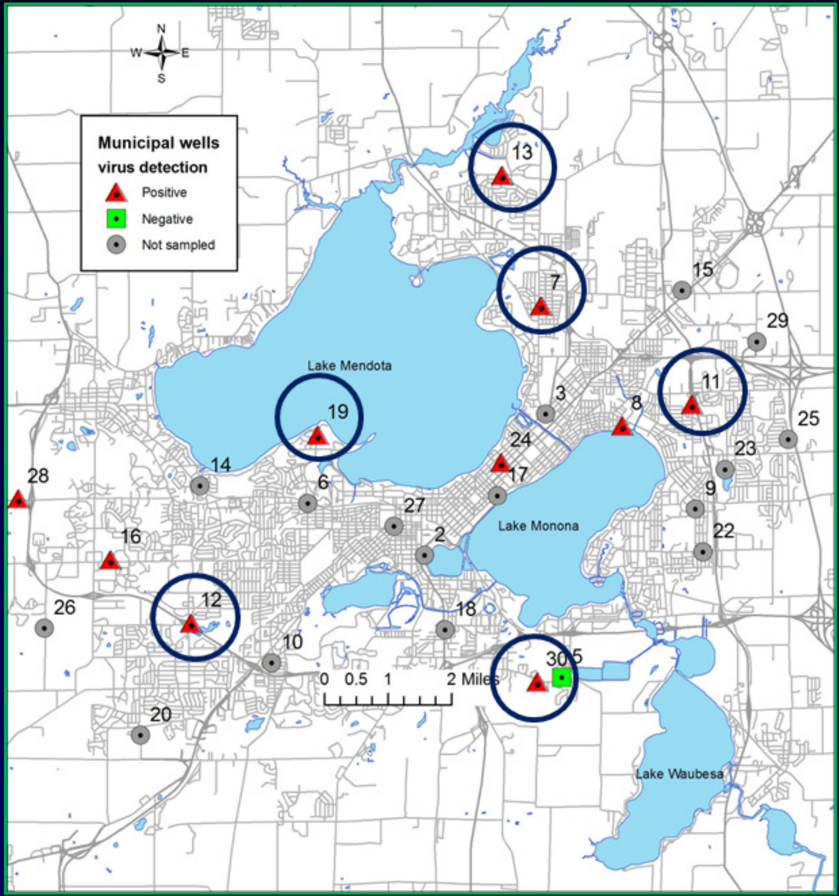
How do the viruses reach deeply cased wells?

1) depositional or erosional stratigraphic windows in the aquitard
2) along damaged, poorly sealed well casings
3) fractures
4) flow through multi-aquifer wells

Borchardt et al., 2007



1. depositional or erosional stratigraphic windows through the Eau Claire aquitard



