Groundwater Heat Pumps

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Acknowledgements

- Wangki Yuen
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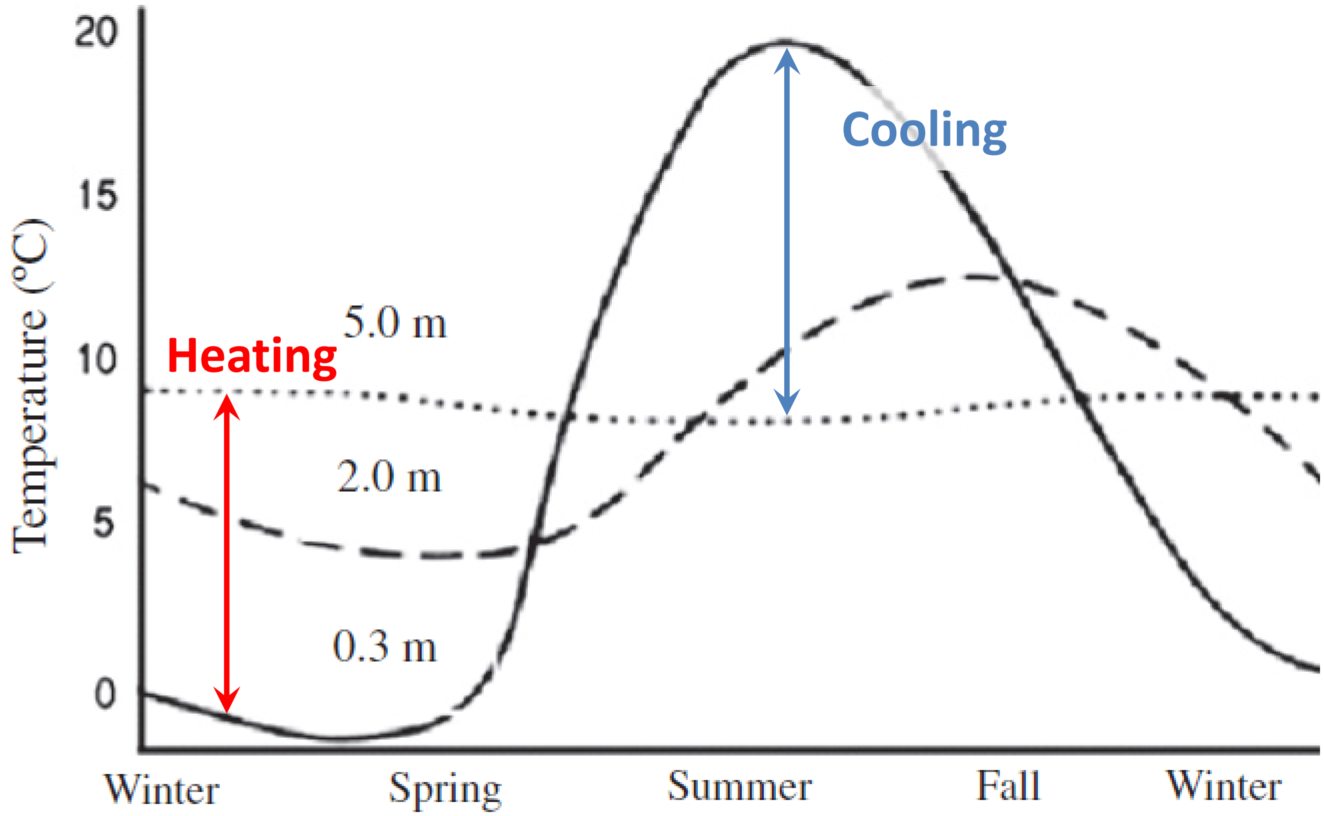
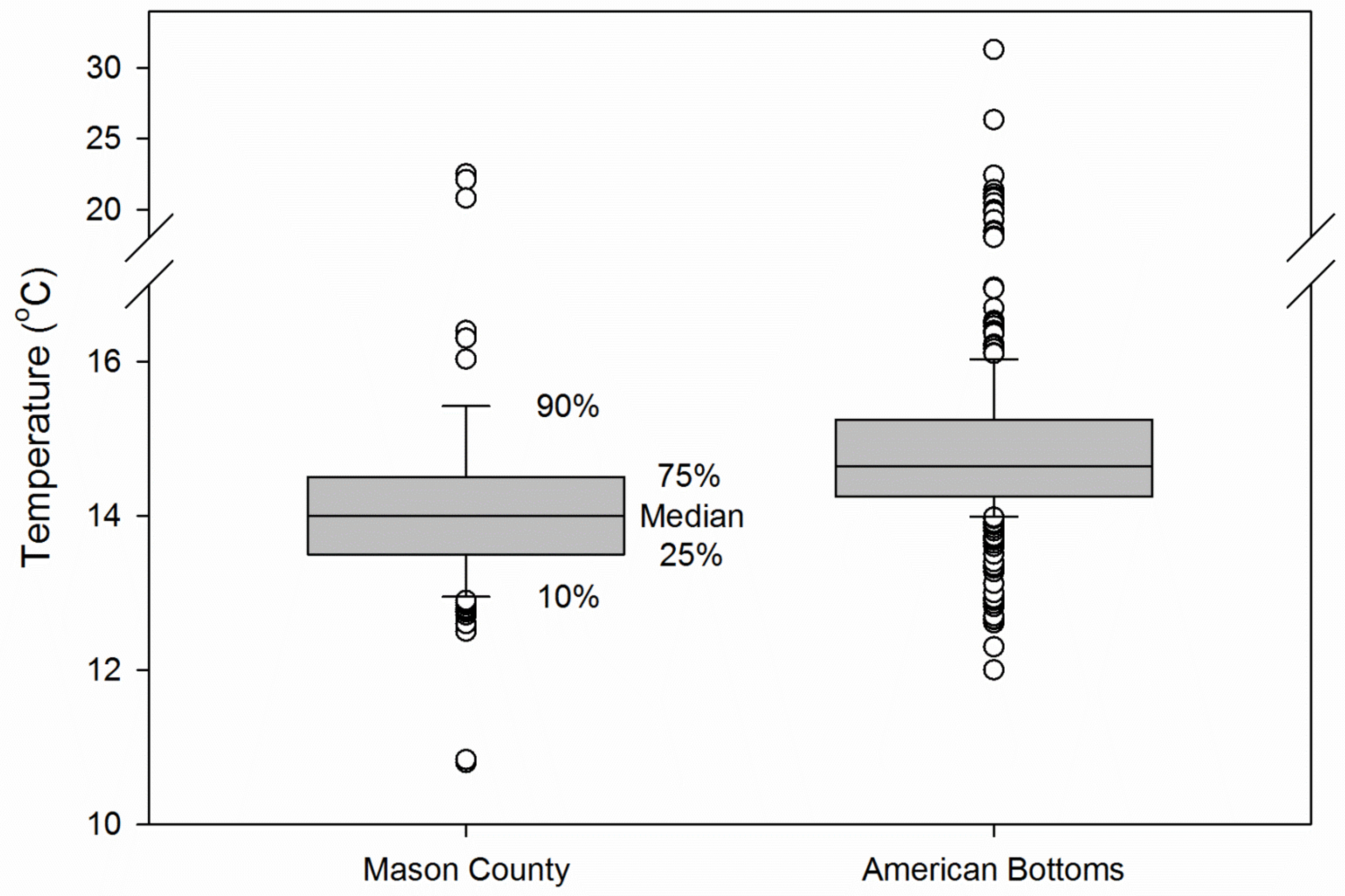


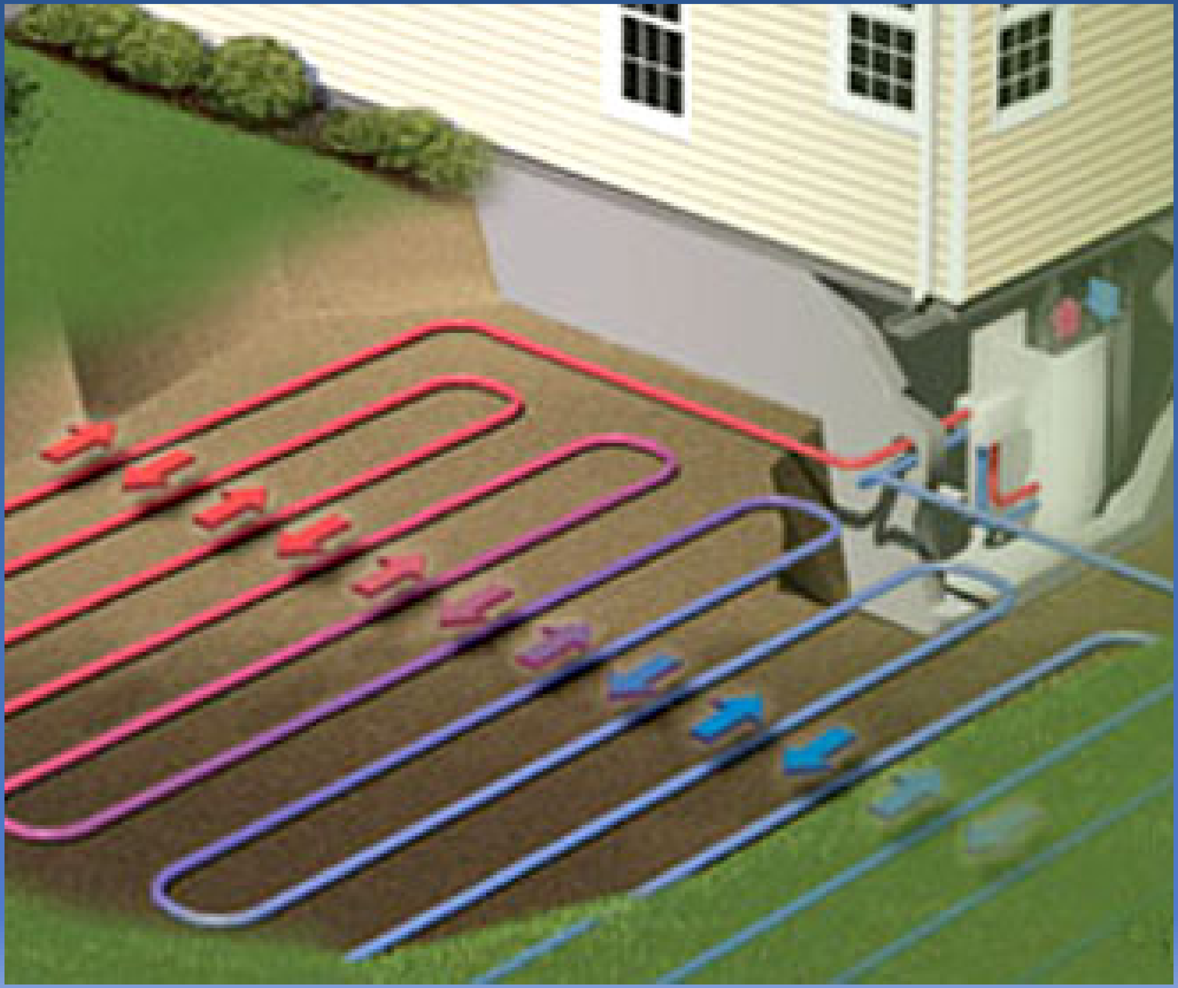
Fig. 3. Annual ground temperature range for different depths for Ottawa, Canada. Modified from Ref. [12].

Self et al. (2013)

