Human viruses as tracers of wastewater pathways into deep municipal wells

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Acknowledgements: co-authors, field workers, and cooperators

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- *Madison Municipal Sewerage District*
- *Wisconsin DNR – Groundwater Joint Solicitation Program*

Background

- Initial virus sampling conducted as part of AWWARF- funded study of aquitards
- We wanted to find out whether viruses were present in a deep, confined bedrock aquifer
- We did not expect to find any because the travel times were supposedly much longer than the virus lifetimes

Summary- initial study

- We confirmed the presence of human enteric viruses in 2 of 3 deep (70-220 m) bedrock wells tested in Madison
- These viruses likely originated in near-surface human waste, possibly leaky sewers
- Results showed that time series sampling is necessary to evaluate viruses in groundwater – results vary from month to month.
- The exact transport routes from the surface to depth were unclear, but calculations show that transport via groundwater flow is possible if the aquitard is fractured

2007-2009 Projects

Assessment of Virus Presence and Potential Virus Pathways in Deep Municipal Wells

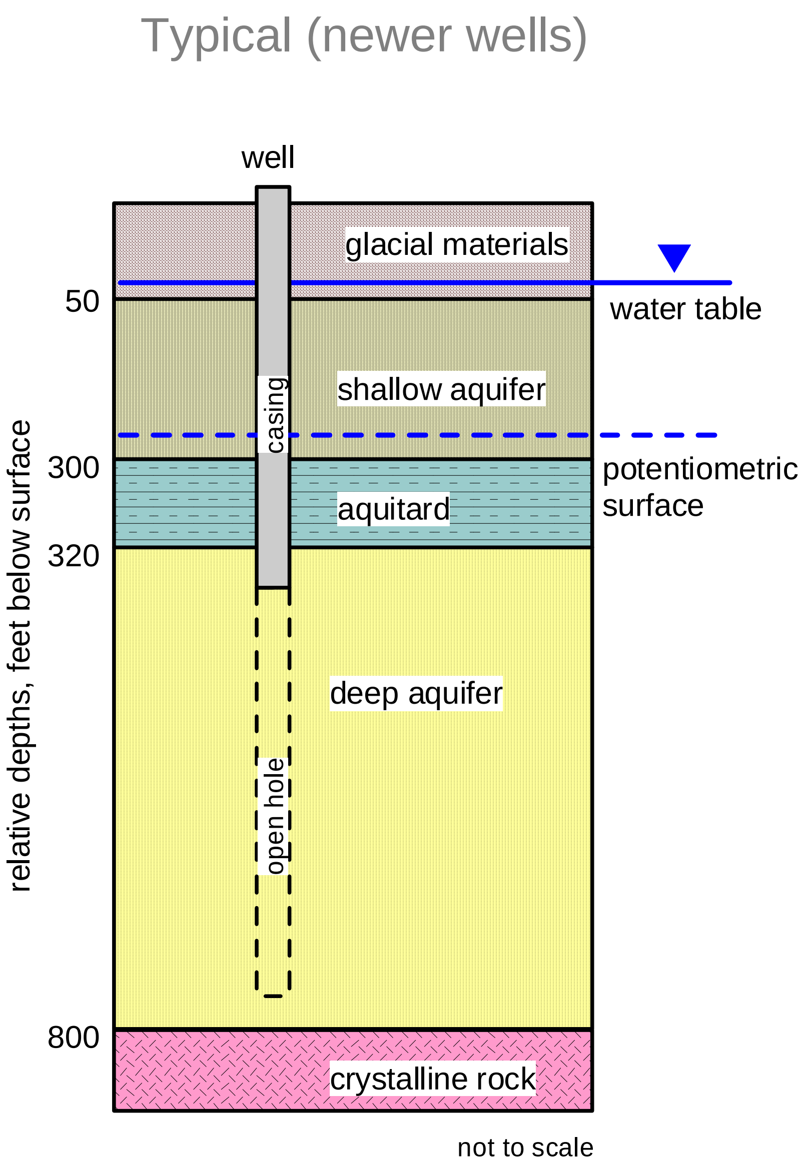
Project objectives and scope

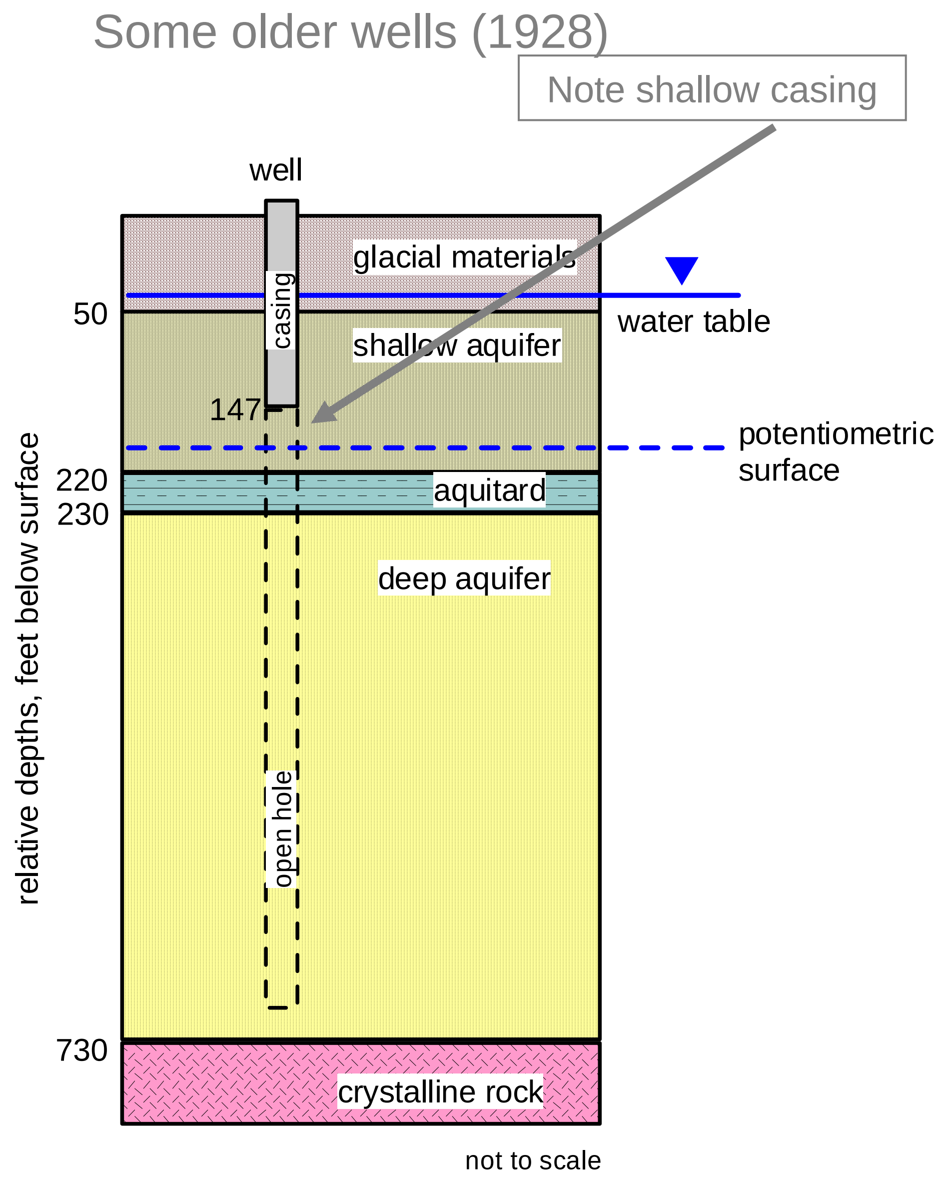
(1) to obtain a time series of virus, isotopic, and geochemical data from several municipal wells completed in a deep bedrock aquifer

(2) to use these data sets to evaluate virus presence and, if present, the potential sources of the viruses and pathways to the wells

(3) to evaluate the possibility that virus transport occurs through the well casing, grout or annular space.