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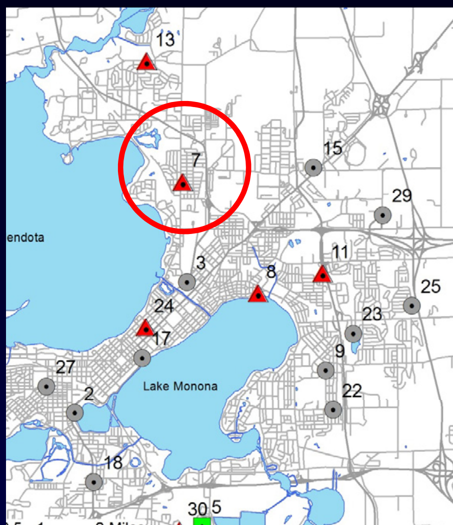
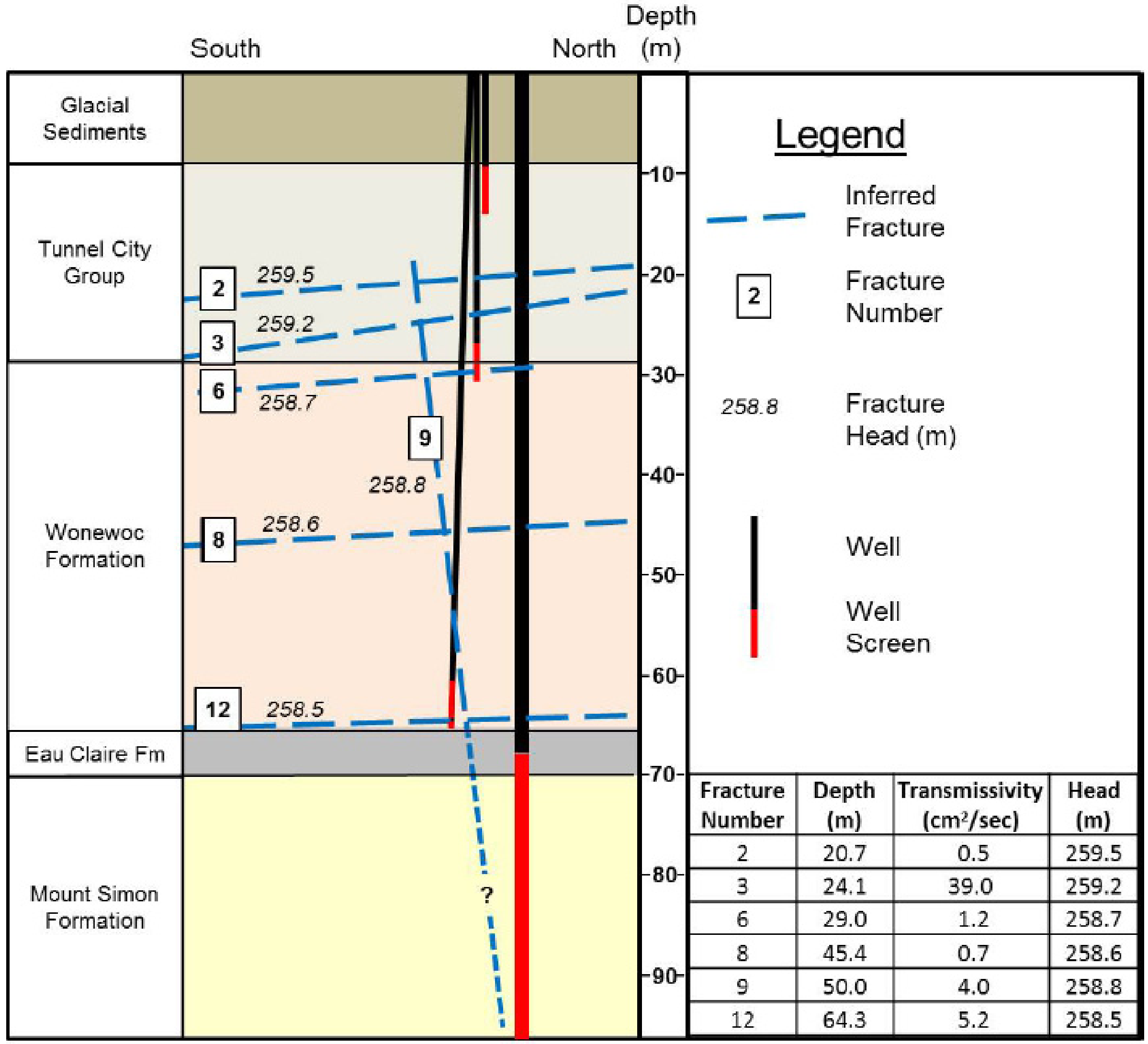
2) along damaged or poorly sealed well casings or breaches in casings