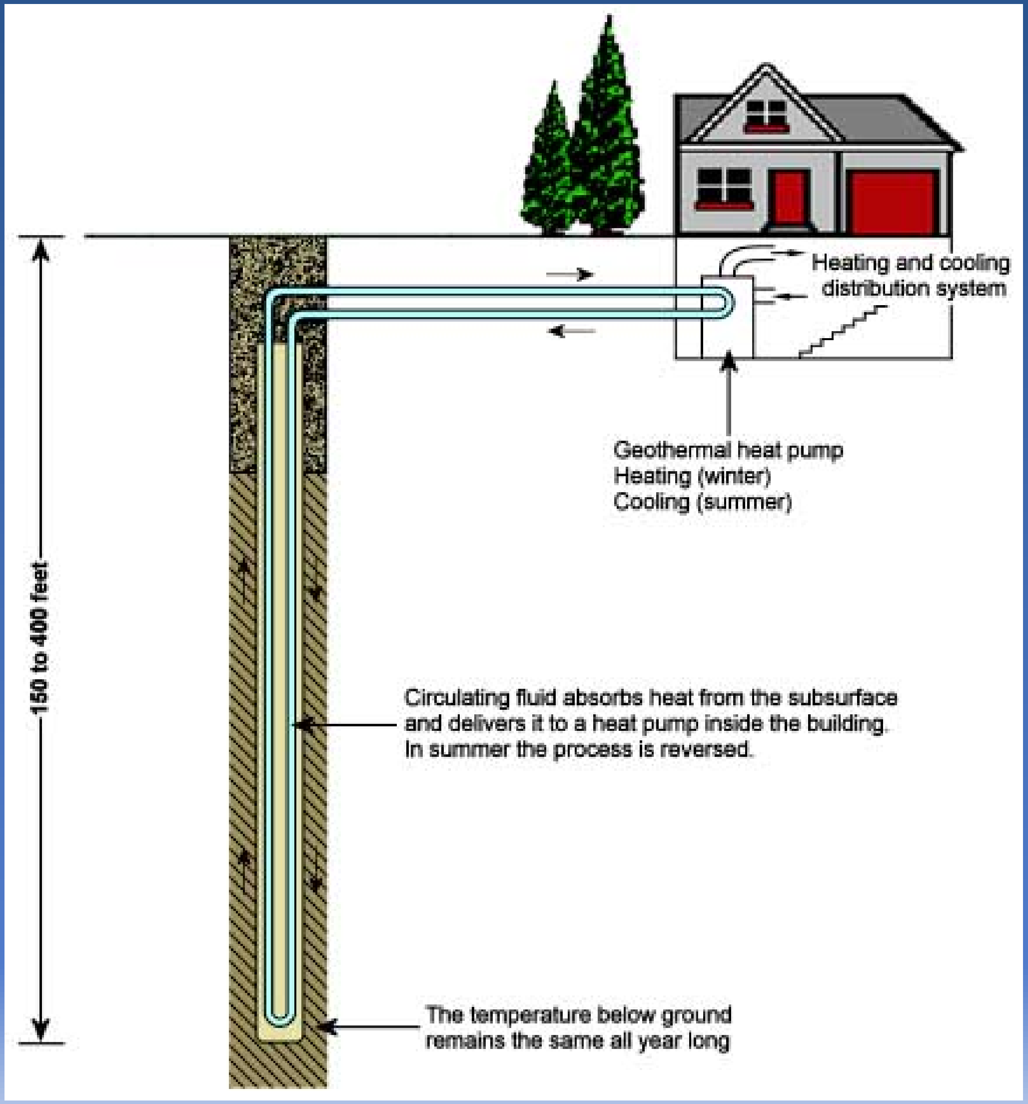
Illinois Groundwater Temperatures



Horizontal Closed Loop

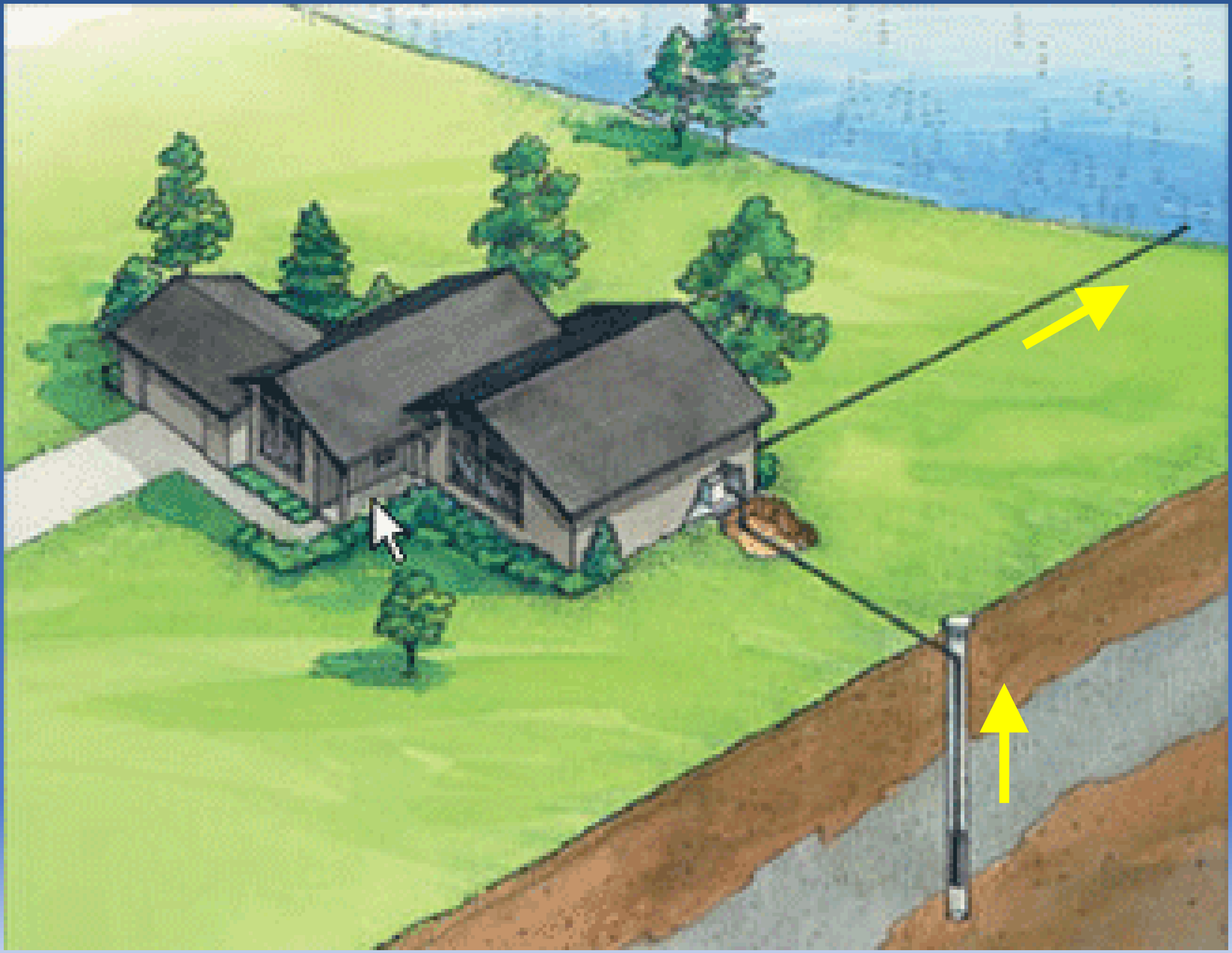


Vertical Closed Loop

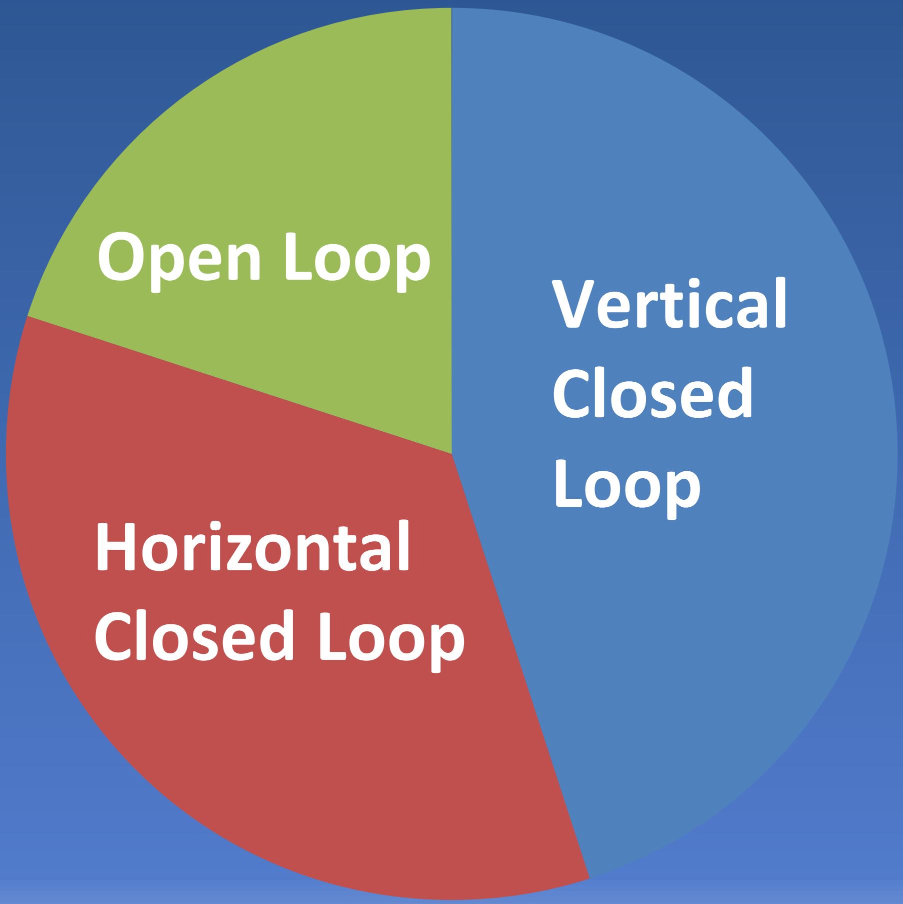


Open Loop Doublet

Open "Loop", Well & Drain



U. S. Ground Source Heat Pumps



Groundwater Availability for Open-Loop Geothermal Applications

American Bottoms
Mason County

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Project Purpose

Assess the feasibility of integrating existing data about groundwater availability and quality to delineate and evaluate areas suitable for open-loop groundwater heat pump systems

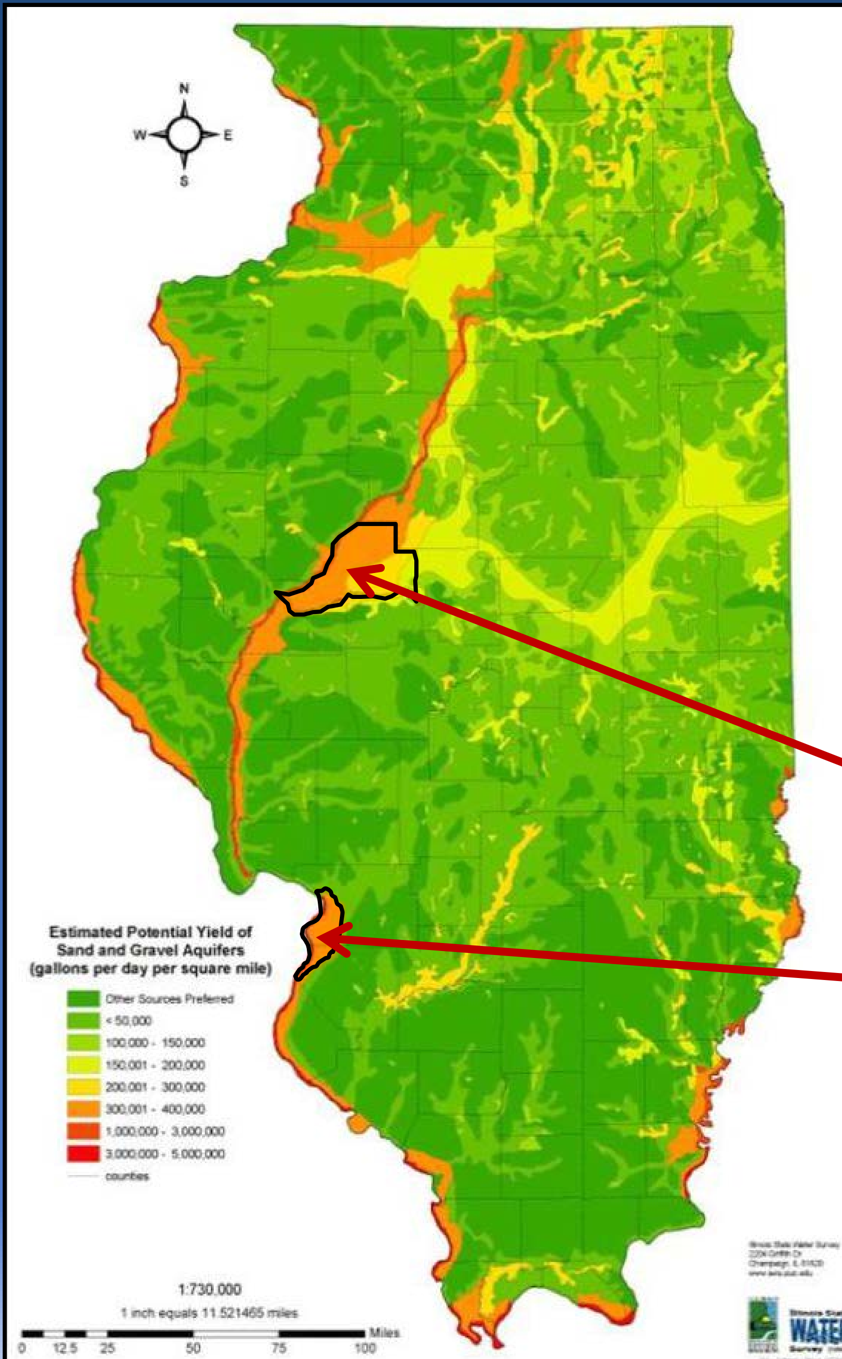
Heat content of groundwater is not typically part of considering groundwater as a source of water supply

Existing data:

- Geologic, hydrogeologic (aquifers), and hydraulic (aquifer properties)
- Groundwater quality (heat exchange performance and efficiency)
- Groundwater use

Data Sources:

- Water-well records served online through ISGS-ILWATER
- Publications, reports
- Unpublished data on file – ISGS and ISWS



Two Pilot Areas

Selection Criteria-Hydrogeology

Prolific aquifer

Yellow = 200,000-300,000 gpd/mi^2

Orange = 300,000-400,000 gpd/mi^2

(ISWS map of estimated potential yield of Illinois' sand & gravel aquifers)