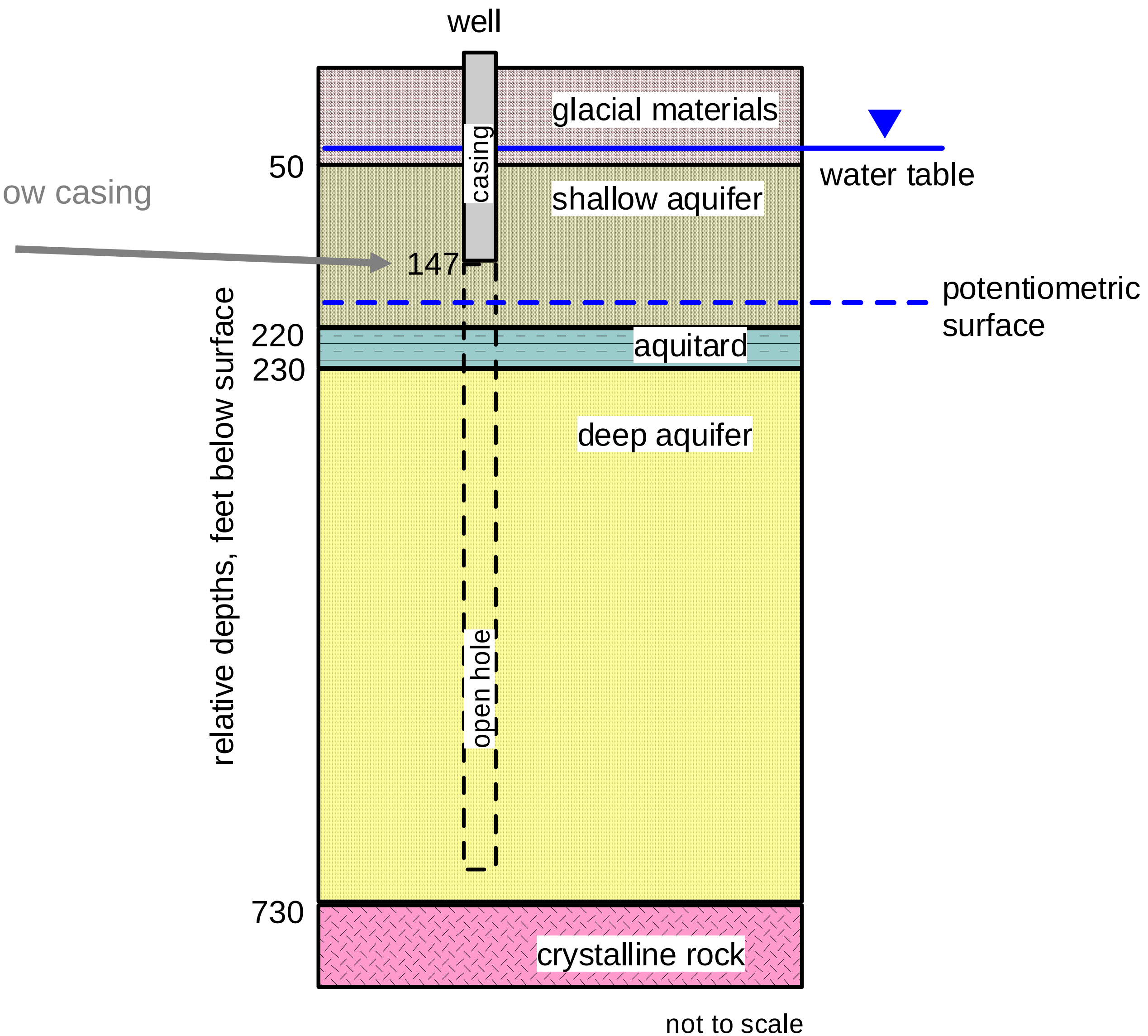
Construction of Madison supply wells



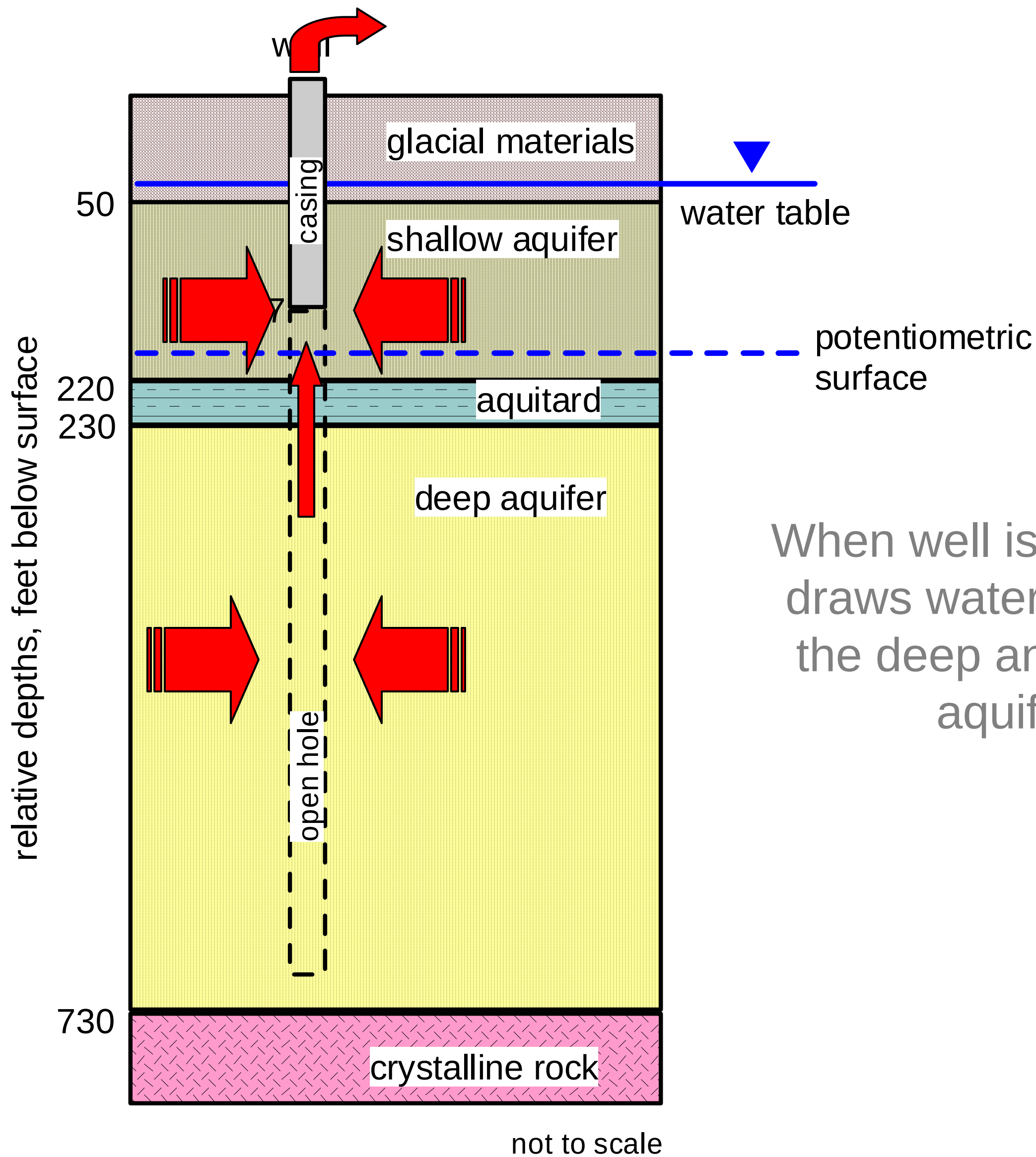


Cross-connecting well

Note shallow casing

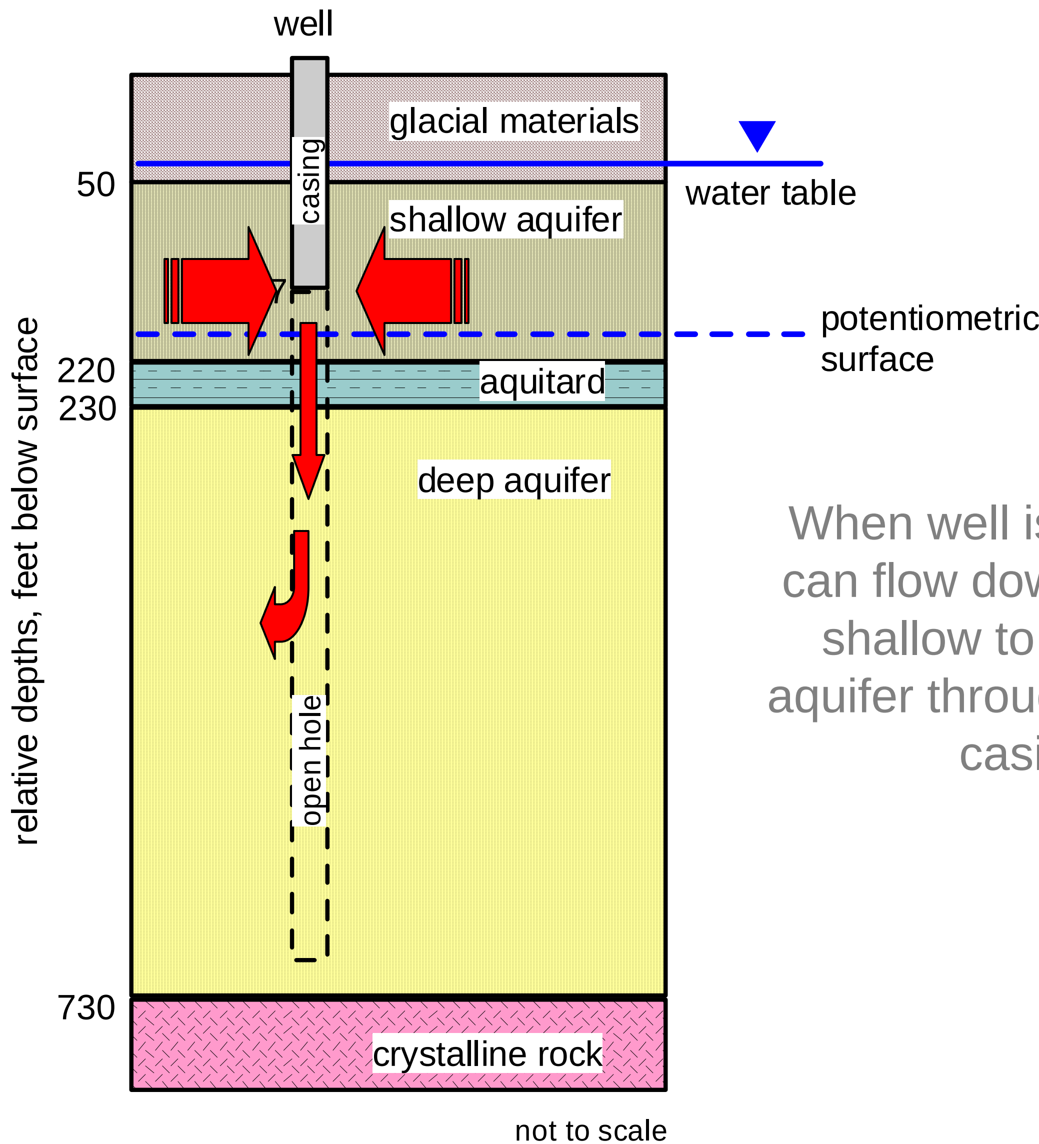


Cross-connecting well

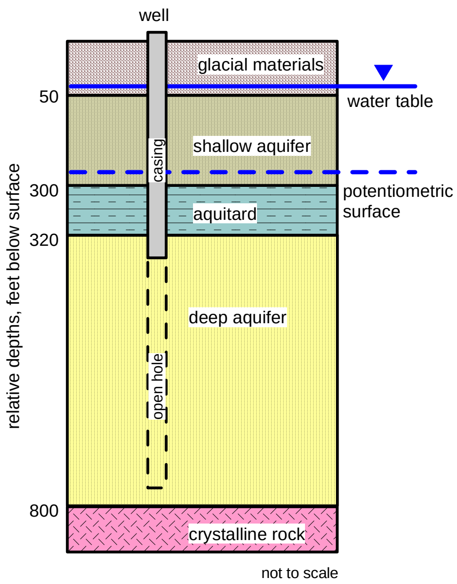


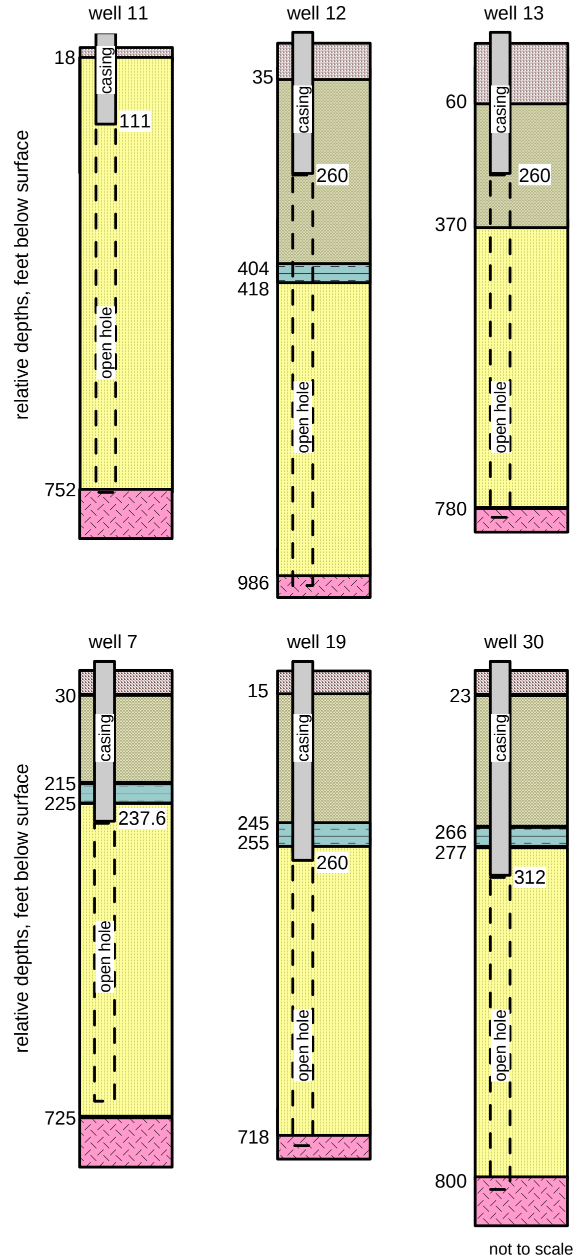
When well is pumping it draws water from both the deep and shallow aquifers