Well casing, Benton, Wisconsin Photo courtesy of DNR

3) fractures



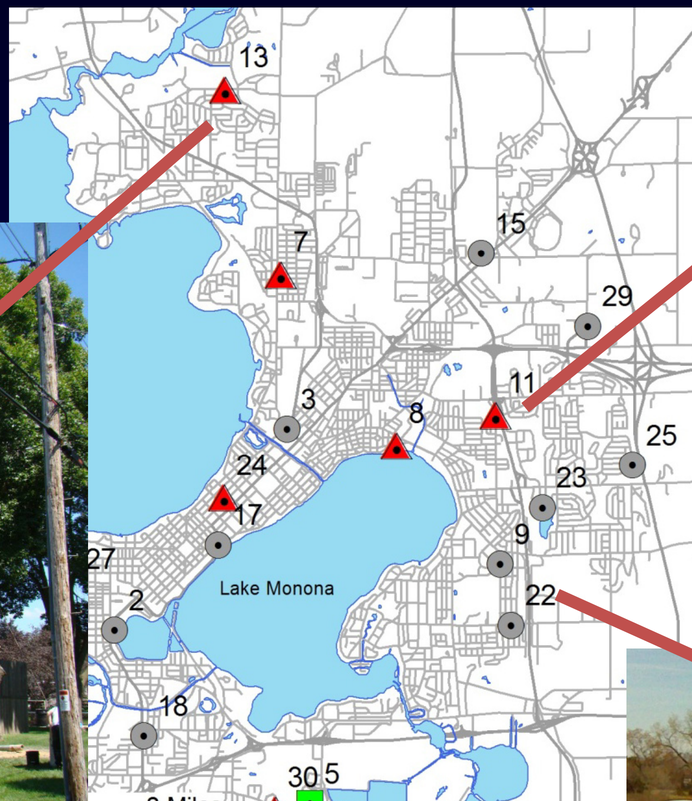


Fracture Number	Depth (m)	Transmissivity (cm^2/sec)	Head (m)
2	20.7	0.5	259.5
3	24.1	39.0	259.2
6	29.0	1.2	258.7
8	45.4	0.7	258.6
9	50.0	4.0	258.8