Wealth of available data

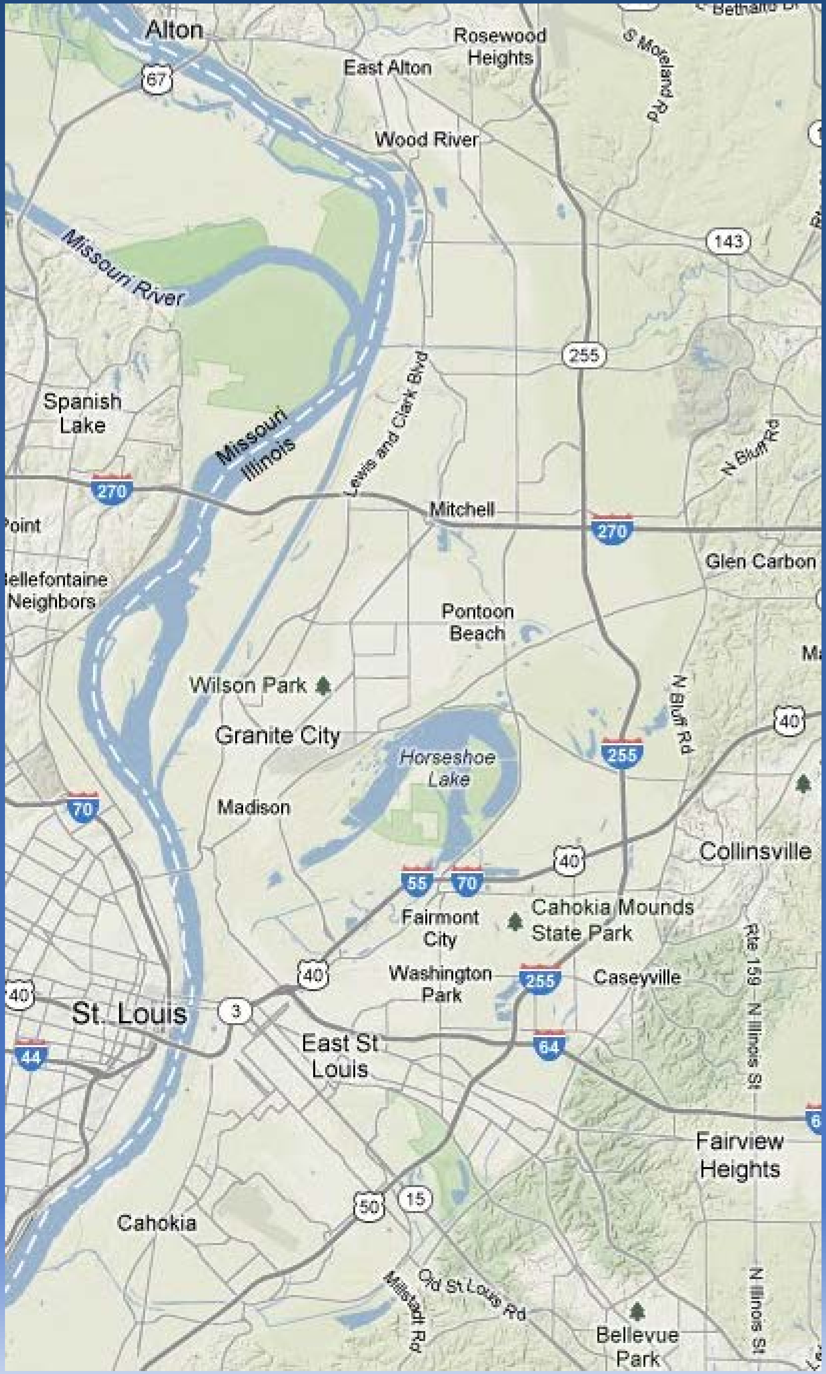
Mason County

Rural setting-agriculture applications

American Bottoms - Madison and St. Clair Counties

urban setting-commercial/industrial applications

groundwater quality problems



American Bottoms

Floodplain

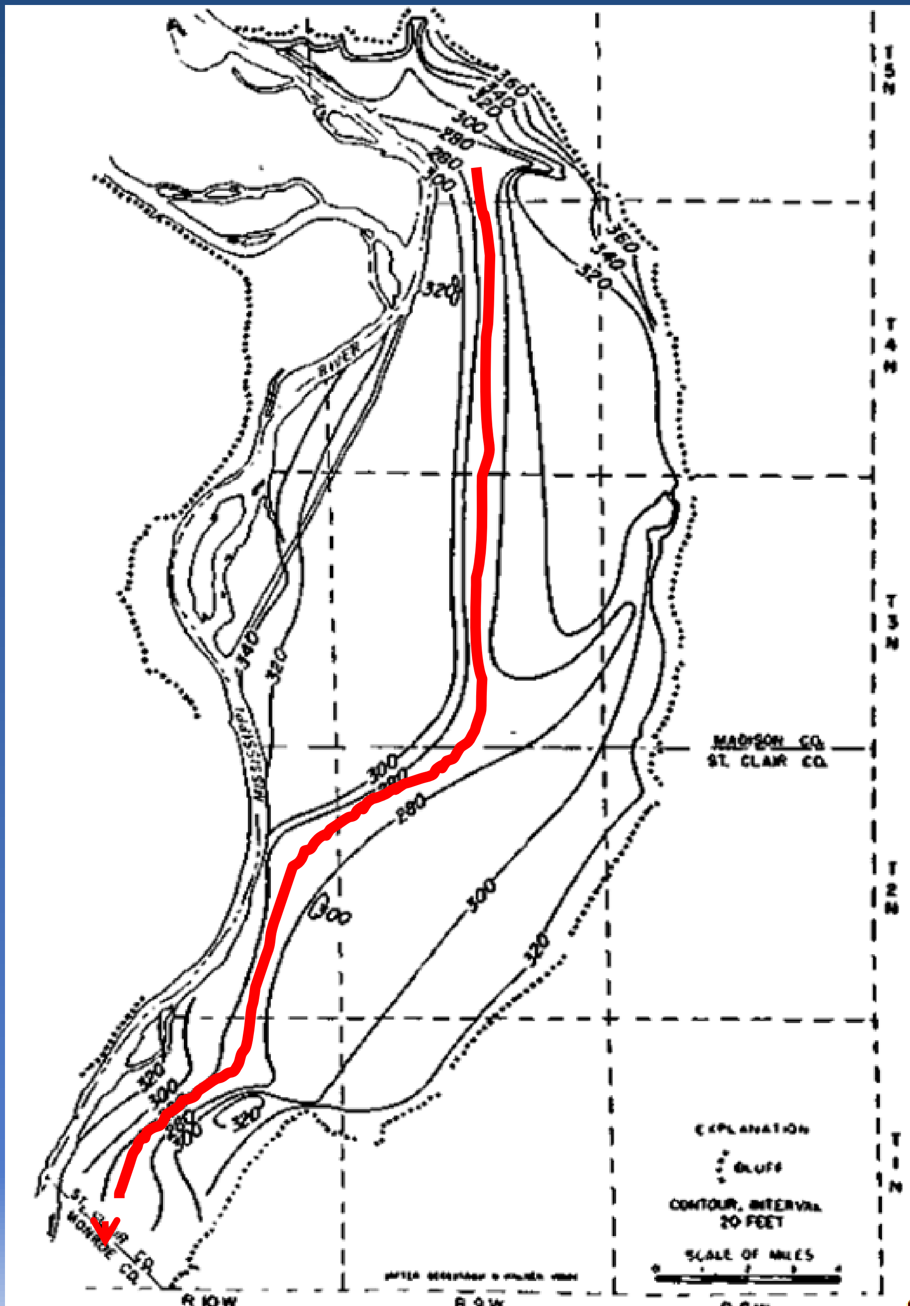
Located in southwest Illinois

Western boundary - Mississippi River

Eastern boundary - Bluff consisting of glacial deposits overlying bedrock

Width: 2 – 9 miles

Length: ~ 30 miles north-south



American Bottoms

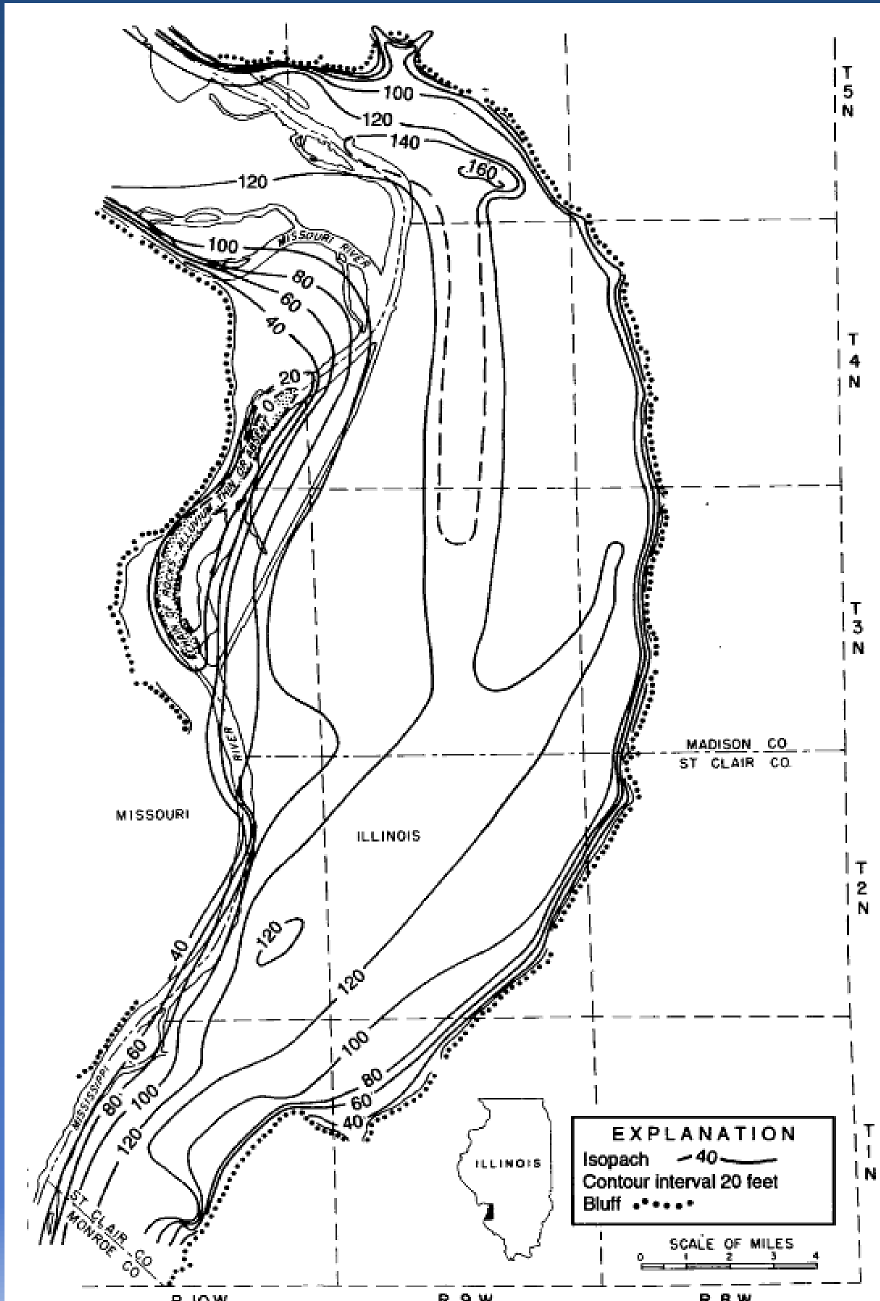
Bedrock surface topography

Elevation is 360' – 400' adjacent to the bluff

Slopes steeply just west of the bluff to elevation 320'

Slopes gently to incised channel at elevation 280' and lower

American Bottoms



(after Bergstrom & Walker, 1956)

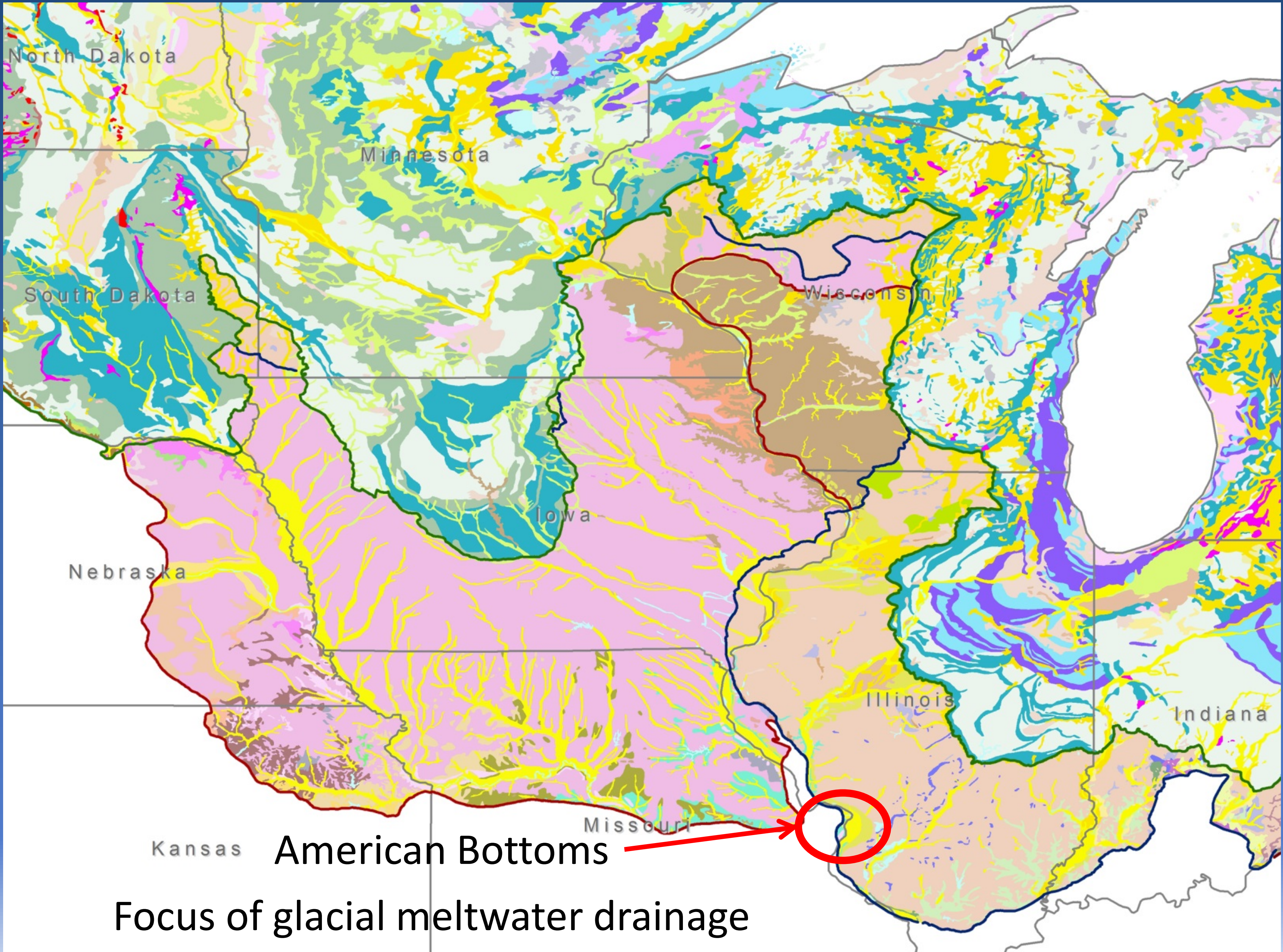
Thickness of valley-fill sediments underlying the floodplain

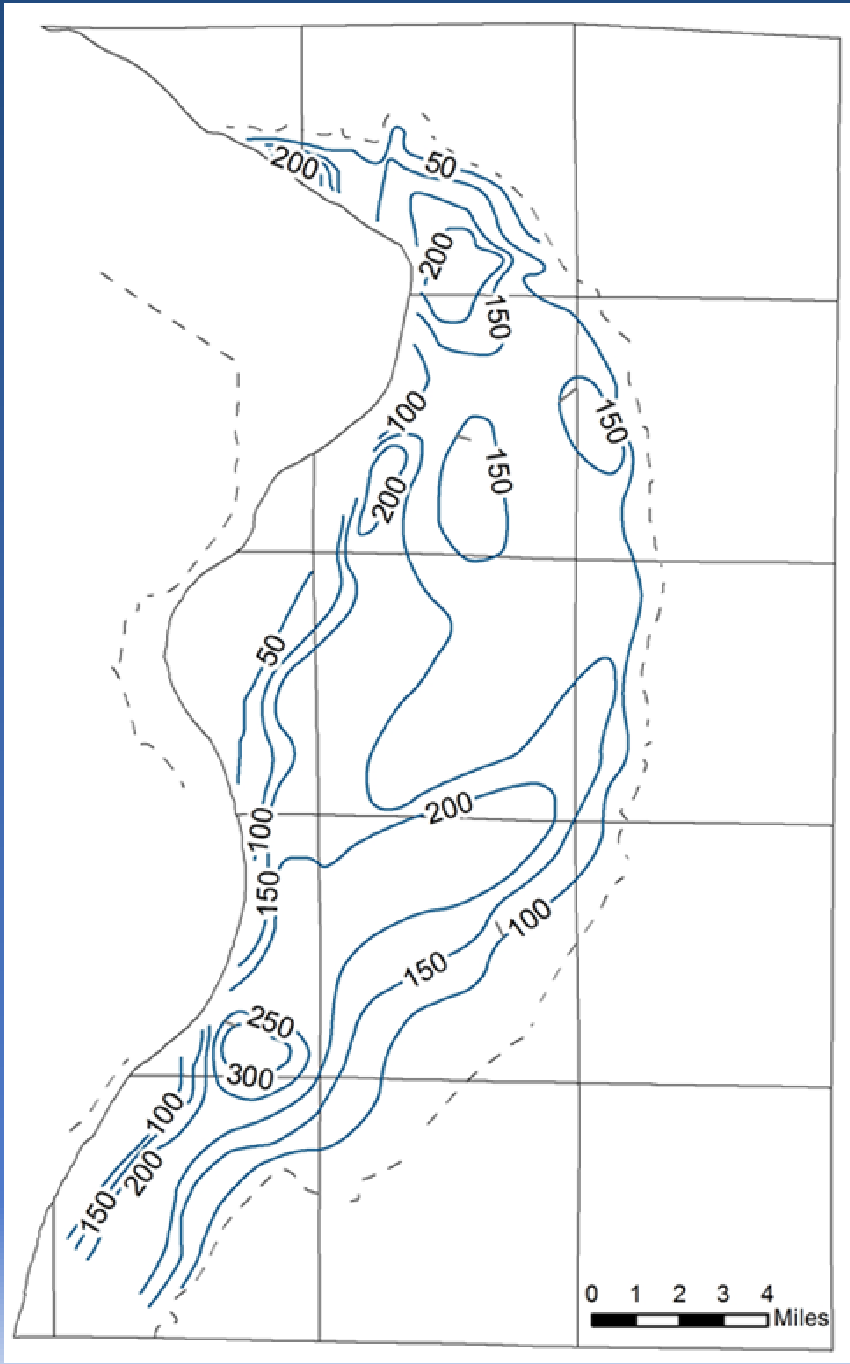
Less than 20' near the bedrock valley wall