Cross-connecting well



When well is off, water can flow down from the shallow to the deep aquifer through the open casing



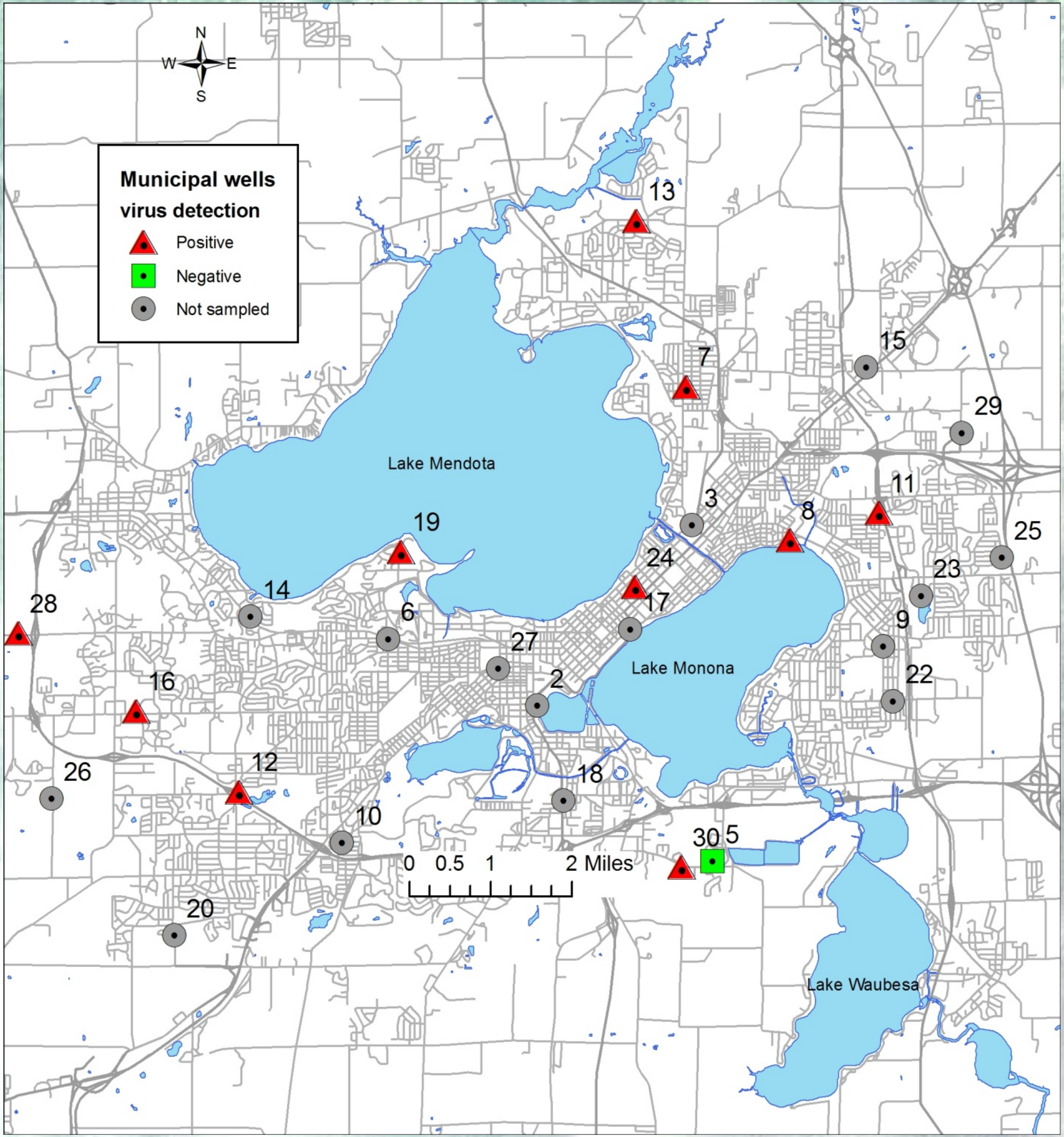


Construction details of the municipal wells sampled throughout the project. Diagram at upper left shows typical hydrostratigraphy and well construction for the Madison area.