12	64.3	5.2	258.5

Gellasch et al., 2012

3) fractures

4) flow across multi-aquifer wells



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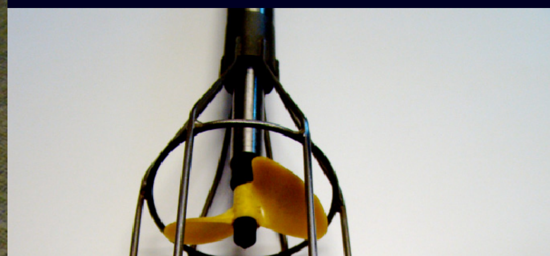
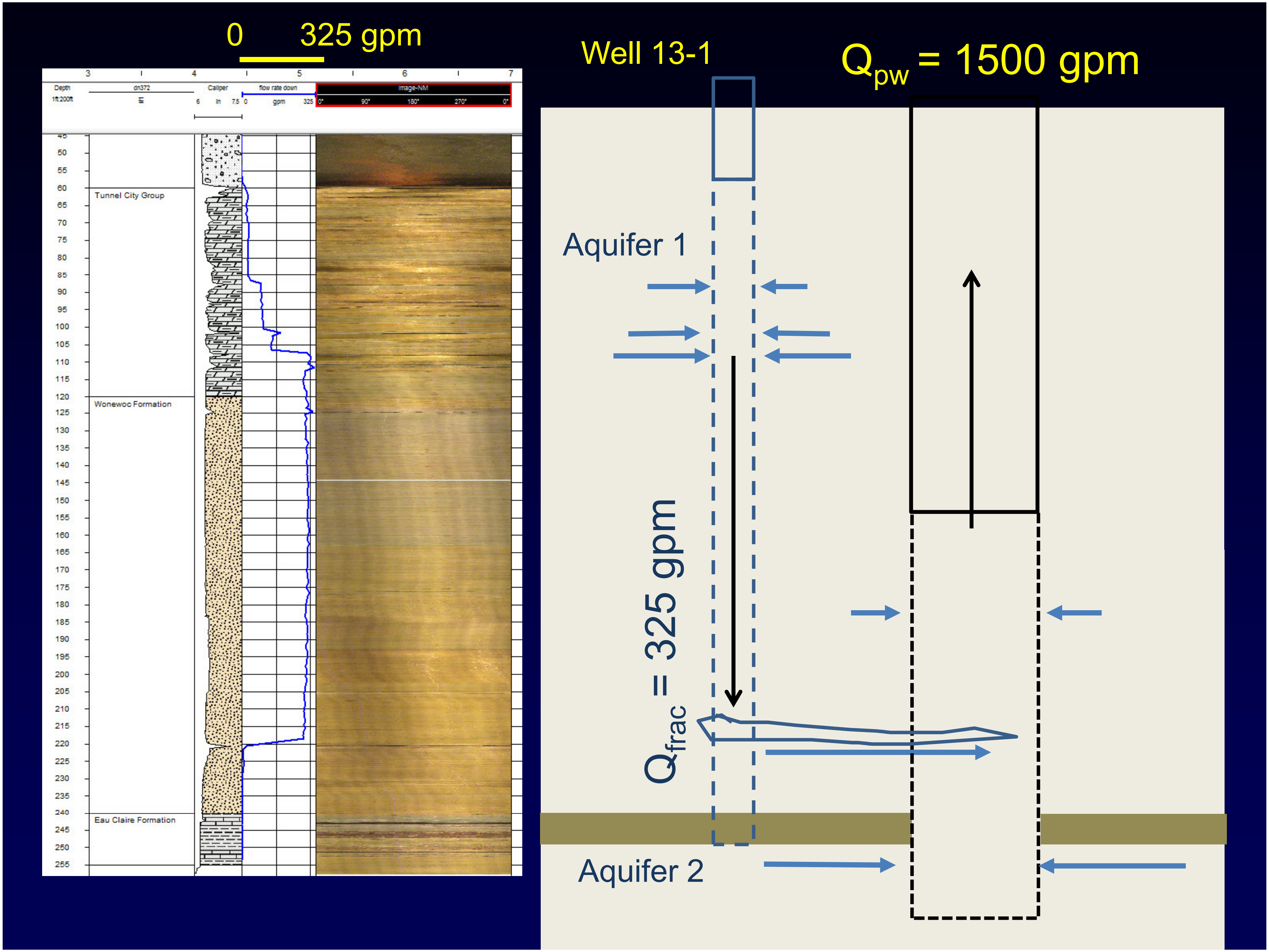
Spinner flowmeter spins in response to flow