Maximum reported thickness is 171' in north part

Thickness typically 100' to 120' over much of the area

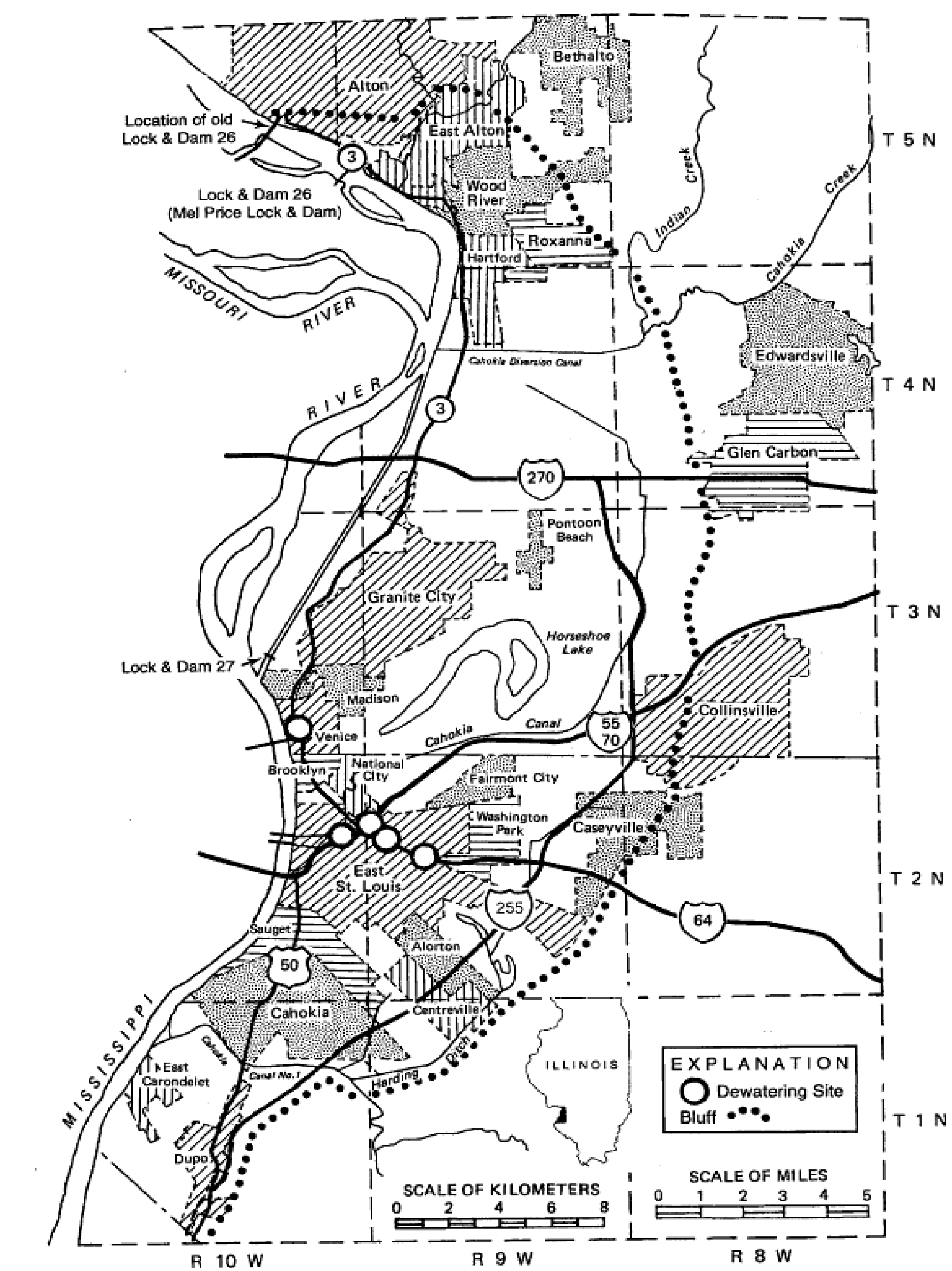
Saturated thickness varies with the potentiometric surface; ranges from about 40' just west of the bluff to somewhat more than 100' elsewhere


North Dakota
Minnesota
South Dakota
Wisconsin
Iowa
Nebraska
Illinois
Indiana
Missouri
Kansas
American Bottoms
Focus of glacial meltwater drainage



American Bottoms

Transmissivity varies from 50,000 gpd/ft near the bluff to 300,000 gpd/ft near the south end



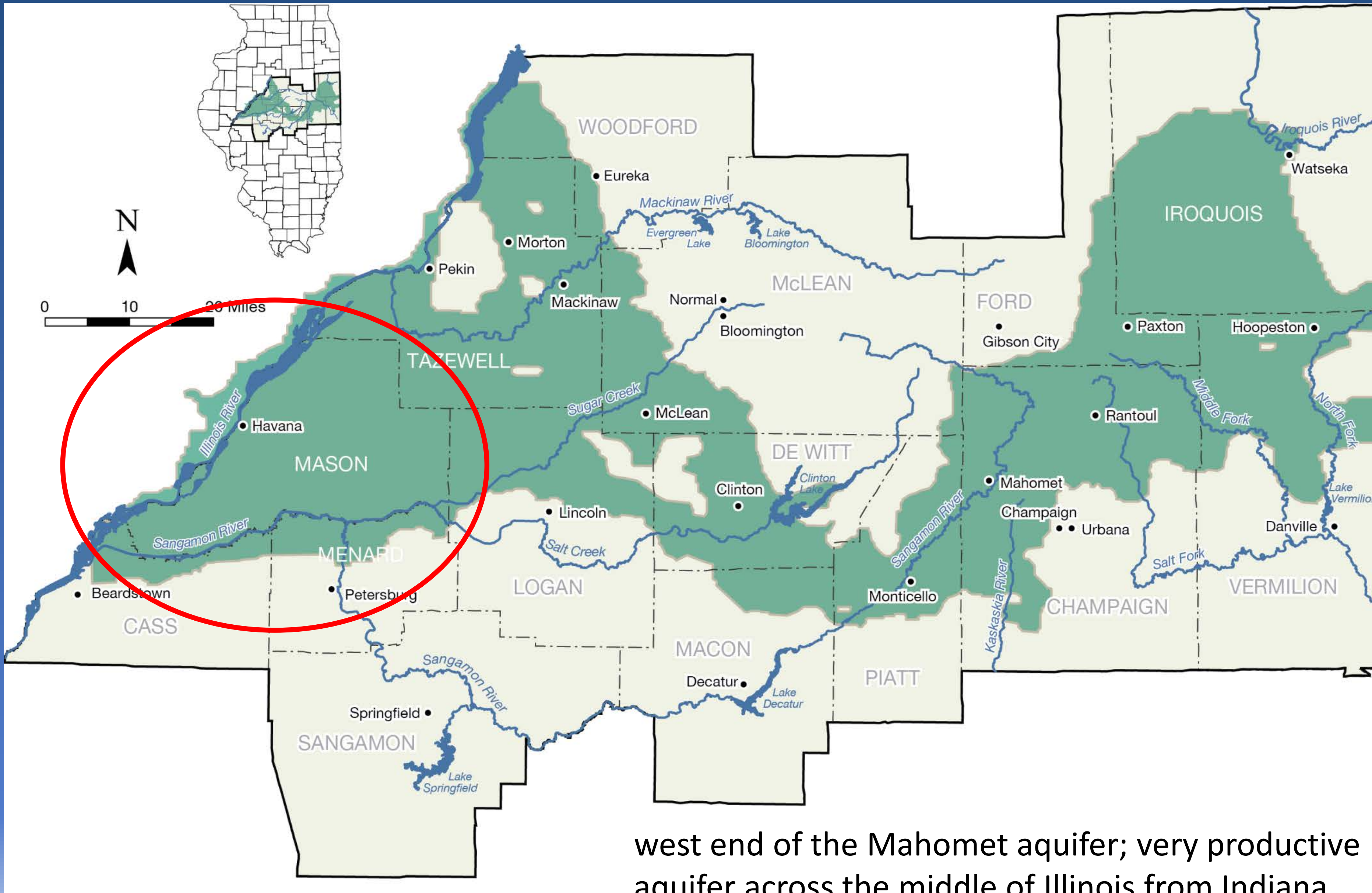
American Bottoms

Groundwater use began in the late 1890s and peaked at 111 mgd in 1956

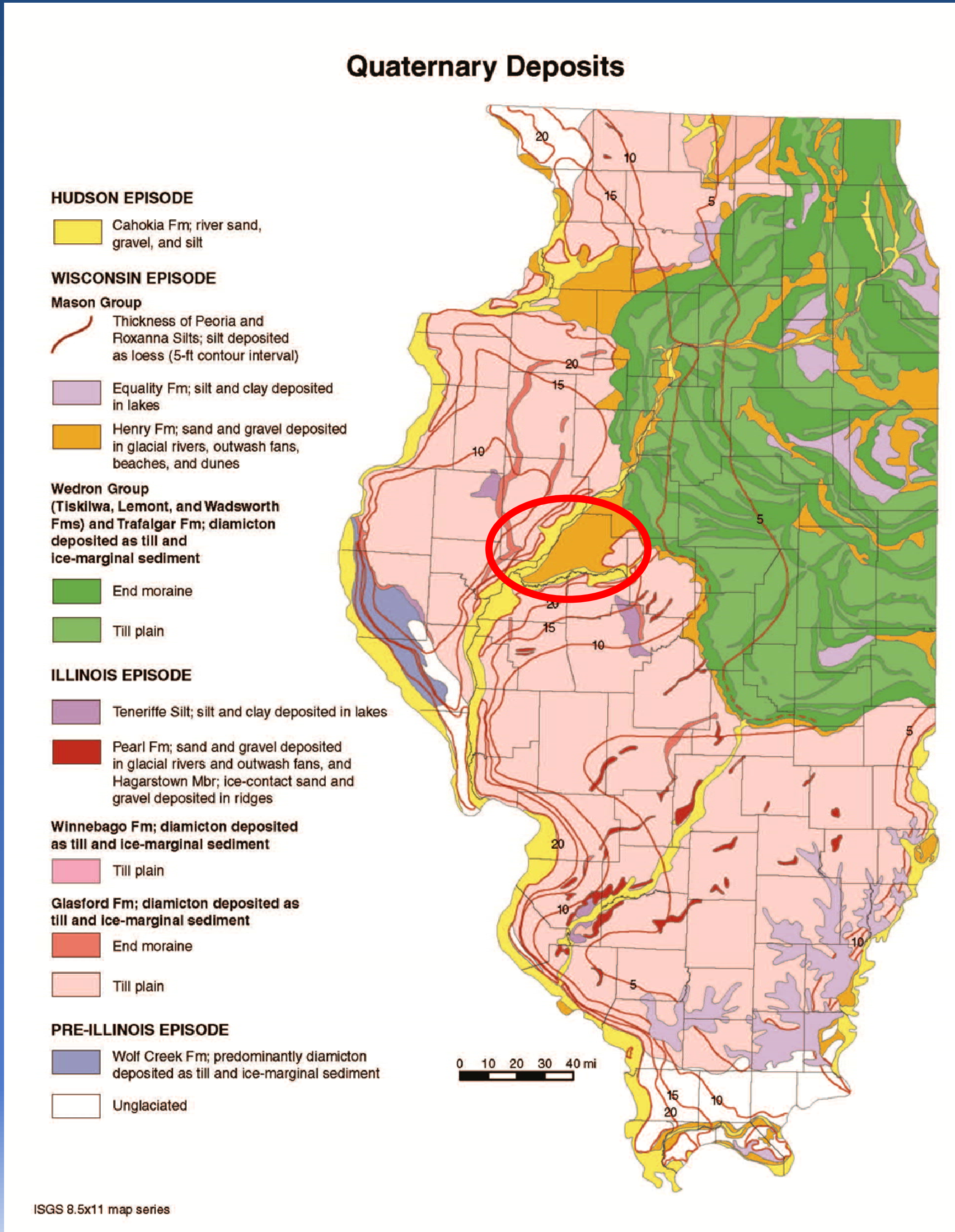
Three-quarters of the groundwater pumped was for industrial users; about 20% was for public supply

Reduction in pumping caused the potentiometric surface to rise, requiring the use of dewatering wells, such as those used by IDOT to prevent flooding of some highways; ~15 mgd

Mason County



west end of the Mahomet aquifer; very productive aquifer across the middle of Illinois from Indiana to the Illinois River