Wells sampled 2007-2009

We began with 10 wells in a variety of locations to be sure we had virus-positive wells to work with.

We later reduced the sampling to 6 wells due to budget and logistic considerations.



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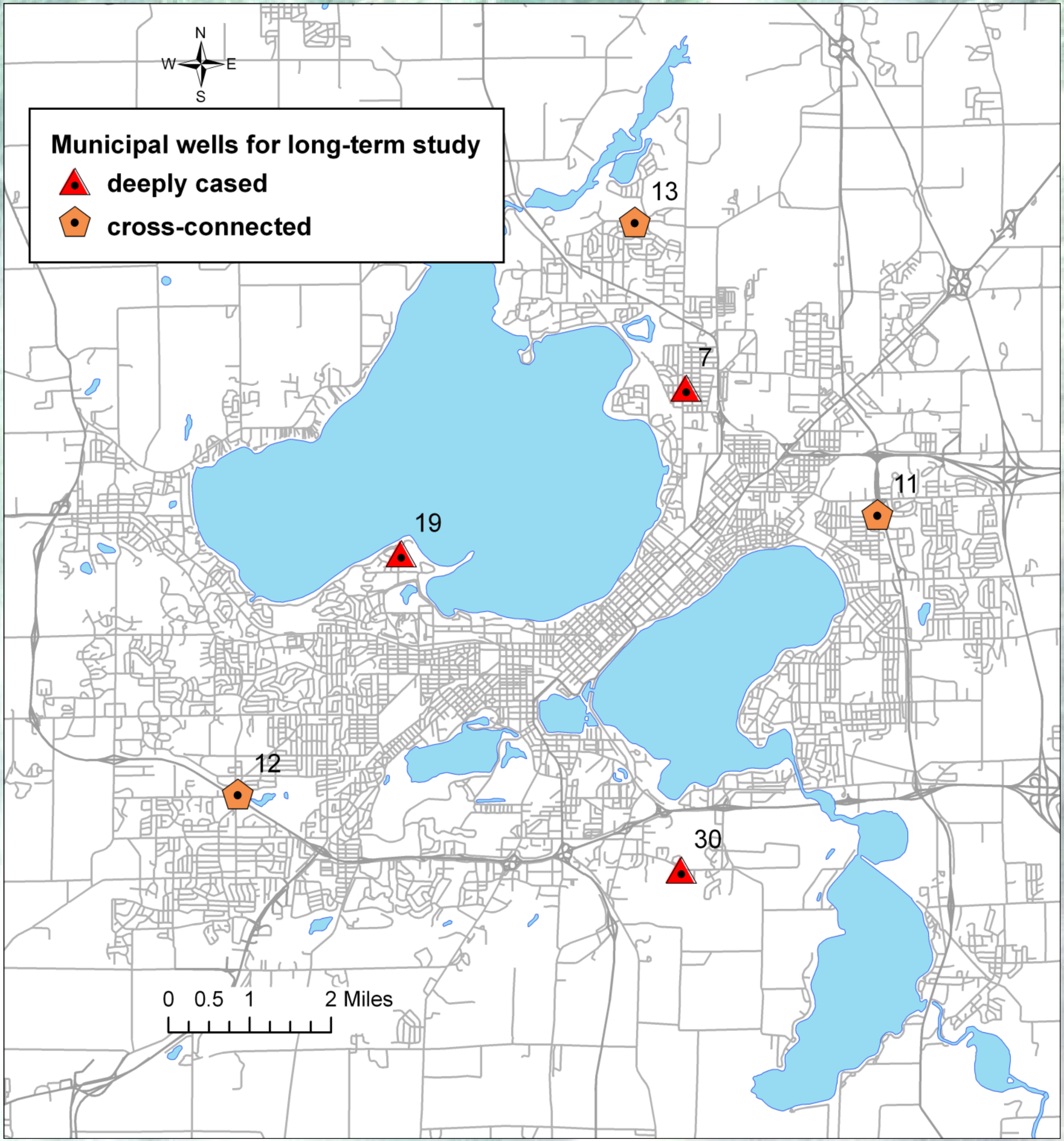

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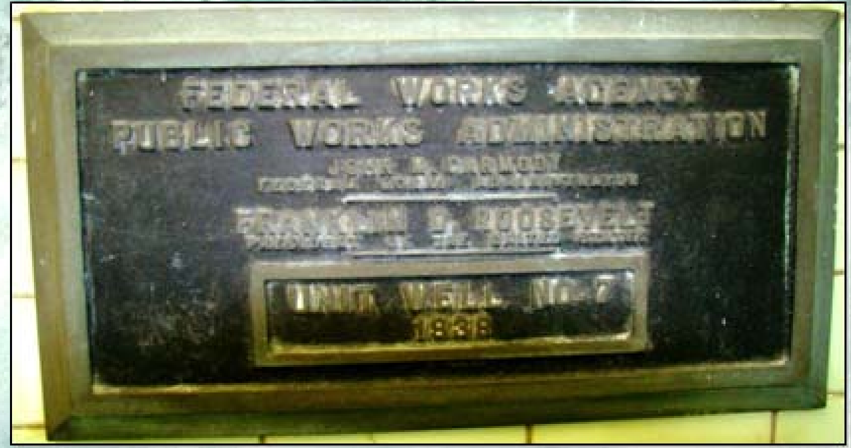
Virus Sampling



Study Methods

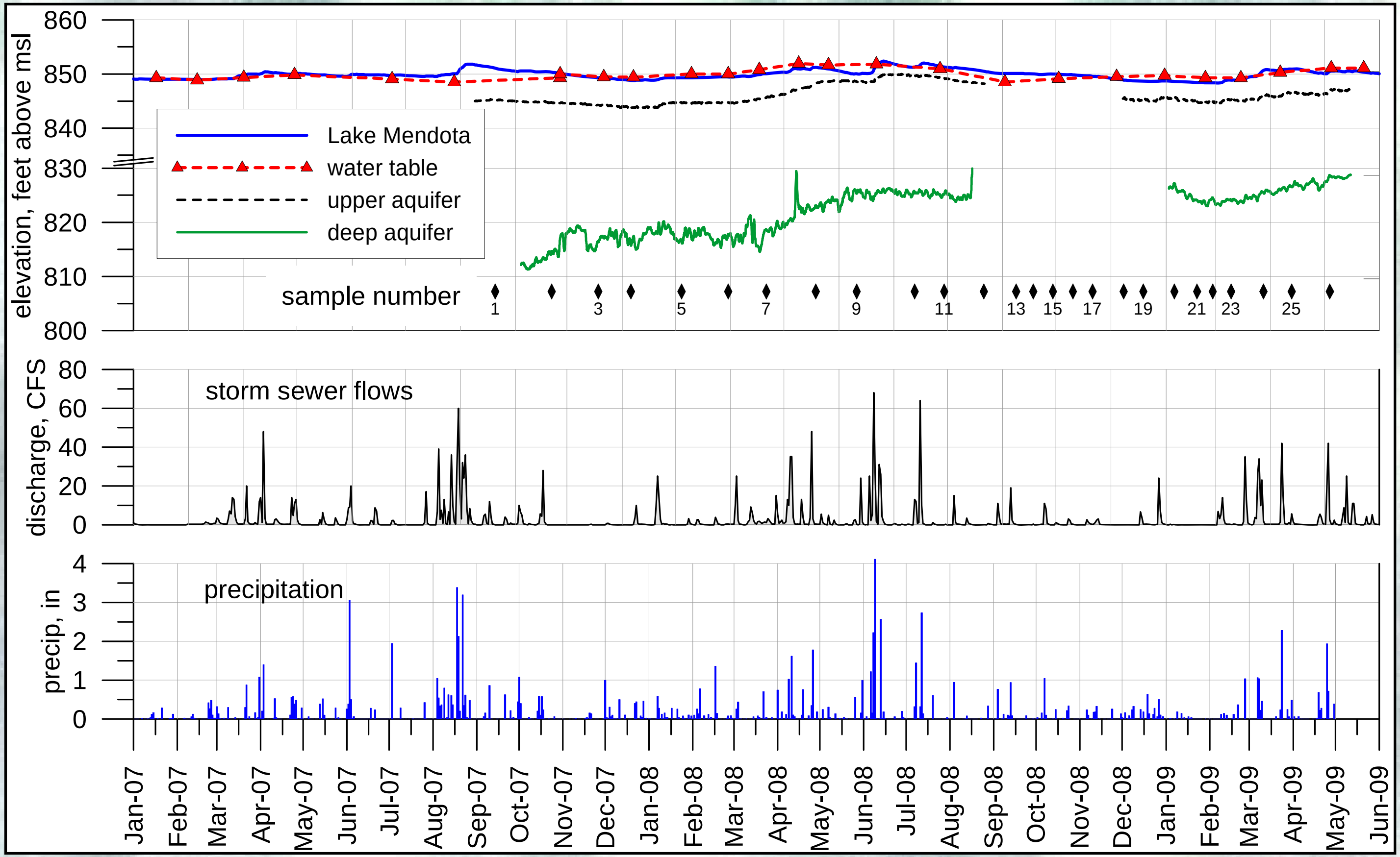
- Virus samples collected monthly. All samples taken prior to chlorination