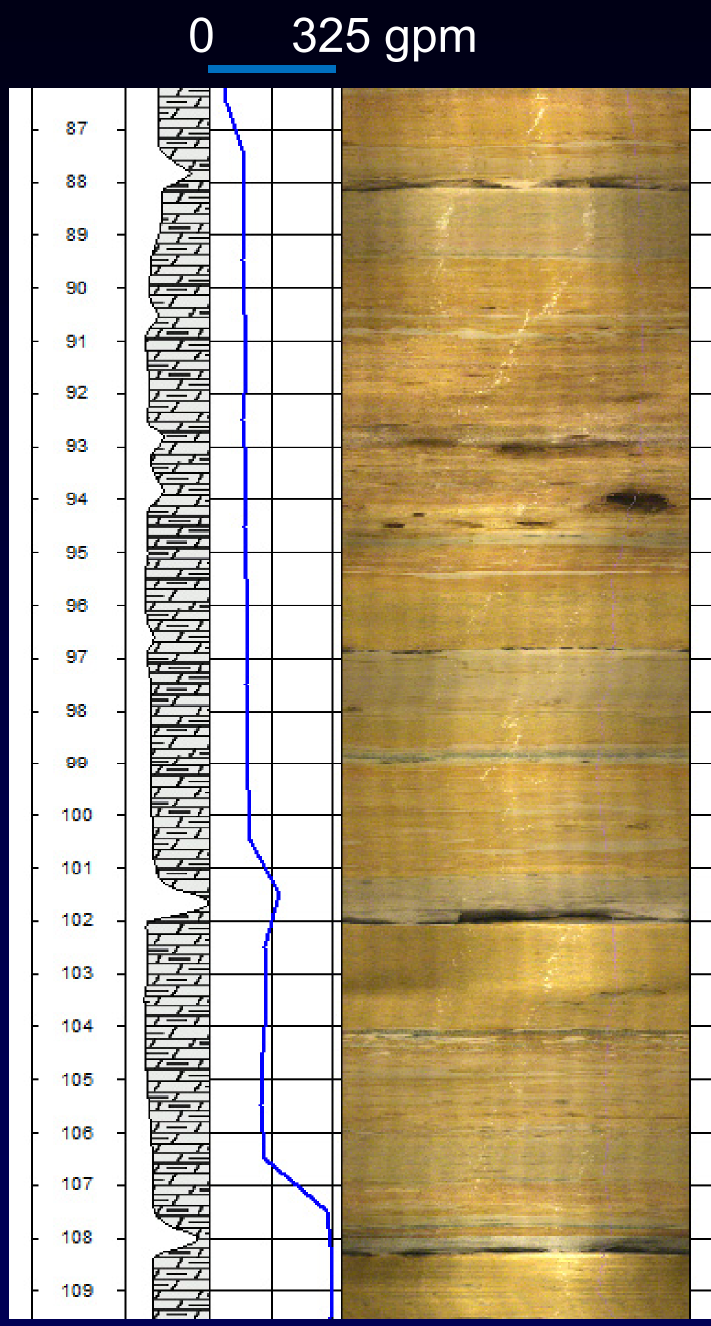


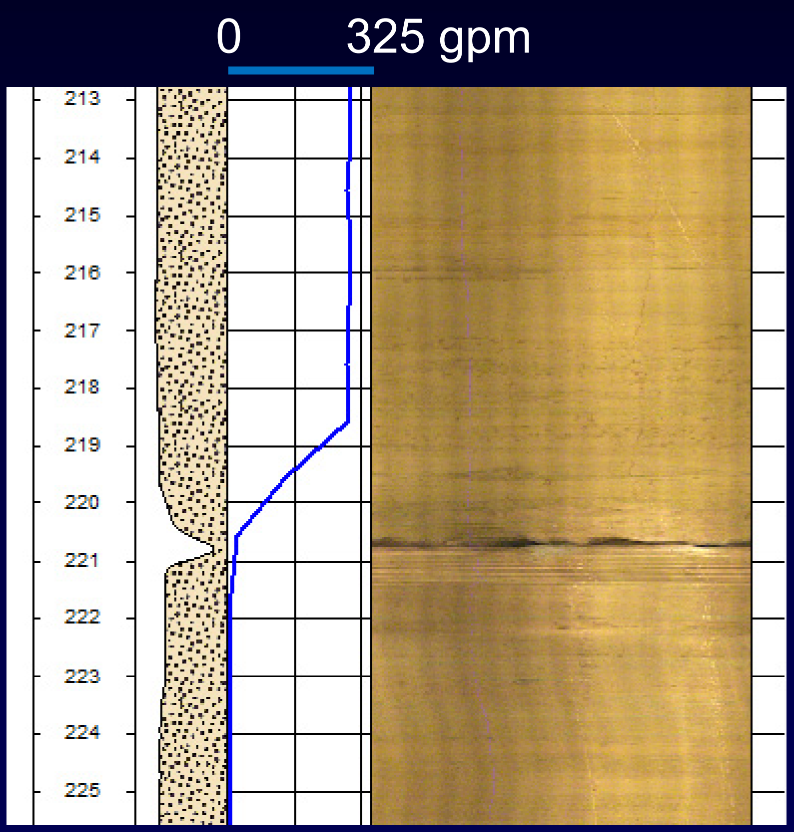


0 325 gpm
Depth
1ft:200ft
dn372
Caliper
6 in 7.5
flow rate down
0 gpm 325
Image-NM
0° 90° 180° 270° 0°
Tunnel City Group
Wonewoc Formation
Eau Claire Formation
Well 13-1
Q_{pw} = 1500 gpm
Aquifer 1
Q_{frac} = 325 gpm
Aquifer 2