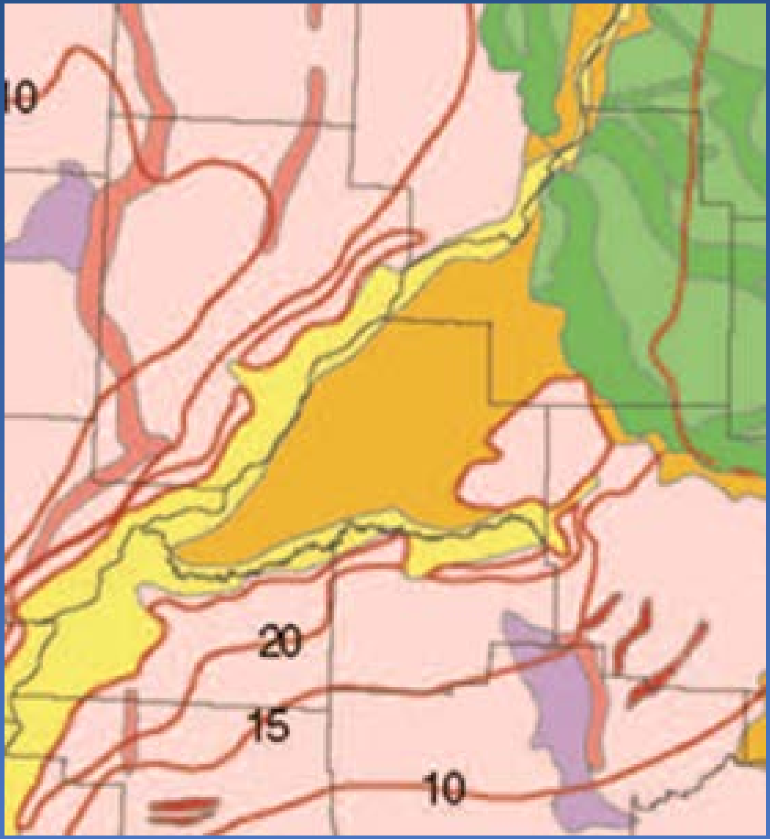


Mason County

Orange and yellow represents sand and gravel

Pink represents till, clay, silt, and some sand and gravel

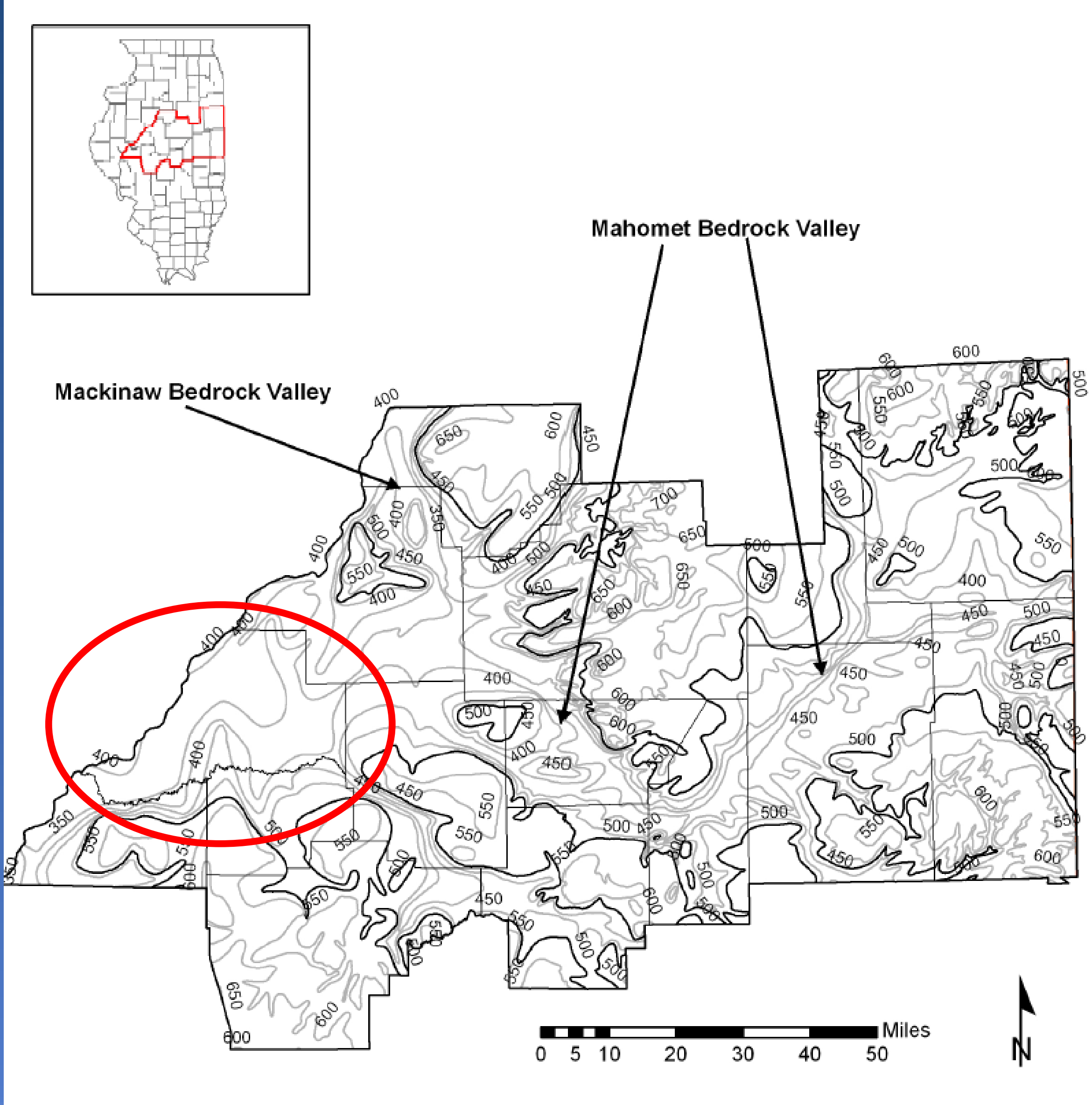
Mason County



All but the southeastern part of Mason County is a sand plain with a rolling landscape - called the Havana Lowland

Mostly sand and gravel underlies the Havana Lowland from land surface to bedrock

Southeast Mason County is an upland consisting mostly of till with sand and gravel deposited during the Illinois Episode of glaciation 125,000 to 180,000 years ago



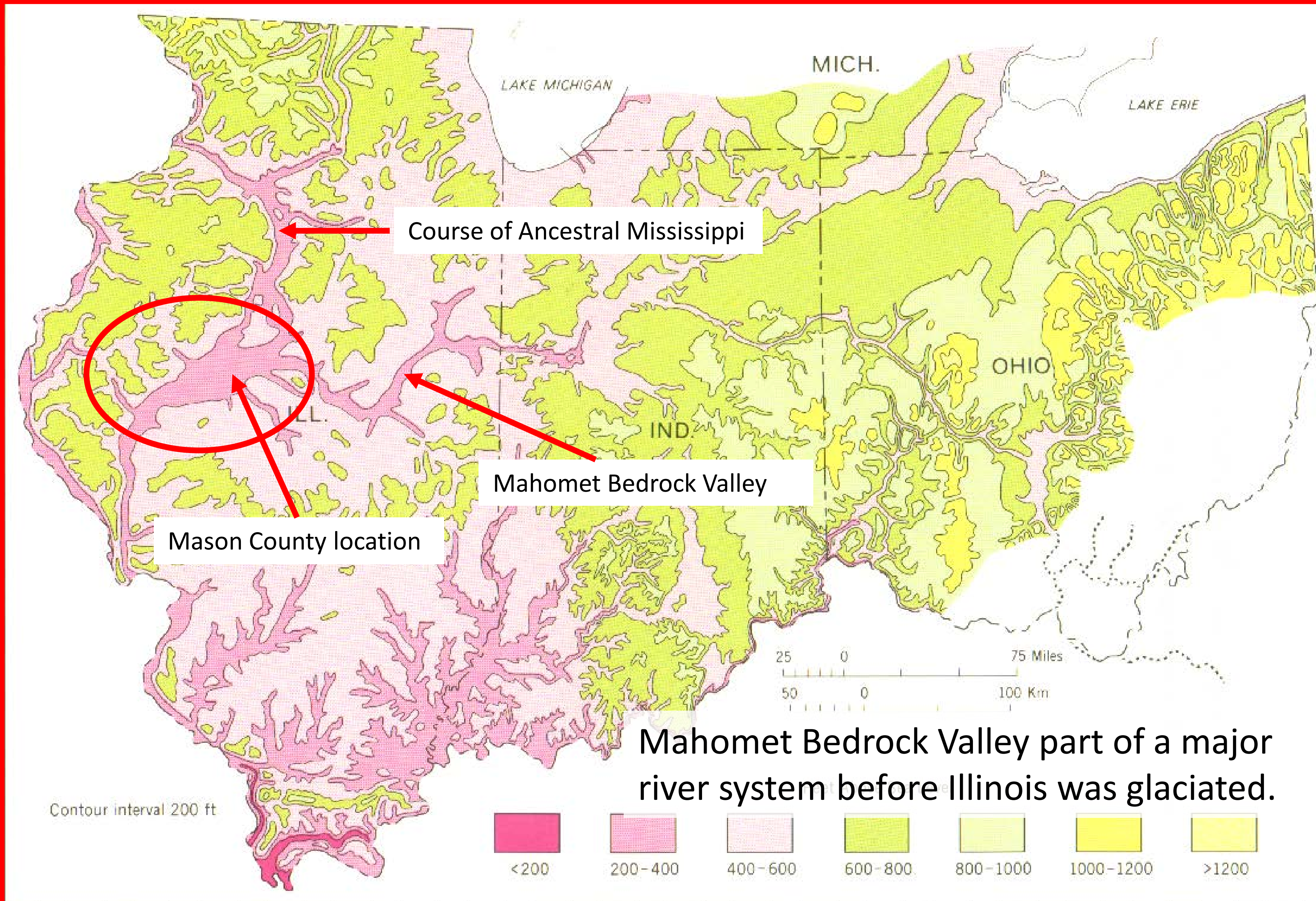
Mason County

Mackinaw Bedrock Valley is the main feature of the bed-rock surface in Mason County

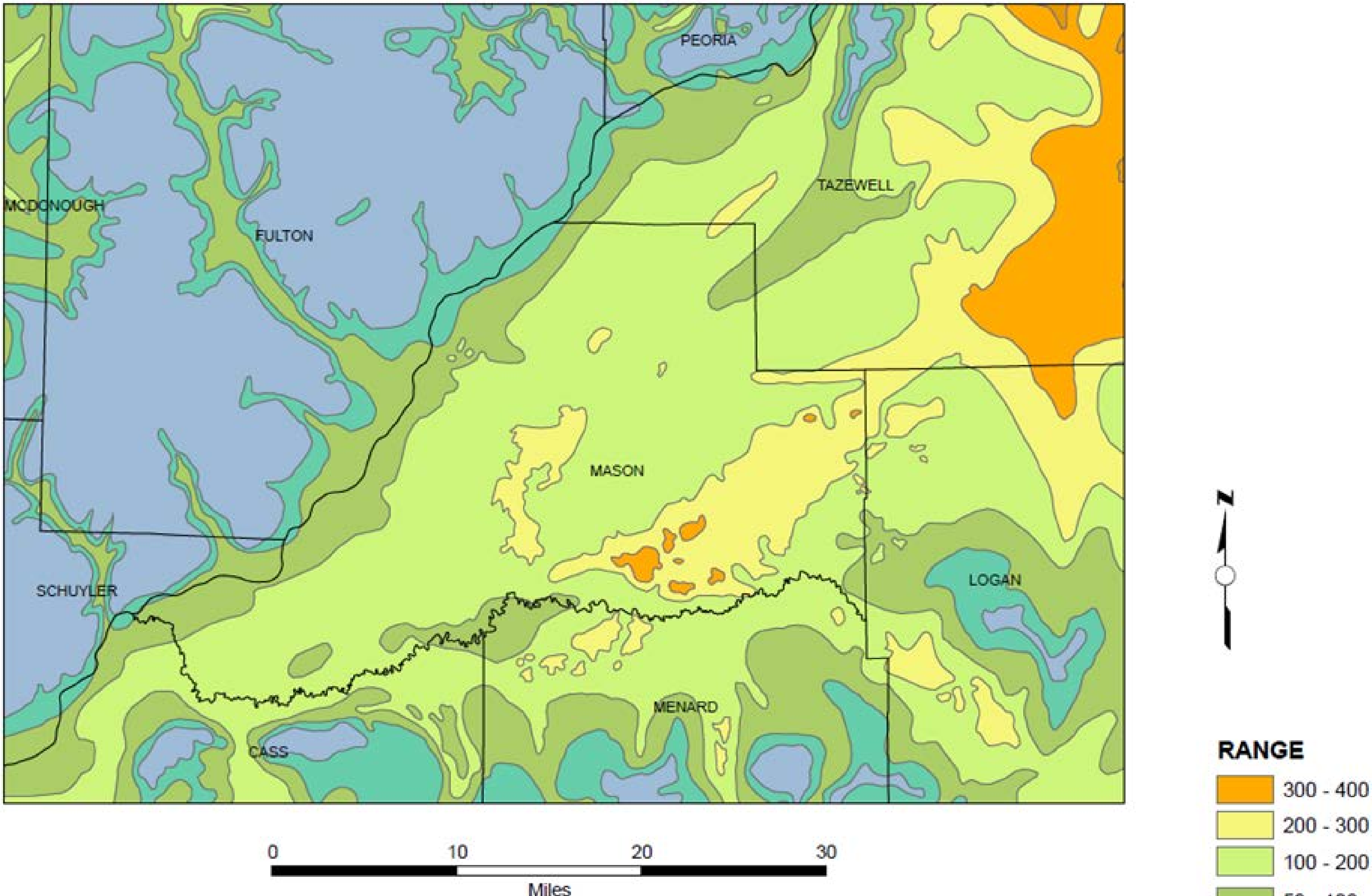
Downstream from confluence with the Mahomet Bedrock Valley