- qRT-PCR/qPCR detection of enterovirus, rotavirus, hepatitis A virus, norovirus, and adenovirus

- Enterovirus and adenovirus serotype determined by nucleic acid sequencing; infectivity determined by cell culture

- Isotopes (^{3}H, ^{2}H, ^{18}O) analyzed at the University of Waterloo Environmental Isotope Lab

Sampling dates, stormwater flows, lake levels, and groundwater levels during the study period.



Overall findings

We found viruses in every well sampled in 2007-2009, though not every time sampled

Summary of virus detections by water source, wells 7, 11, 12, 13, 19, 30 only.

		virus detection (gc/l)			
water source	number of samples	percent positive	min	max	mean
wells	148	46.6	0.00	6.27	0.65
Lake Mendota	17	82	0.00	532*	44*
sewage influent	26	100.0	12,900	36,310,000	2,010,000

*maximum concentration detected in Lake Mendota was 69,900 gc/l on 3/1/09. This sample is an outlier that may indicate raw sewage in the lake; it was excluded from the statistical summary.

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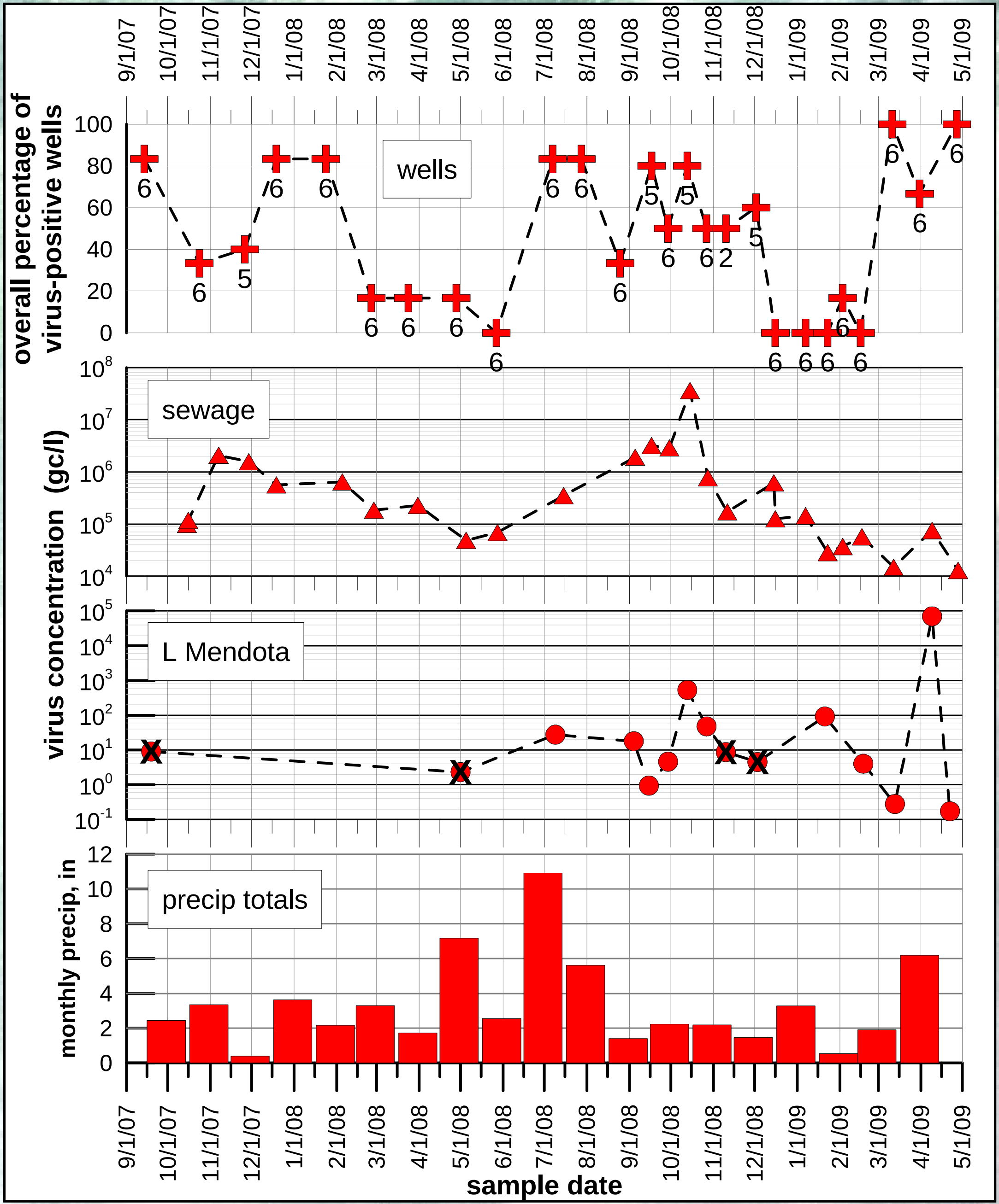
Most frequently detected viruses, by rank. Number of detections in parentheses. Multiple viruses indicate a rank tie.

Rank	wells	sewage	lakes
1	A41 (38)	A41 (18)	A41 (12)
2	A31 (12)	A31 (15)	A2, E3 (3)
3	A2 (11)	A2, E3 (5)	A31, E11, E30 (2)
4	E3 (5)	E9 (4)	--
5	E30, A7 (4)	A6, E11 (3)	--
6	Cox A16, Cox B3, Cox B4, E11 (3)	Cox A16, Cox B4 (2)	--
7	A5, E6, E9, E71 (1)	A5, A7, E6, E30, E71, E? (1)	--

Coincidence with time

The coincidence of virus detections in wells, lakes, and sewage is surprising.

Overall virus detections in wells, monthly precipitation totals, and virus concentrations in Lake Mendota and sewage influent. Numbers next to well samples indicate number of wells sampled on that date. Lake samples marked with an "X" indicate that the sample tested positive for infectivity.