Well 13-1

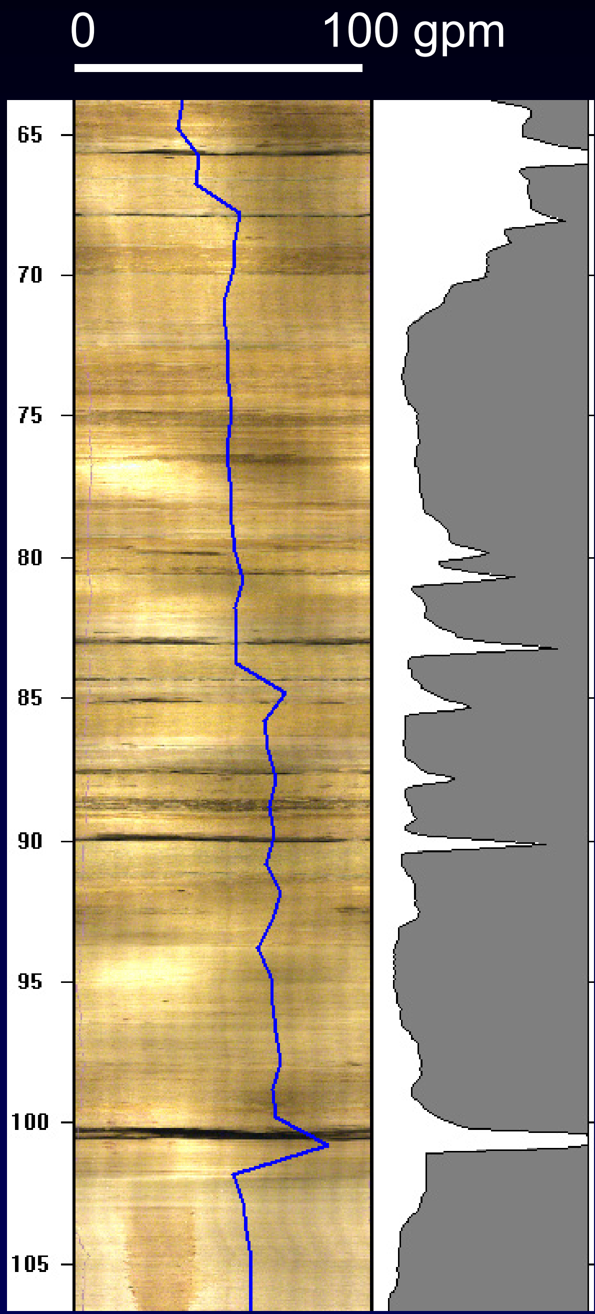
flow: positive values are downward

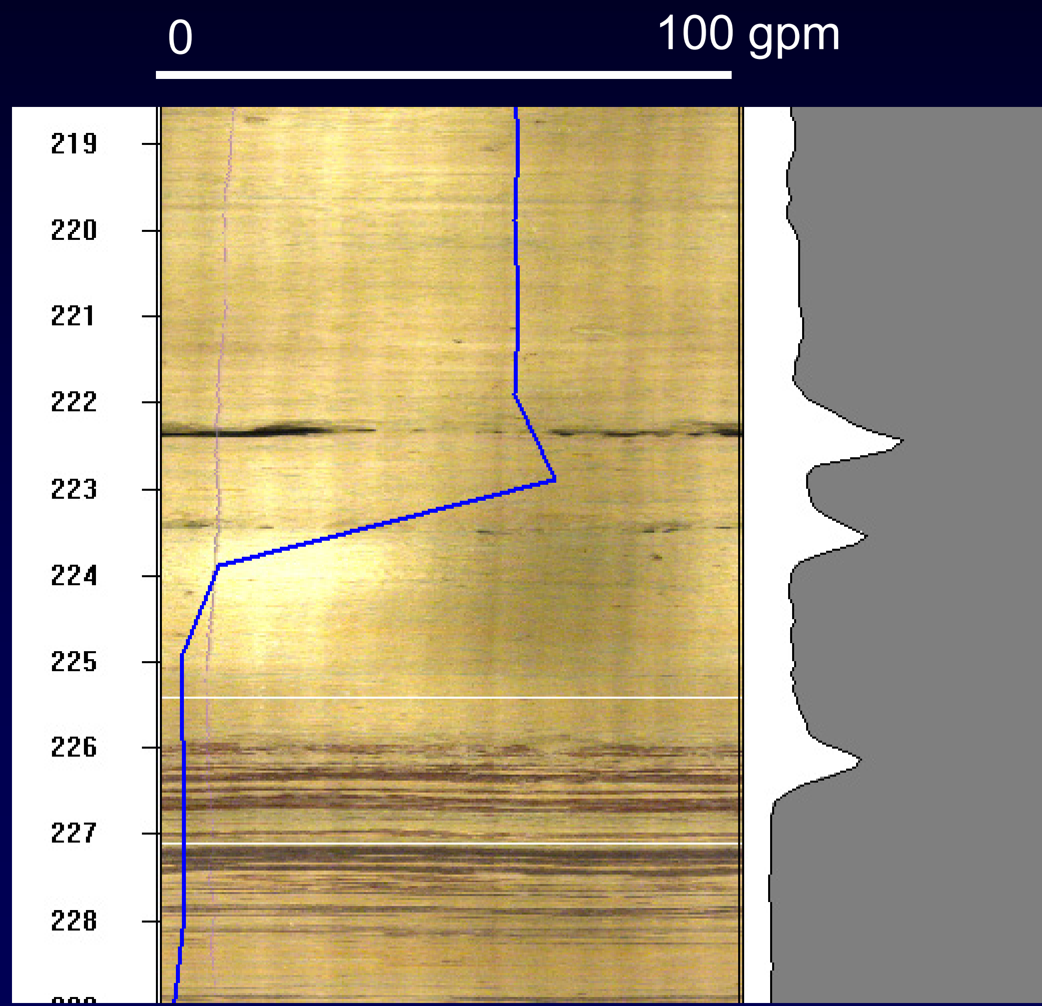




Well 11-1, non-pumping

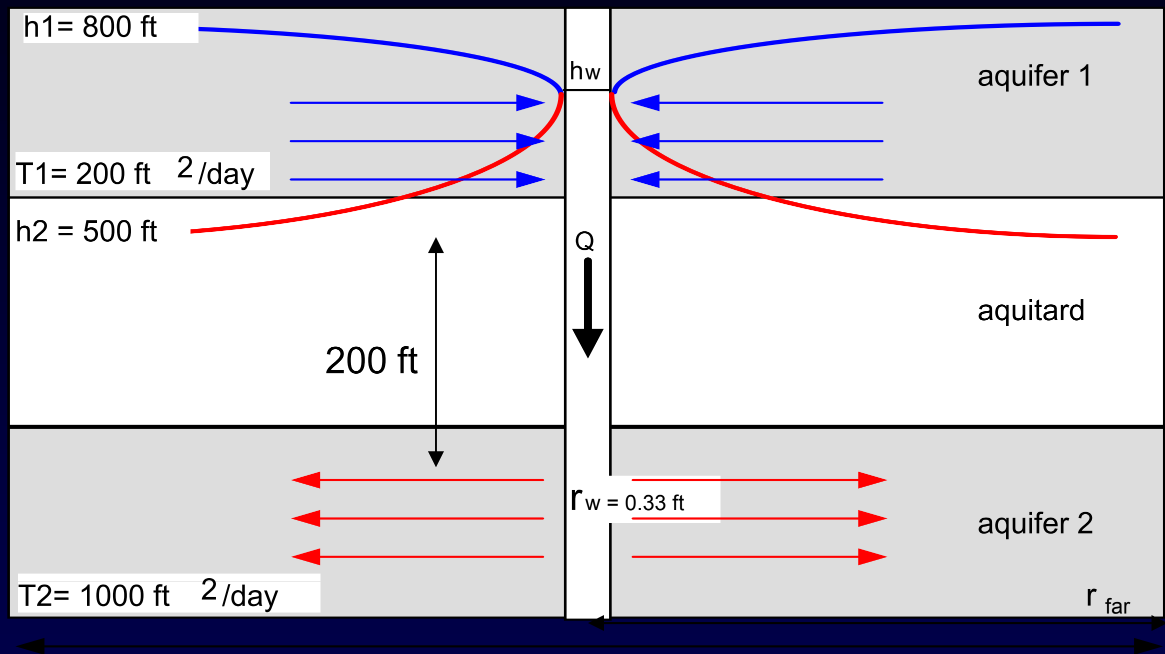
flow: positive is downward





Video from well 11- 1, located 30 feet from a multi-aquifer production well

Flow through a multi-aquifer well



$$h_1 - h_w = \frac{Q_{out}}{2\pi T_1} \ln \frac{r_{far}}{r_w}$$

$$Q_{out} = -Q_{in} = Q_{well}$$

$$h_2 - h_w = \frac{Q_{in}}{2\pi T_2} \ln \frac{r_{far}}{r_w}$$

Three equations and three unknowns: h_w, and Q_{in} and Q_{out}

$$Q_{well} = \frac{(h_1 - h_2)2\pi}{\ln\left(\frac{r_{far}}{r_w}\right)\left(\frac{1}{T_1} + \frac{1}{T_2}\right)}$$