Bedrock valleys formed as preglacial river systems

Midwest Bedrock Surface Topography

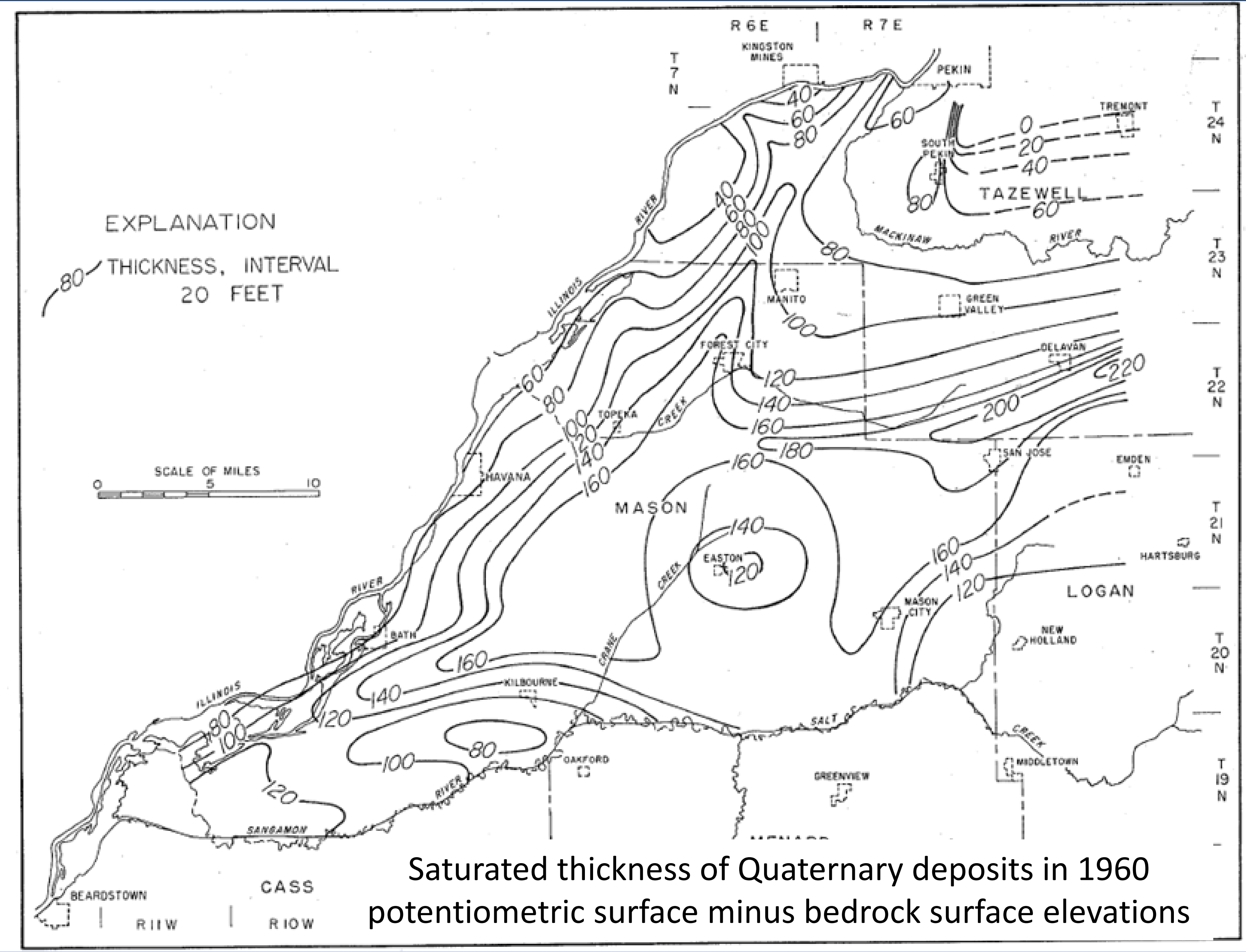


Mason County



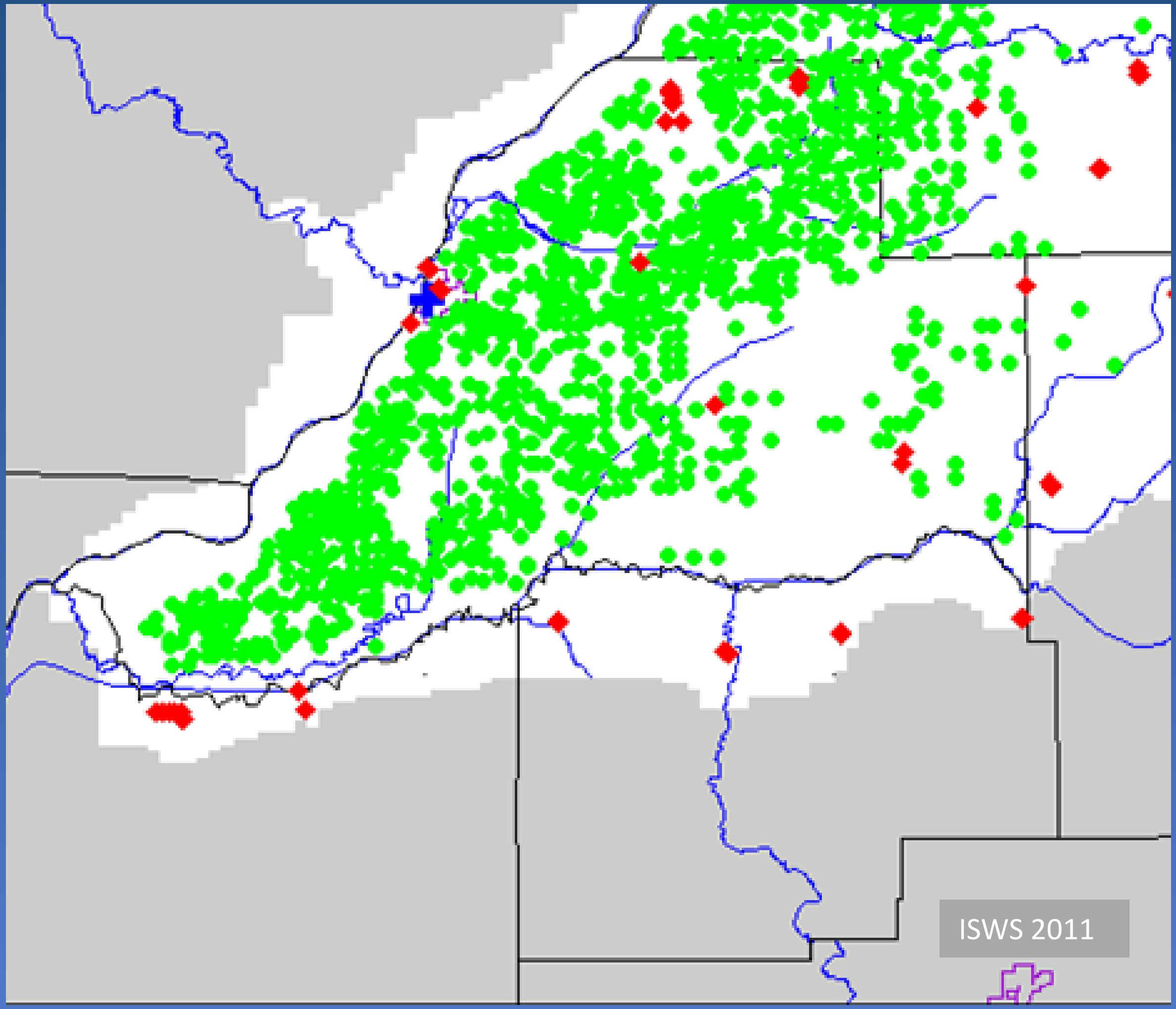
Thickness of Quaternary deposits in feet
land surface minus bedrock surface elevations

Mason County



Saturated thickness of Quaternary deposits in 1960
potentiometric surface minus bedrock surface elevations

Mason County



Number and distribution of high-capacity wells in Mason County indicative of the productivity of the Mahomet aquifer.

● High-capacity irrigation wells ◆ High-capacity municipal wells

Summary - Geothermal Opportunities

American Bottoms and Mason County underlain by very productive aquifers.

Wells and equipment for pumping groundwater represent much of the cost associated with developing open-loop geothermal systems. Many wells, including unused and abandoned wells, exist in both areas - a potential to reduce development costs: minimize piping, power consumption, and water-temperature loss.

Illinois Groundwater Source Geothermal Resource

Part 2: Heating and Cooling Potentials

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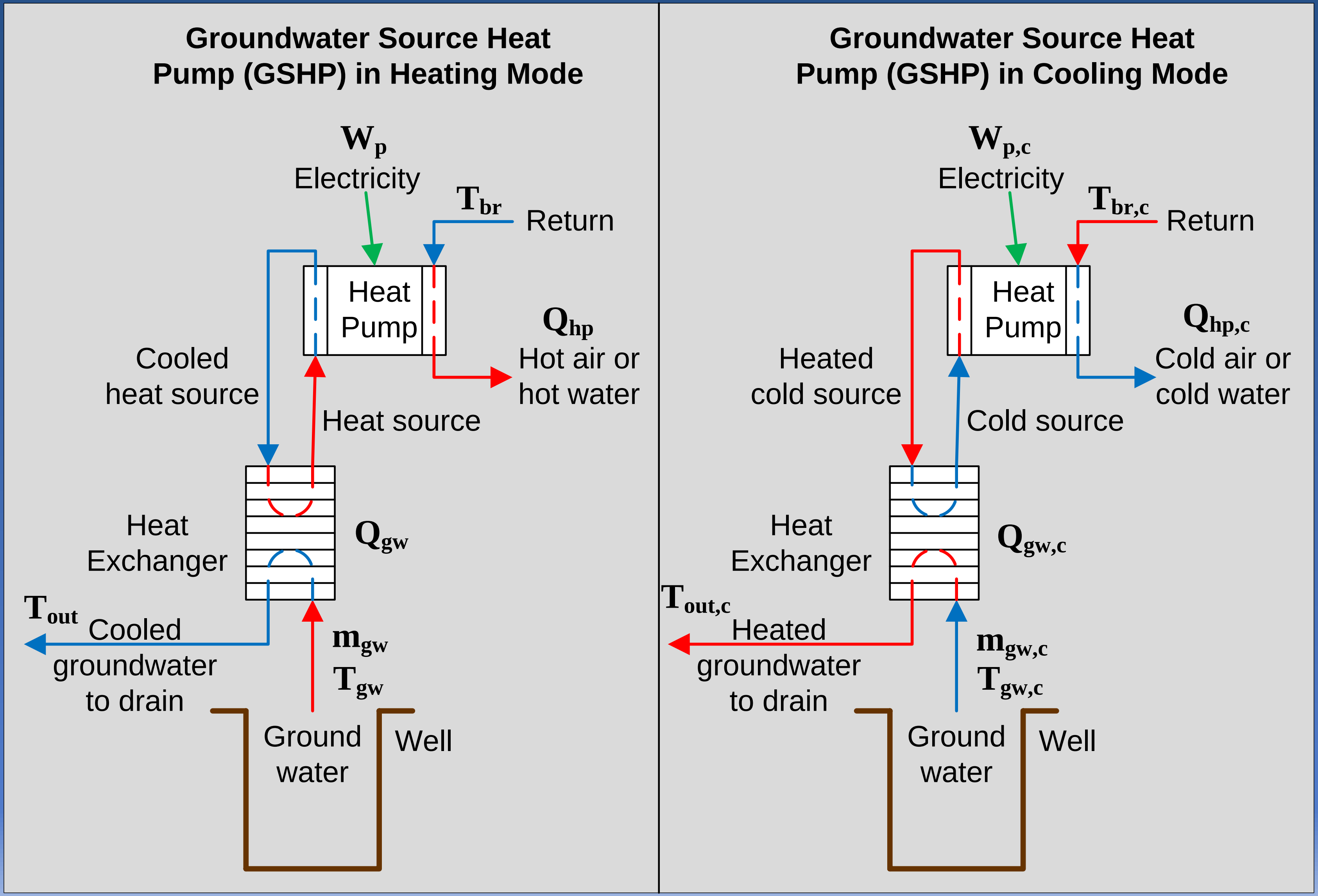
Heating and Cooling Potentials – with application of GSHPs

- ❑ Groundwater Source Heat Pump (GSHP) Model
- ❑ Weather Data of the Two Studied Areas
- ❑ Heating and Cooling Requirements of Typical Single Family Houses
- ❑ Estimate of Heating and Cooling Potentials of the Studied Areas

GSHP Model



Groundwater Source Heat Pump (GSHP) in Heating Mode
W_p
Electricity
T_{br}
Return
Heat Pump
Q_{hp}
Hot air or hot water
Cooled heat source
Heat source
Heat Exchanger
Q_{gw}
T_{out}
Cooled groundwater to drain
m_{gw}
T_{gw}
Ground water
Well
Groundwater Source Heat Pump (GSHP) in Cooling Mode
$W_{p,c}$
Electricity
$T_{br,c}$
Return
Heat Pump
$Q_{hp,c}$
Cold air or cold water
Heated cold source
Cold source
Heat Exchanger
$Q_{gw,c}$
$T_{out,c}$
Heated groundwater to drain
$m_{gw,c}$
$T_{gw,c}$
Ground water
Well

Energy Balance of Heating Mode

$$Q_{gw} = m_{gw} C_p \Delta T$$

$$\Delta T = T_{gw} - T_{out}$$

$$COP = \frac{Q_{hp}}{W_p}$$

$$Q_{hp} = Q_{gw} + W_p$$

$$Q_{hp} = \left(\frac{COP}{COP - 1} \right) Q_{gw}$$

Energy Balance of Cooling Mode

$$Q_{gw,c} = m_{gw,c} C_p \Delta T_c$$

$$\Delta T_c = T_{out,c} - T_{gw,c}$$

$$COP_c = \frac{Q_{hp,c}}{W_{p,c}}$$

$$Q_{hp,c} = Q_{gw,c} - W_{p,c}$$

$$Q_{hp,c} = \left(\frac{COP_c}{COP_c + 1} \right) Q_{gw,c}$$

Coefficient of Performance (COP)

- **Heating mode**

$$COP = \frac{Q_{hp}}{W_p} = \frac{\text{heating capacity}}{\text{electric power input}}$$

- **Cooling mode**

$$COP_c = \frac{Q_{hp,c}}{W_{p,c}} = \frac{\text{cooling capacity}}{\text{electric power input}}$$

Range of COP

- **Open-system GSHP heating mode**

  $COP = 3.0$ to 4.0

- **Open-system GSHP cooling mode**

  $COP_c = 3.5$ to 6.7

  $EER = 11.0$ to 23.0

EER - Energy Efficient Ratio, Btu/(hr-W)

(Ref: Natural Resources Canada: Buyer's Guide for the Commercial Earth Energy Systems, 2002)

Groundwater Supply and Return Temperatures

- Supply temperature (heating & cooling)

  $T_{gw} = T_{gw,c} = 15$ °C

- Return temperature
  - Heating mode: T_{gw} - 5 °C = 10 °C
  - Cooling mode:

    24 °C (bldg. return temp.) + 2 °C (heat exchanger approach) = 26 °C

Weather data of Mason County (at station of Mason City, IL)

Element	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Max °F	33.1	39.2	52.0	65.1	75.6	84.3	87.4	85.3	79.5	67.3	51.0	37.6	63.1
Min °F	15.7	20.6	30.5	40.5	51.3	60.4	64.1	62.2	54.5	43.5	32.4	21.3	41.4
Mean °F	24.4	29.9	41.3	52.8	63.5	72.4	75.8	73.8	67.0	55.4	41.7	29.5	52.3
HDD base 65	1259	983	736	375	150	11	0	10	59	312	698	1102	5695
CDD base 65	0	0	0	8	101	232	333	281	118	15	0	0	1088

(Source: ISWS website (1971-2000 NCDC Normals) http://mrcc.isws.illinois.edu/climate_midwest/historical/temp/il/115413_tsum.html)

Weather data of American Bottoms (at station of St. Clair County, IL)