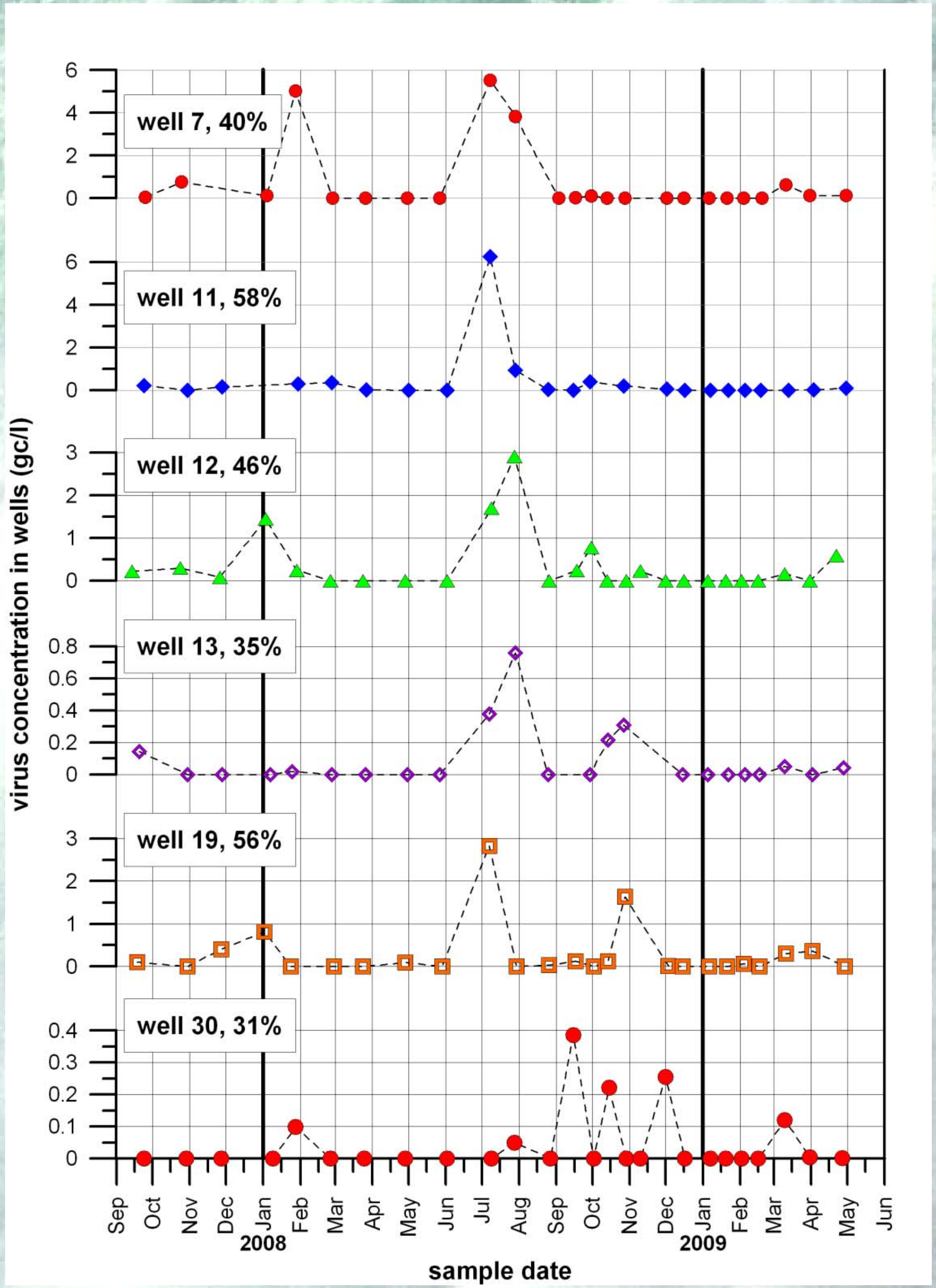


Well Virus Concentrations - Coincidence with Time

percentages indicate positive detections

note scale changes

Coincidence of peaks in wells miles apart suggests a regional problem



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16 different species (serotypes) of viruses were identified in wells, sewage, and lake water during this study, and in many cases wells and sewage contained identical virus serotypes. Detected viruses include Enteroviruses echovirus 3, echovirus 11, Coxsackie A16, B3, and B4, Adenoviruses 2, 7, 31, and 41.

Sample round		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
median sample date		14-Sep-07	24-Oct-07	26-Nov-07	19-Dec-07	24-Jan-08	26-Feb-08	24-Mar-08	28-Apr-08	27-May-08	7-Jul-08	28-Jul-08	25-Aug-08	17-Sep-08	29-Sep-08	13-Oct-08	27-Oct-08	10-Nov-08	2-Dec-08	16-Dec-08	7-Jan-09	23-Jan-09	3-Feb-09	16-Feb-09	11-Mar-09	31-Mar-09	27-Apr-09
sewage	A41	x		x	x		x			x	x	NS	x	x			x	x	x	x	x	x	x	x	x	x	x
	A31				x				x	x	x	NS	x		x	x	x	x	x	x	x	x	x		x		x
	A2	x	x		x	x		x				NS														x	
	E3		x								x	NS							x	x	x						
	E30											NS												x	x		
	A7										x	NS															
	E11		x	x			x		x			NS															
	CoxA16										■	NS	■														
	CoxB3											NS															
	CoxB4			x								NS												x			
all wells	A41	x		x	x	x		x			x	x	x	x	x	x	x	x	x				x		x	x	x
	A31					x					x	x	x				x		x						x		
	A2	x		x	x	x					x			x													x
	E3		x								x	x															
	E30																								x	x	
	A7	x				x					x	x															
	E11		x	x					x																		
	CoxA16										■	■															
	CoxB3											x				x											
	CoxB4																								x		
lakes	A41	x	NS	NS	NS	NS	NS	NS		NS	x	NS		x	x	x	x	x	x			x			x		
	A31		NS	NS	NS	NS	NS	NS		NS		NS				x		x									
	A2	x	NS	NS	NS	NS	NS	NS	x	NS	x	NS															
	E3		NS	NS	NS	NS	NS	NS		NS	x	NS														x	x
	E30		NS	NS	NS	NS	NS	NS		NS	x	NS															
	A7		NS	NS	NS	NS	NS	NS		NS		NS															
	E11		NS	NS	NS	NS	NS	NS		NS		NS												x	x		
	CoxA16		NS	NS	NS	NS	NS	NS		NS		NS															
	CoxB3		NS	NS	NS	NS	NS	NS		NS		NS															
	CoxB4		NS	NS	NS	NS	NS	NS		NS		NS															

There is coincidence between serotypes present in sewage and serotypes present in groundwater.