Hart et al. 2006; Sokol, 1963

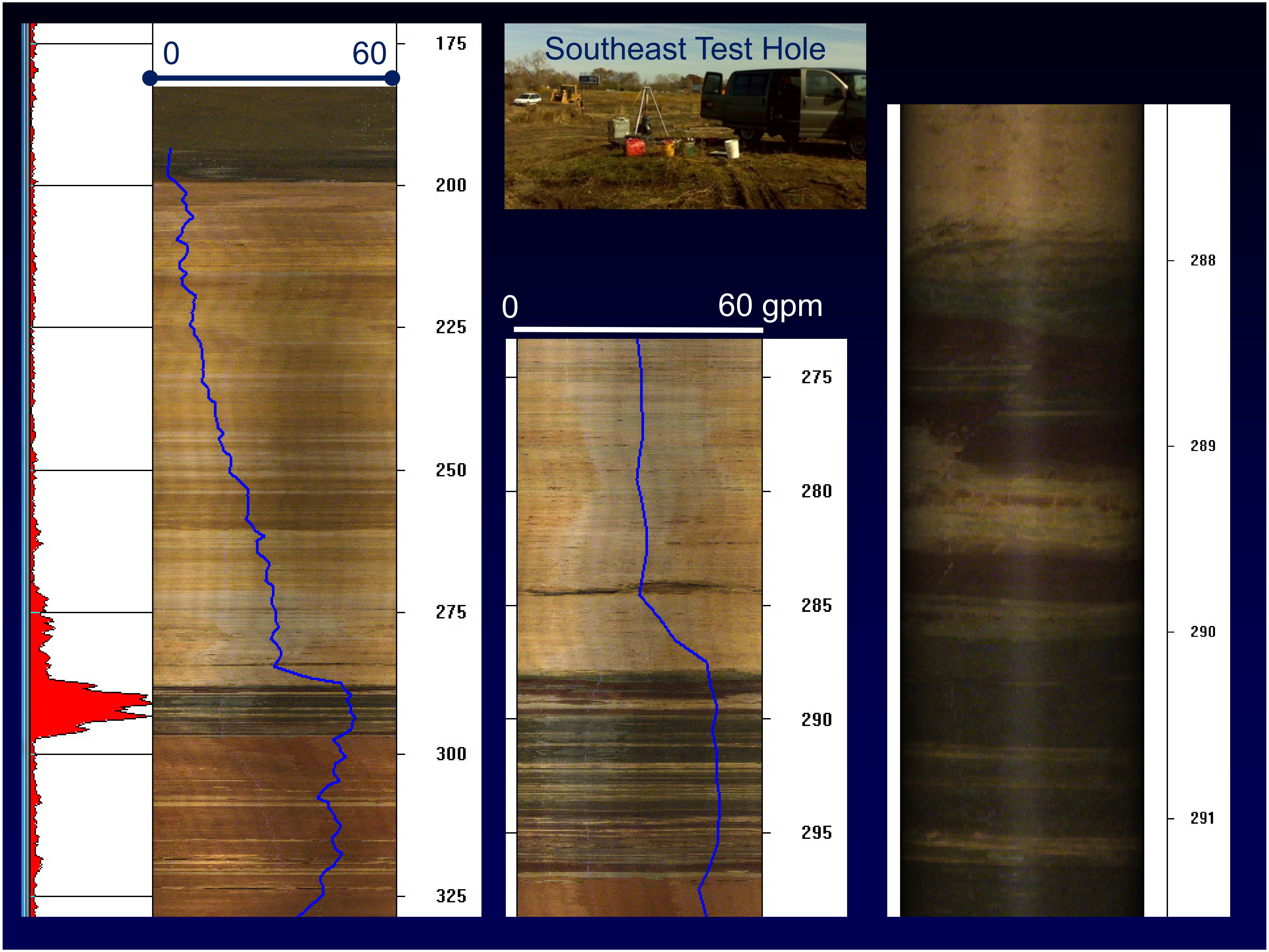
Are measured flows reasonable?

$$Q_{well} = \frac{(h_1 - h_2)2\pi}{\ln\left(\frac{r_{far}}{r_w}\right)\left(\frac{1}{T_1} + \frac{1}{T_2}\right)}$$

6-inch diameter well

$$Q_{well} = \frac{(900\,ft - 800\,ft)2\pi}{\ln\left(\frac{2500\,ft}{0.25\,ft}\right)\left(\frac{1}{625\,ft^2/day} + \frac{1}{4000\,ft^2/day}\right)}$$

$= 37{,}000\ ft^3/day$ (190 gpm)


Southeast Test Hole
0
60
175
200
225
250
275
300
325
0
60 gpm
275
280
285
290
295
288
289
290
291

Conclusions

What is the source of the viruses? Sanitary sewers

How do the viruses reach deeply cased wells? Through natural and man-made fractures. Every well in the urban environment should be considered vulnerable because the source is widespread, high-volume pumping induces high gradients, and fractures allow rapid transport of small volumes of ground water.

What are the impacts of leaky sewers on urban groundwater (quality and quantity)?

…understand problems associated with the nation's aging underground pipes and our drinking water quality

What is the travel time through a multi-aquifer well to a confined production well?