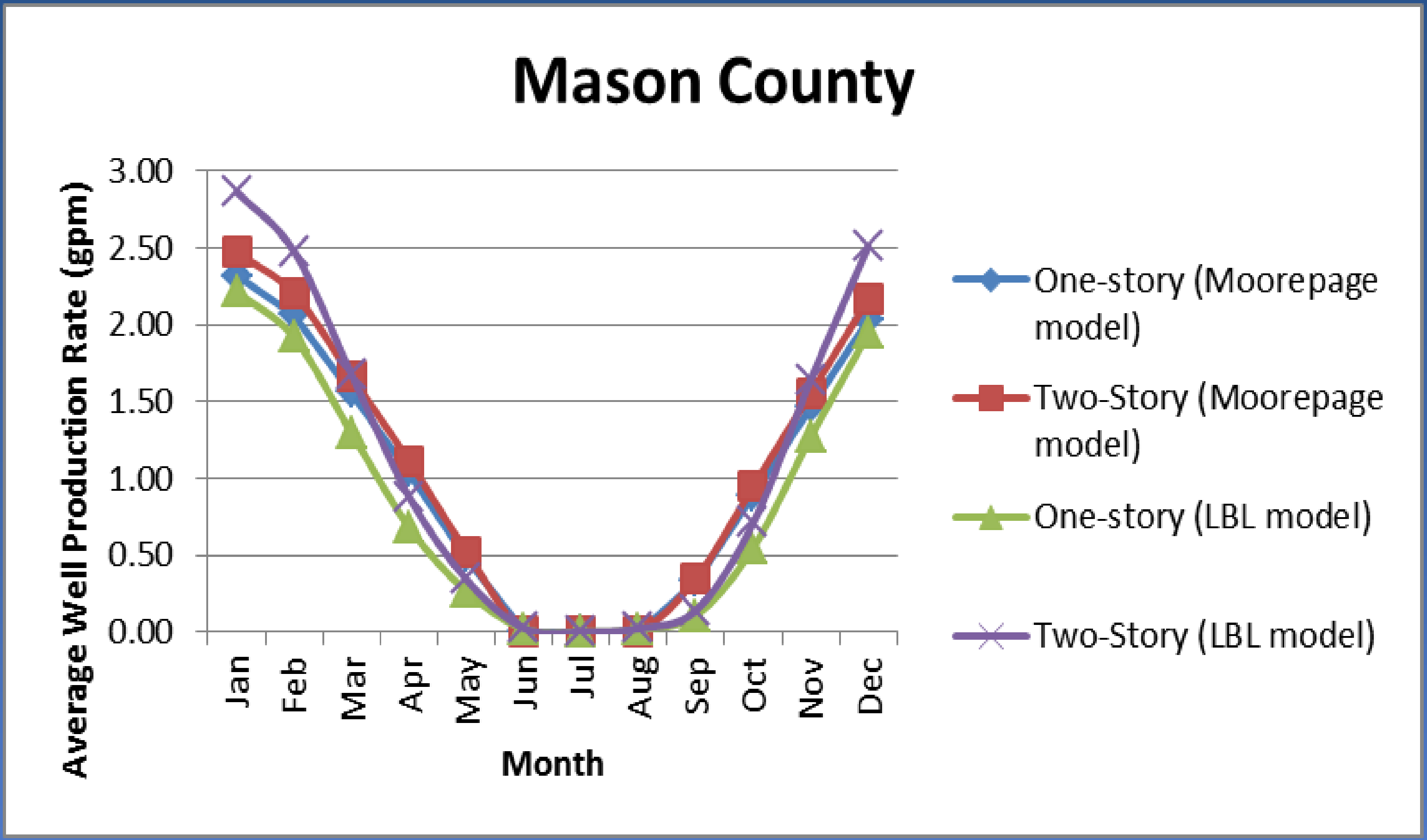
Element	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Max °F	38.1	44.5	55.4	66.7	75.7	84.2	88.7	86.8	79.7	69.1	54.6	42.6	65.5
Min °F	20.0	24.2	35.1	45.5	55.1	64.0	68.4	66.4	58.2	46.6	35.5	25.8	45.4
Mean °F	29.1	34.4	45.3	56.1	65.4	74.1	78.6	76.6	69.0	57.9	45.1	34.2	55.5
HDD base 65	1114	859	613	281	105	6	0	2	43	248	599	956	4826
CDD base 65	0	0	0	14	116	278	421	362	161	26	0	0	1378

(Source: ISWS website (1971-2000 NCDC Normals) http://mrcc.isws.illinois.edu/climate_midwest/historical/temp/il/111160_tsum.html)

Heating Requirements of Typical Single Family Houses

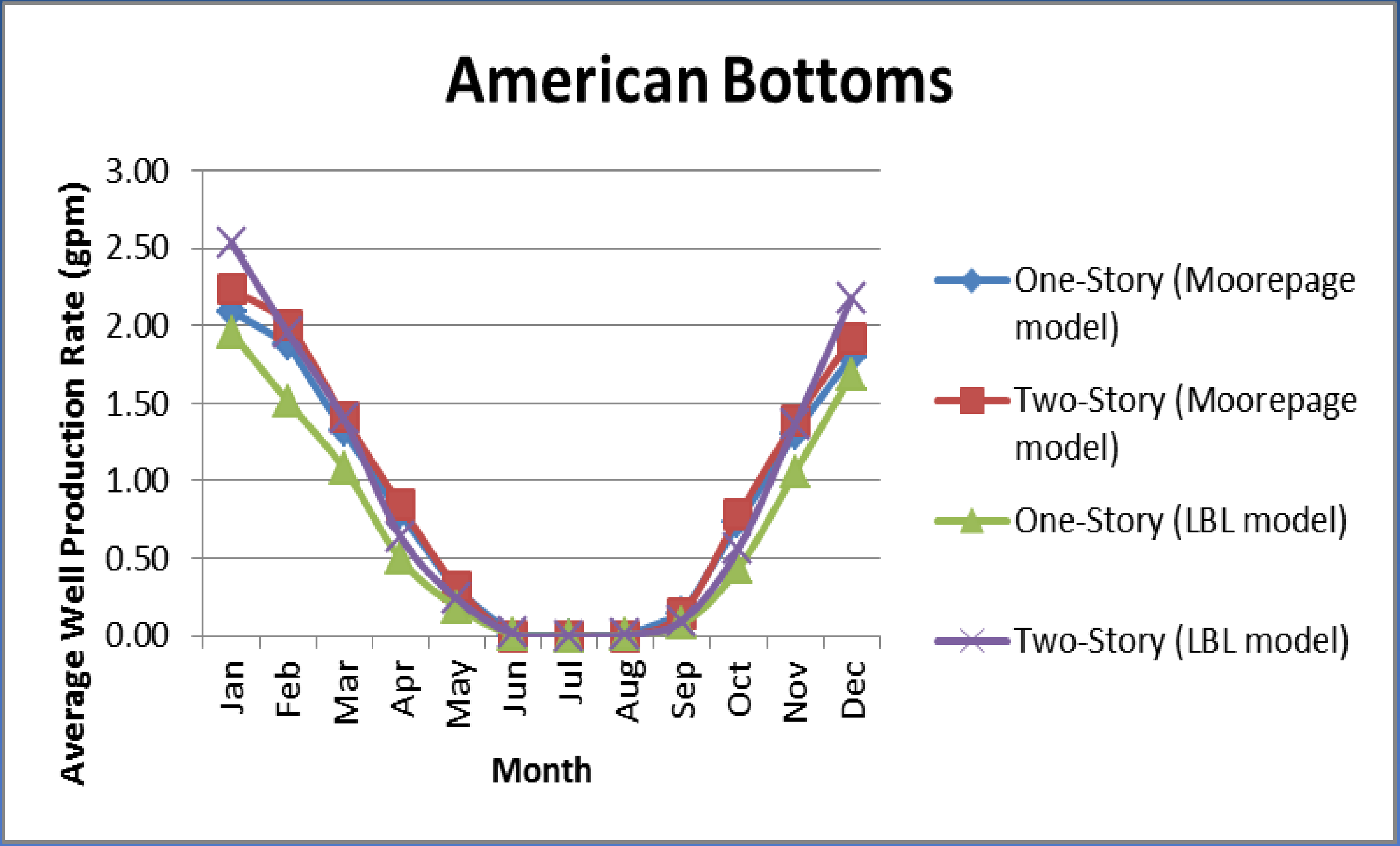
- LBL model: Lawrence Berkeley Laboratory Report (Huang et al., 1986)
- Moorepage Model: a calculator at Moorepage.net (2012)
- In both models:
  - Heating Load (HL) of the bldg. per month is calculated first;
  - monthly averaged mass flowrate (m_{gw}) of the groundwater is determined

Comparison between the Two Models



(Good agreement between the two models)

Comparison between the Two Models



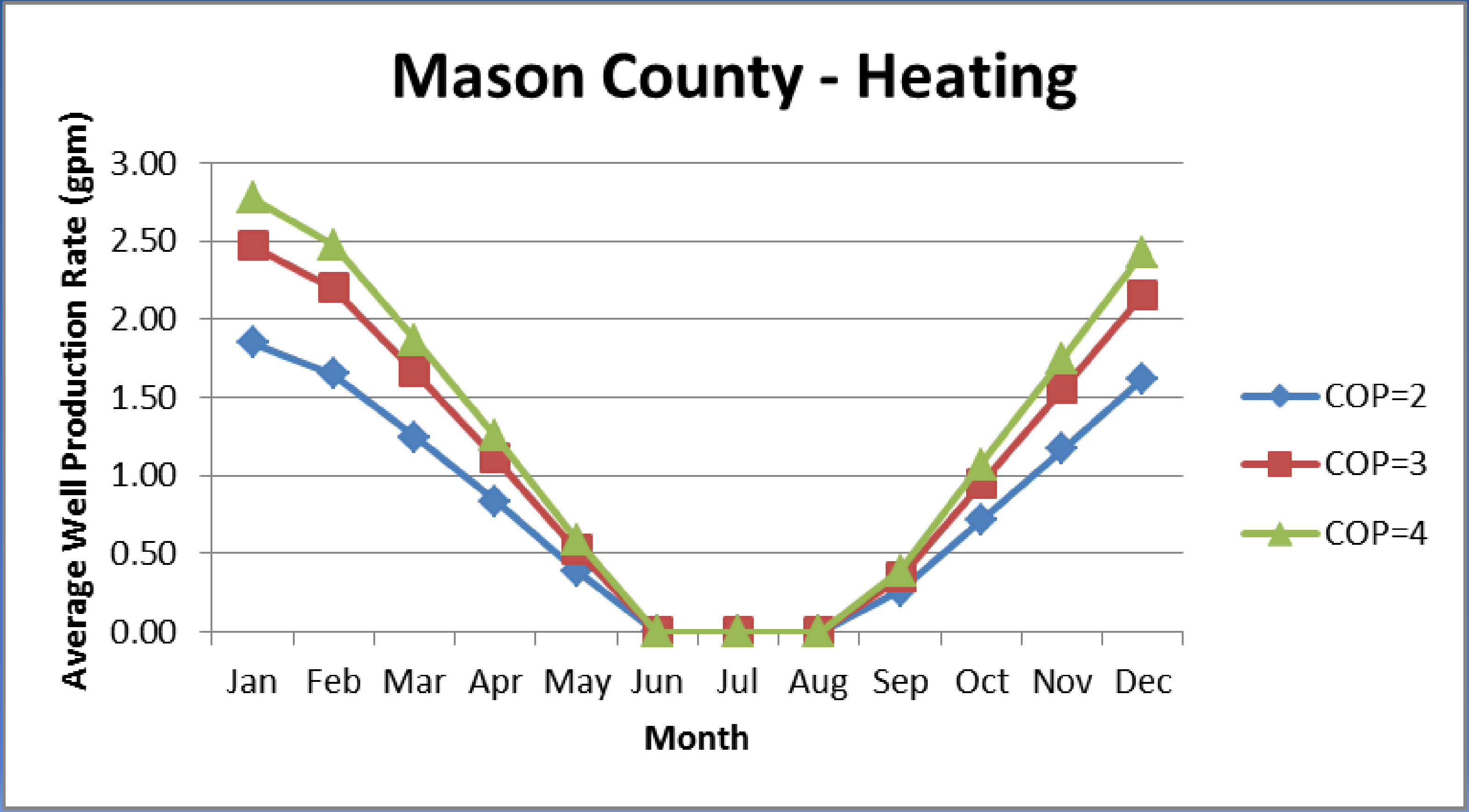
(Good agreement between the two models)

Sensitivity Study on Heating and Cooling Requirements

Estimated the monthly average well production rate (gpm) required for each house:

- Based on the weather data
- Choosing COP values within the typical ranges of commercial heat pump systems
  - In heating mode: COP = 2, 3, 4
  - In cooling mode: COP_c = 3, 5, 7

Sensitivity Analysis
(two-story single family bldg.)