Sample round		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
median sample date		14-Sep-07	24-Oct-07	26-Nov-07	19-Dec-07	24-Jan-08	26-Feb-08	24-Mar-08	28-Apr-08	27-May-08	7-Jul-08	28-Jul-08	25-Aug-08	17-Sep-08	29-Sep-08	13-Oct-08	27-Oct-08	10-Nov-08	2-Dec-08	16-Dec-08	7-Jan-09	23-Jan-09	3-Feb-09	16-Feb-09	11-Mar-09	31-Mar-09	27-Apr-09
sewage	A41	x		x	x		x			x	x	NS	x	x			x	x	x	x	x	x	x	x	x	x	x
	A31				x				x	x	x	NS	x		x	x	x	x	x	x	x	x	x		x		x
	A2	x	x		x	x		x				NS														x	
	E3		x								x	NS							x	x	x						
	E30											NS												x	x		
	A7										x	NS															
	E11		x	x			x		x			NS															
	CoxA16											NS															
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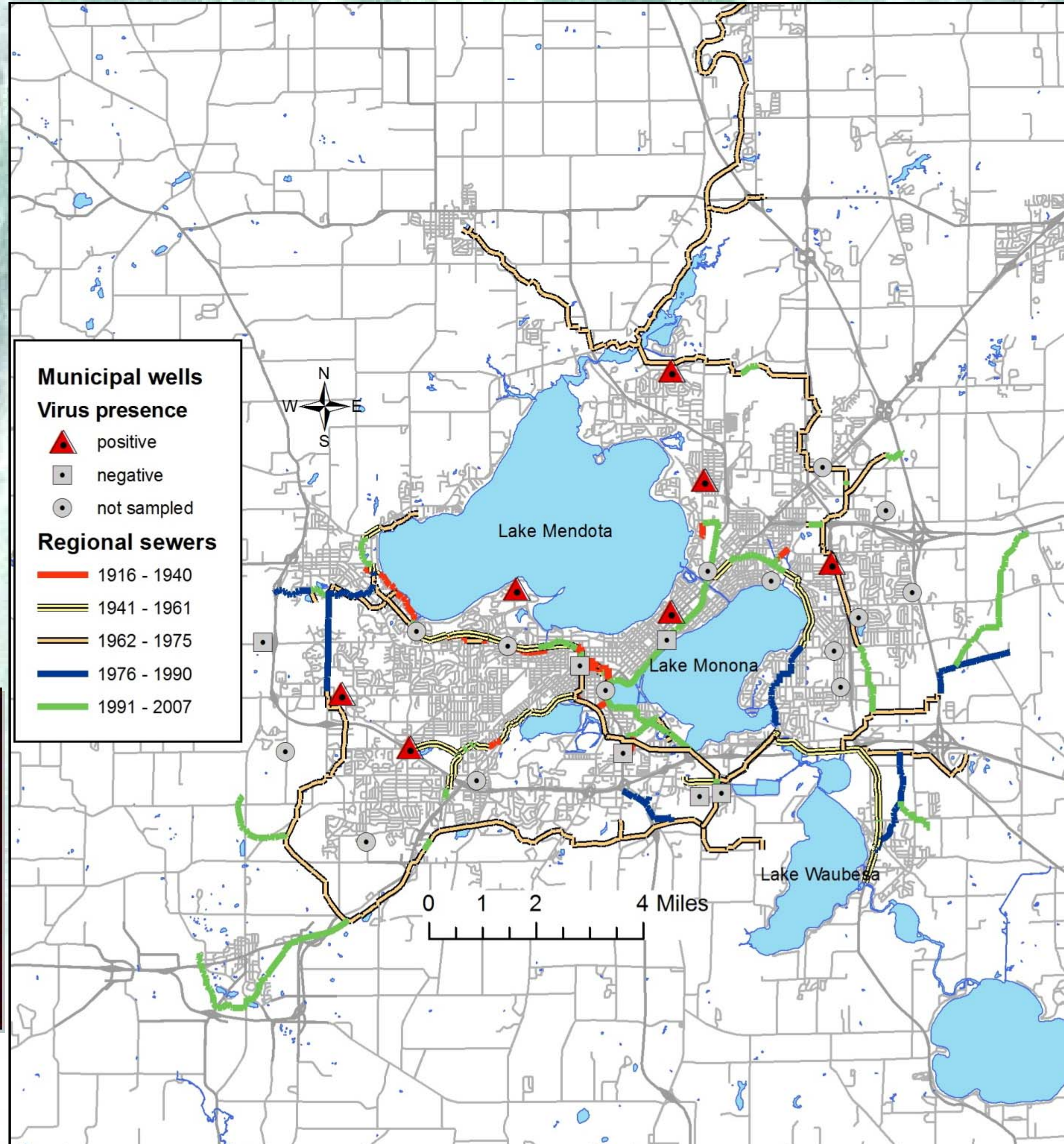
	CoxB4			x								NS												x			
all wells	A41	x		x	x	x		x			x	x	x	x	x	x	x	x	x				x		x	x	x
	A31					x					x	x	x				x		x						x		
	A2	x		x	x	x					x			x													x
	E3		x								x	x															
	E30																								x	x	
	A7	x				x					x	x															
	E11		x	x					x																		
	CoxA16																										
	CoxB3											x				x											
	CoxB4																								x		
lakes	A41	x	NS	NS	NS	NS	NS	NS		NS	x	NS		x	x	x	x	x	x			x			x		
	A31		NS	NS	NS	NS	NS	NS		NS		NS				x		x									
	A2	x	NS	NS	NS	NS	NS	NS	x	NS	x	NS															
	E3		NS	NS	NS	NS	NS	NS		NS	x	NS														x	x
	E30		NS	NS	NS	NS	NS	NS		NS	x	NS															
	A7		NS	NS	NS	NS	NS	NS		NS		NS															
	E11		NS	NS	NS	NS	NS	NS		NS		NS												x	x		
	CoxA16		NS	NS	NS	NS	NS	NS		NS		NS															
	CoxB3		NS	NS	NS	NS	NS	NS		NS		NS															
	CoxB4		NS	NS	NS	NS	NS	NS		NS		NS															

Sewers are ubiquitous in urban areas.

This graphic shows only regional connector sewers. There are hundreds of miles of local sewers.

The older sewers are nearly 100 years old.

Source: http://www.surrey.ca



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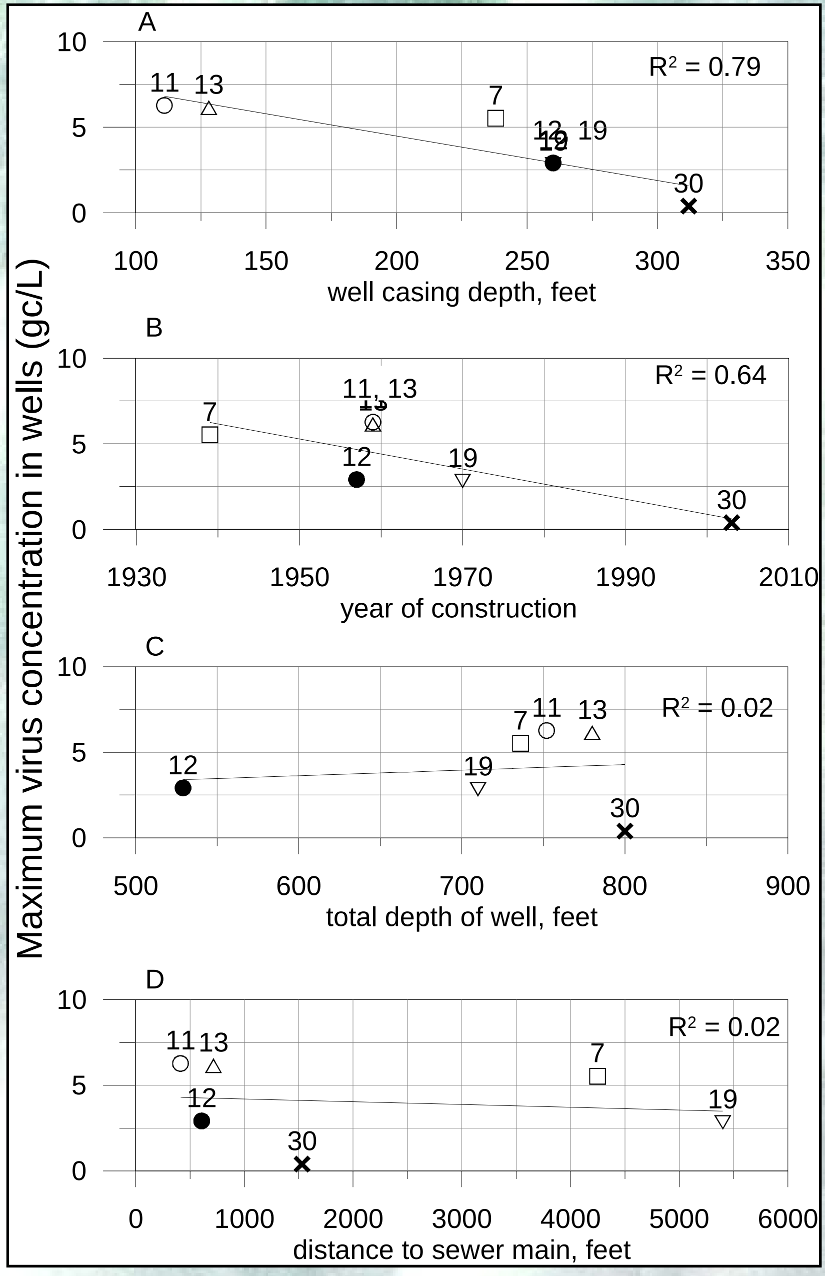
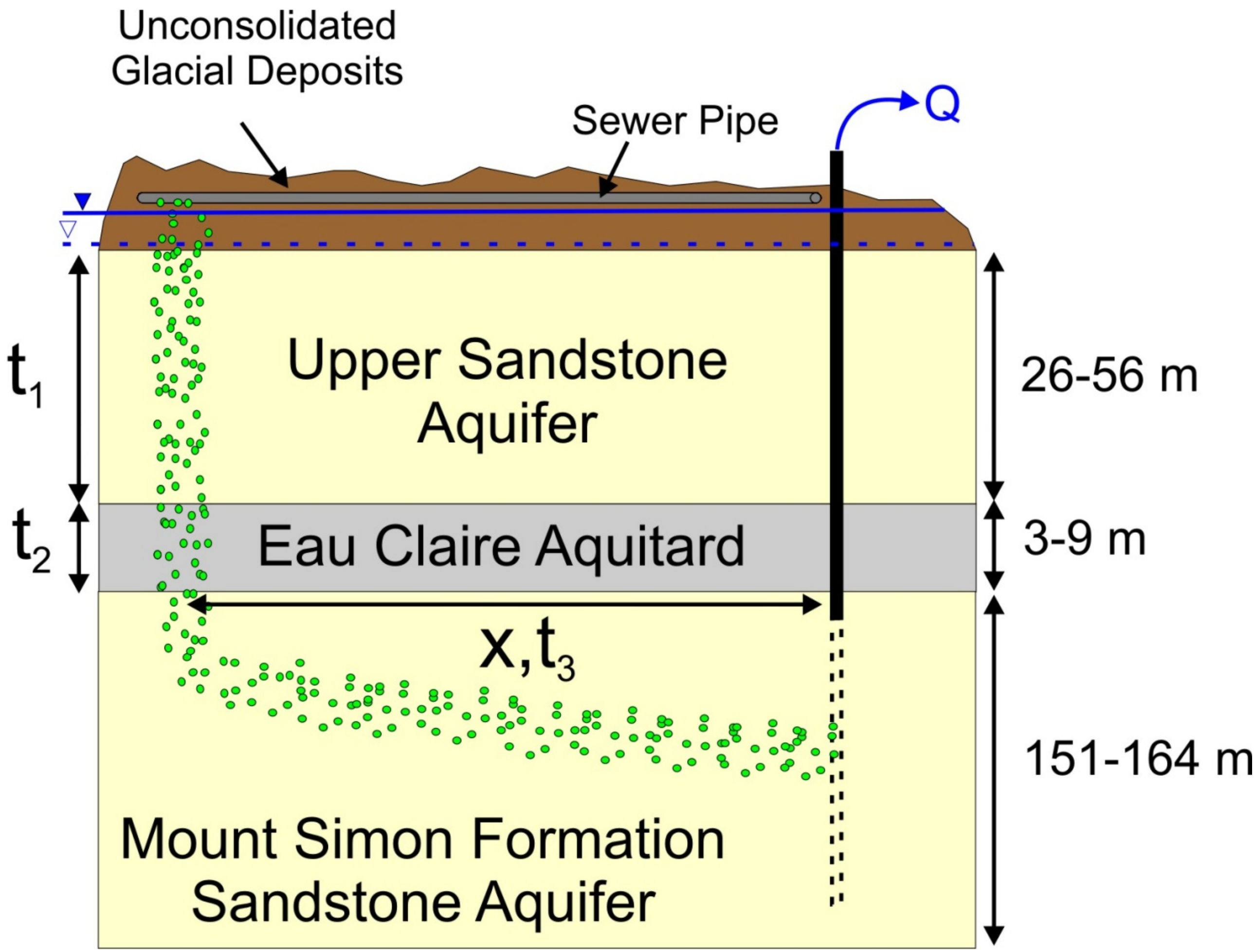
Virus detections are somewhat correlated to casing depth and well age



How Did the Viruses Reach the Deep Aquifer? (assume continuous aquitard)

Is $t_1 + t_2 + t_3$ < Virus survival time (~ 2 years) ?



$K_{bulk\text{-}vert} \sim 2 \times 10^{-4}$ cm/s

$\phi_{matrix} \sim 17\%$

$K_{bulk\text{-}vert} \sim 2 \times 10^{-4}$ cm/s

$K_{matrix\text{-}vert} \sim 8 \times 10^{-10}$ cm/s

$\phi_{matrix} \sim 7\%$

$\phi_{fracture} \sim$?

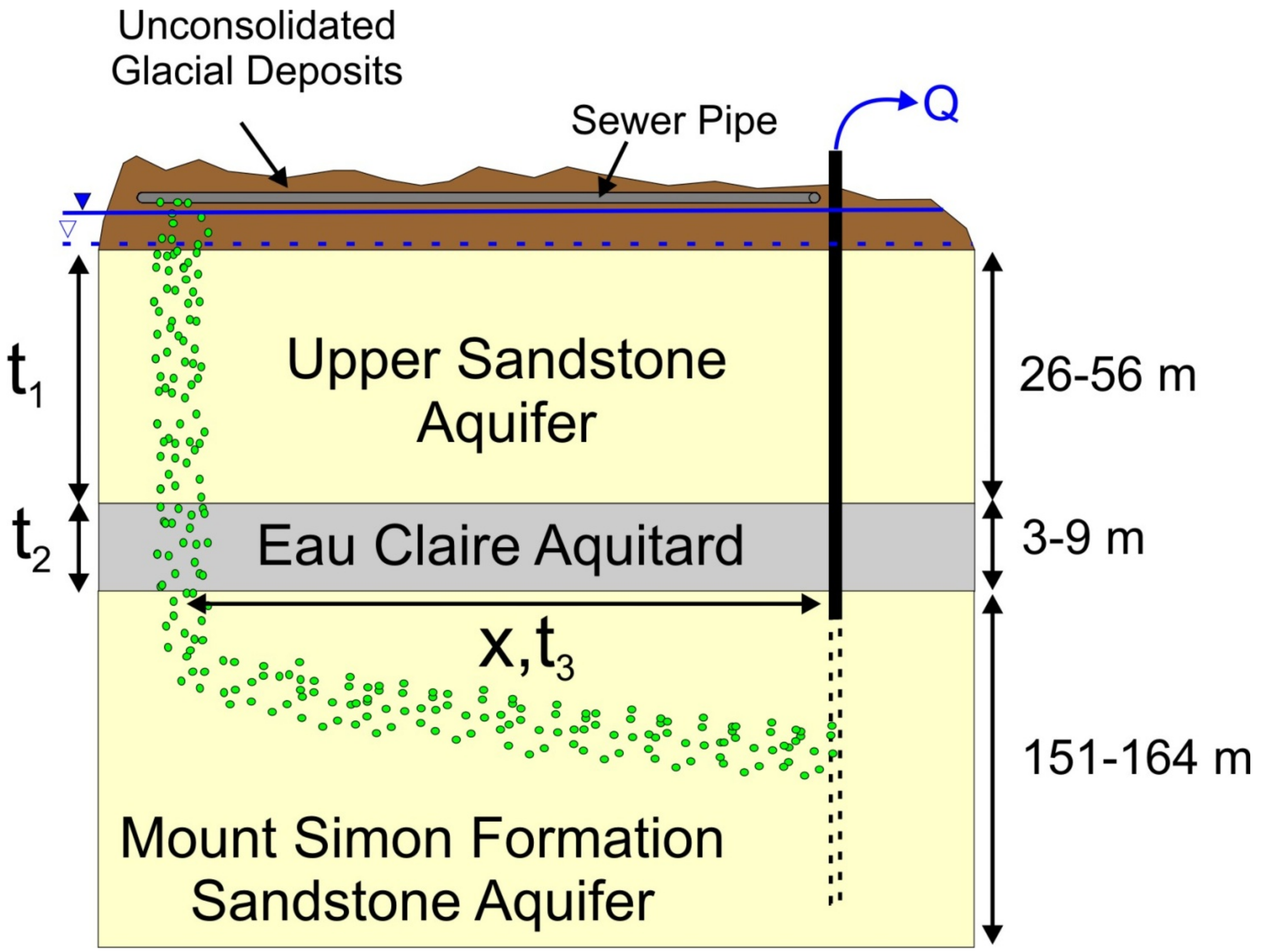
$K_{bulk\text{-}horiz} \sim 3.5 \times 10^{-3}$ cm/s

$\phi_{matrix} \sim 16\%$

$\phi_{fracture} \sim$?

If we pick the right parameters, transport to the aquifer could occur with the virus lifetime

Is $t_1 + t_2 + t_3$ < Virus survival time (~ 2 years) ?



But, other transport pathways are also possible

Possible Transport Pathways Through Aquitard

1) fractures

2) depositional or erosional stratigraphic windows

3) down cross-connecting open wells or boreholes

4) along damaged, deteriorated, poorly sealed well annulus or breaches in well casings

We still have not determined the pathway – research continues!

We still hope to trace pathways to the aquifer…

- Our attempts at in-well sampling in a municipal well failed because of small annular space and the danger of getting equipment stuck

- Currently a PhD student (C. Gellasch) is sampling one municipal well and adjacent monitoring wells with support from the US Army

- We have a proposal in to the USEPA STAR program – no word yet on funding

- The Madison Water Utility is encouraging about vertical sampling in future projects

Take-home messages…

Groundwater supplied from deep, confined bedrock aquifers is usually assumed to be protected from contamination and free of pathogenic organisms, but…

…the presence of viruses in deep wells in Madison, Wisconsin shows that pathogenic surface contaminants can reach deep aquifers over relatively short time spans

furthermore…

- Viruses were found in every well tested
- Virus presence in well water can be correlated to rainfall and snowmelt events during 2008 and 2009
- Correlation of viral serotypes suggests that viruses can be useful as groundwater tracers
- Leaky sewers are a likely virus source

Recent Publications

Borchardt, M. A.; Bradbury, K.R.; Gotkowitz, M. B.; Cherry, J. A.; Parker, B. L.. 2007. Human enteric viruses in groundwater from a confined bedrock aquifer. *Environmental Science and Technology*. 41(18); 6606-6612

Bradbury, K.R., M.A. Borchardt, M. Gotkowitz, and R.J. Hunt. 2008. *Assessment of Virus Presence and Potential Virus Pathways In Deep Municipal Wells*. WGNHS Open-File report 2008-08. 48 p.