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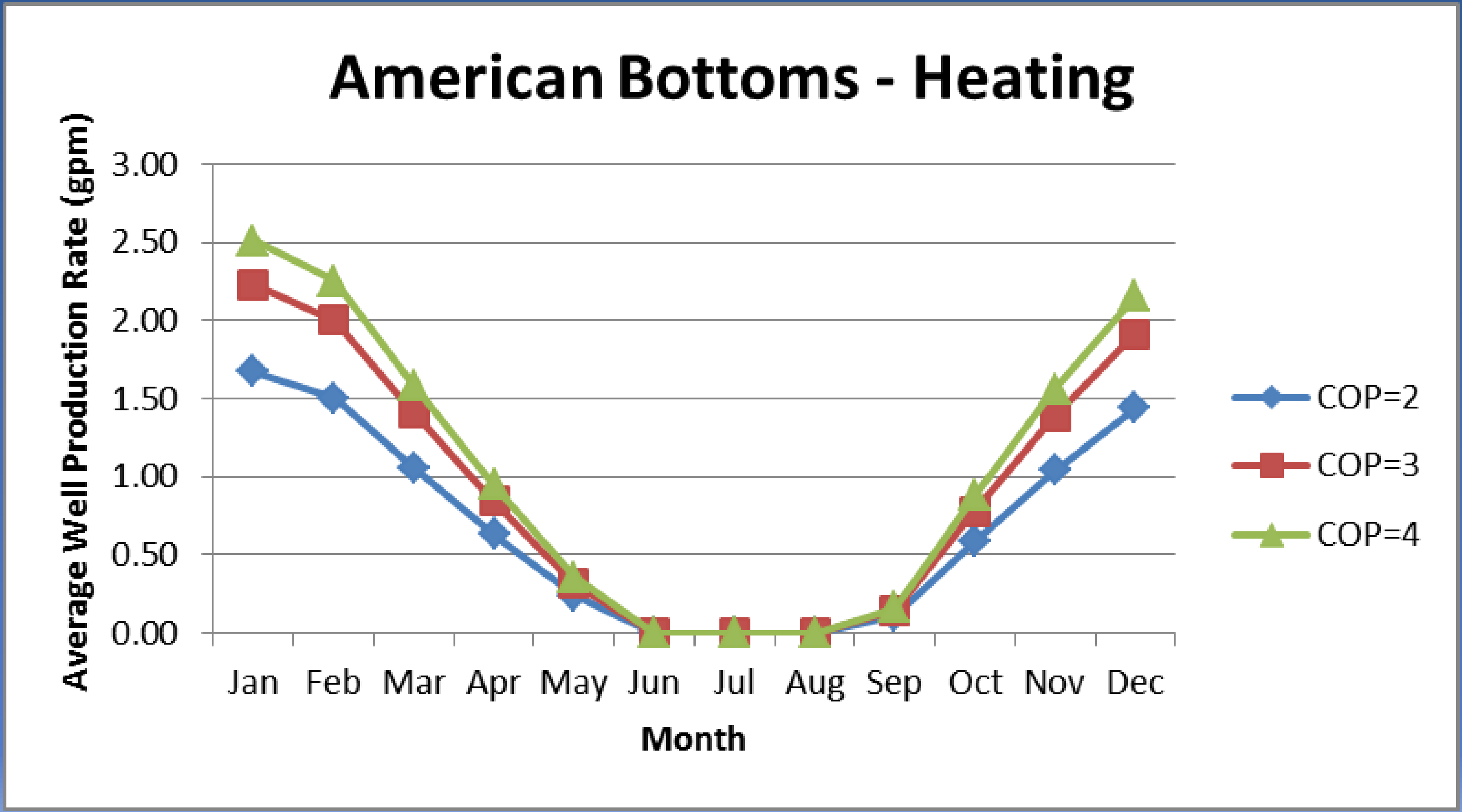
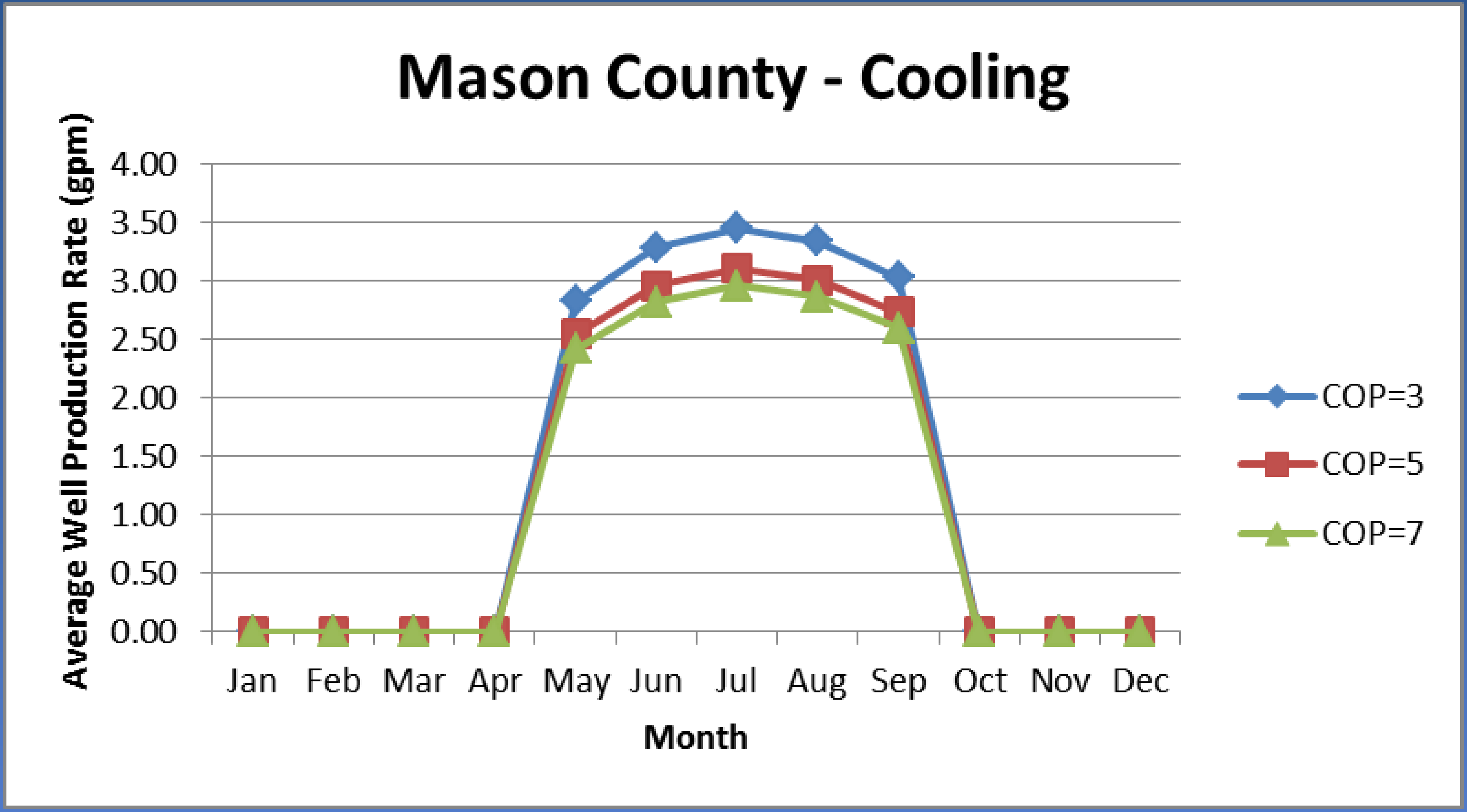
(two-story single family bldg.)

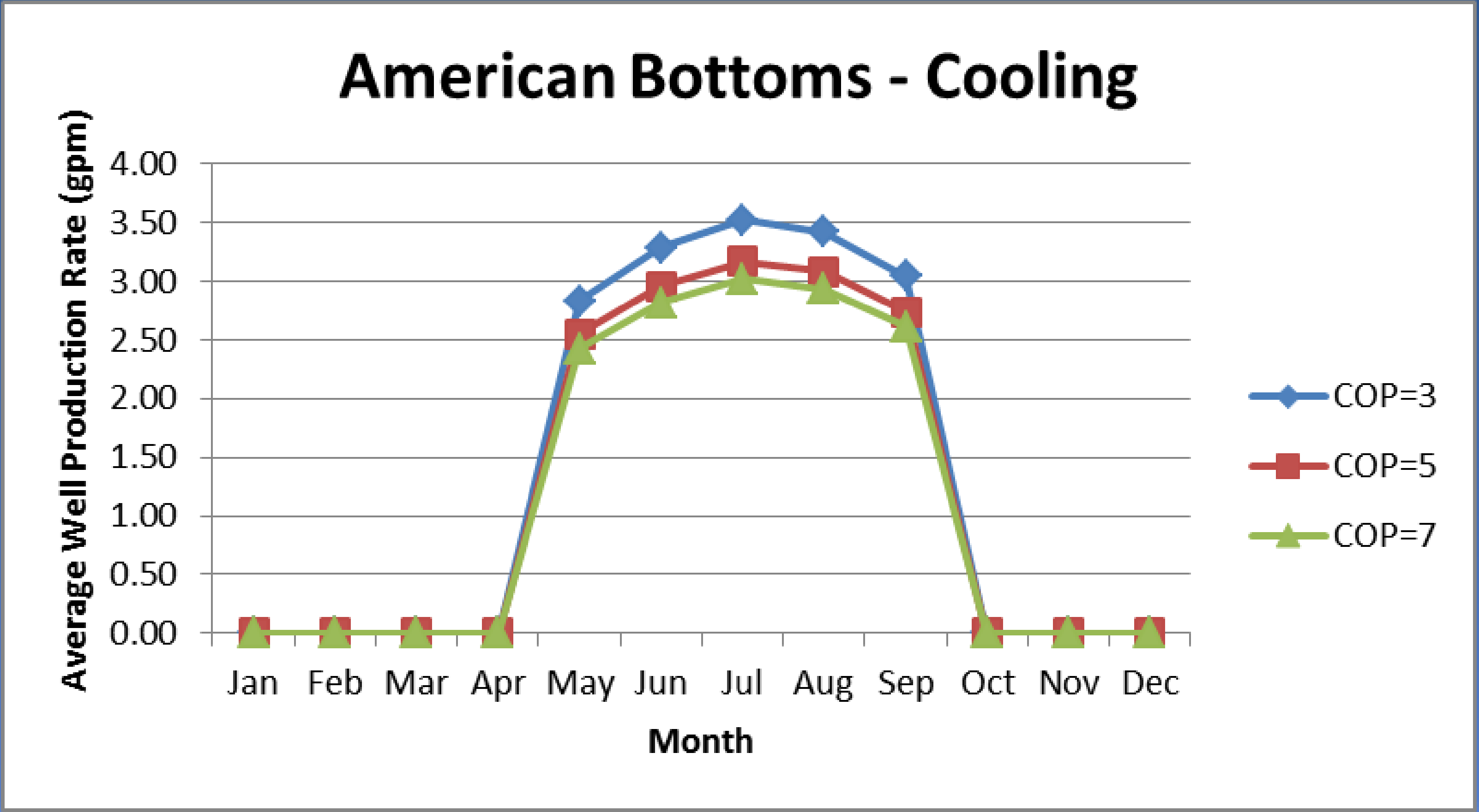


Sensitivity Analysis (two-story single family bldg.)



Highest monthly average well production rate/house = 3.45 gpm

Sensitivity Analysis (two-story single family bldg.)



Highest monthly average well production rate/house = 3.52 gpm

Estimate of the Heating and Cooling Potentials of the Studied Areas

Two studied areas

- Mason County area:
  - Mason County and four townships in adjoining Tazewell County
- American Bottoms area:
  - the entire floodplain area of Madison & St. Clair Counties

Estimate of the Heating and Cooling Potentials of the Studied Areas

- choosing the highest monthly pumping rate/house = 3.5 gpm;
- using the documented pumping rates at each area
- estimated the total number of the houses using GSHP in each studied area

Estimated Numbers of the Houses that Can be Supplied by GSHP

Studied Area	Subtotal Pumping	Numbers of the houses
	Rates (gpm)	that the GSHP can supply
1. American Bottoms*		
- Madison County	20,189	5,736
- St. Clair County	4,222	1,199
Total:	24,411	6,935
2. Mason County**		
Total:	88,889	25,765

* Schicht (1965)

** Roadcap et al. (2011)

*** area of the two-story house: 2240 sq. ft.

Groundwater Heating and Cooling Potentials

Areas	Annual Potentials	Units	
		(Btu/year)	(kJ/year)
Mason County	heating =	1.22E+12	1.29E+12
	cooling =	2.39E+12	2.52E+12
	heating & cooling =	3.61E+12	3.81E+12
American Bottoms	heating =	2.79E+11	2.94E+11
	cooling =	6.51E+11	6.87E+11
	heating & cooling =	9.30E+11	9.81E+11
	Total =	4.54E+12	4.79E+12

Total Heating and Cooling Potentials
4.79×10^{12} kJ = 1.33×10^{9} kWh

UIUC Abbott Power Plant
(Nameplate Capacity: 47.0 MW)

3 times the electricity generated assuming all turbines at the power plant were to run continuously for one year

OR

- 57 times the electricity generated in 2005 (20,429 MW)

Groundwater has great heating and cooling potentials

- great resource for heat pump applications

Groundwater Quality and Groundwater Heat Pumps

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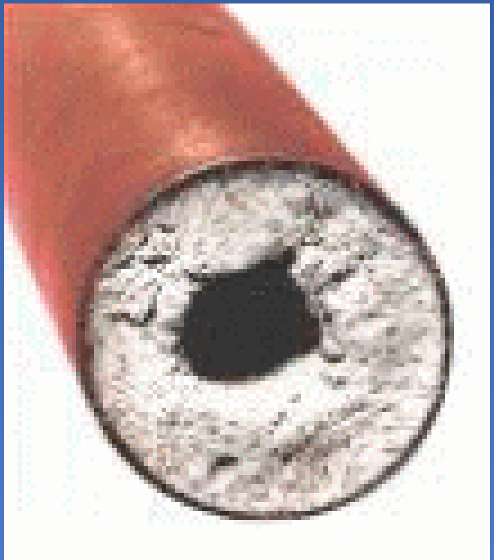
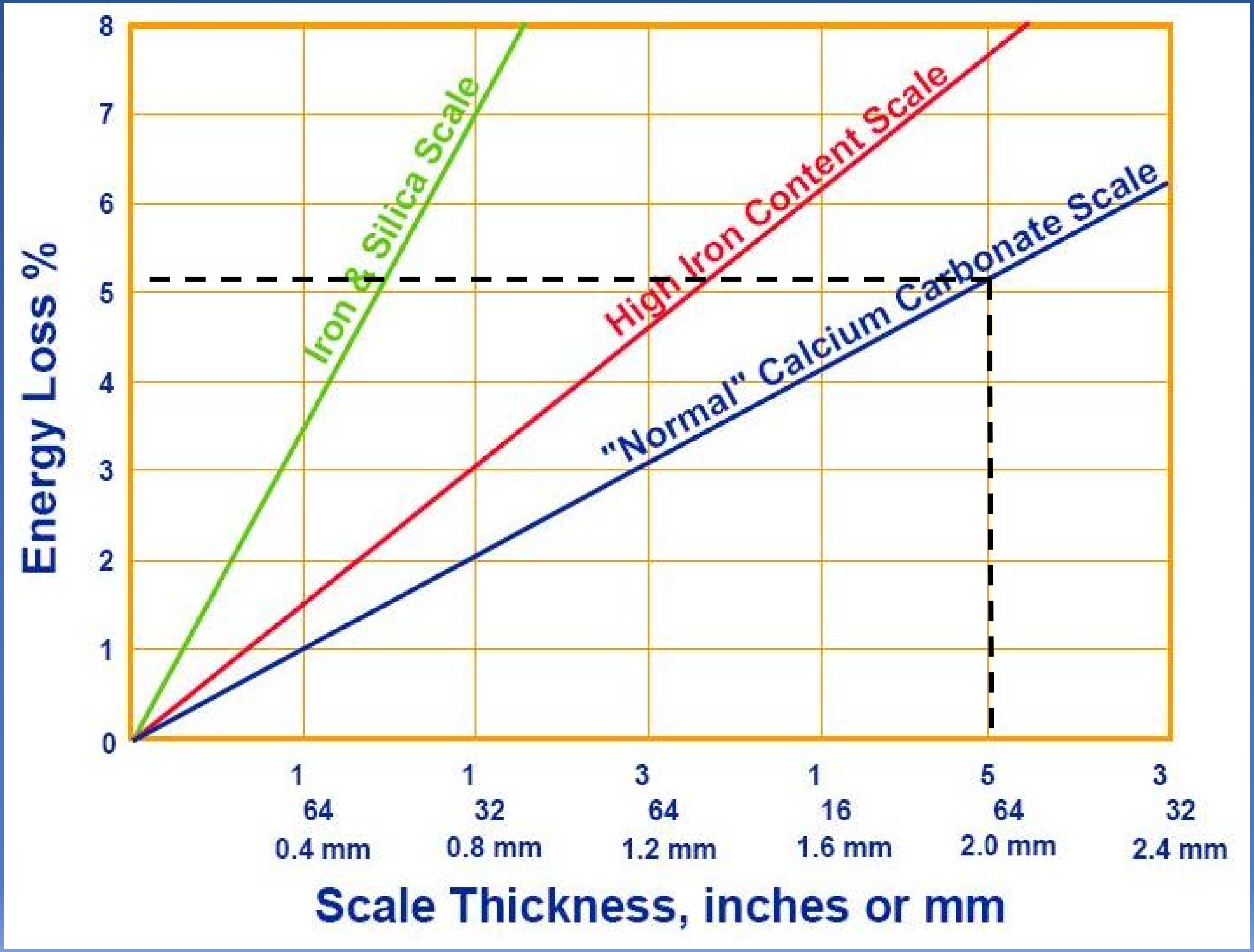
Groundwater quality may affect groundwater heat pumps through:

Fouling



Corrosion

Fouling and Heat Transfer Efficiency

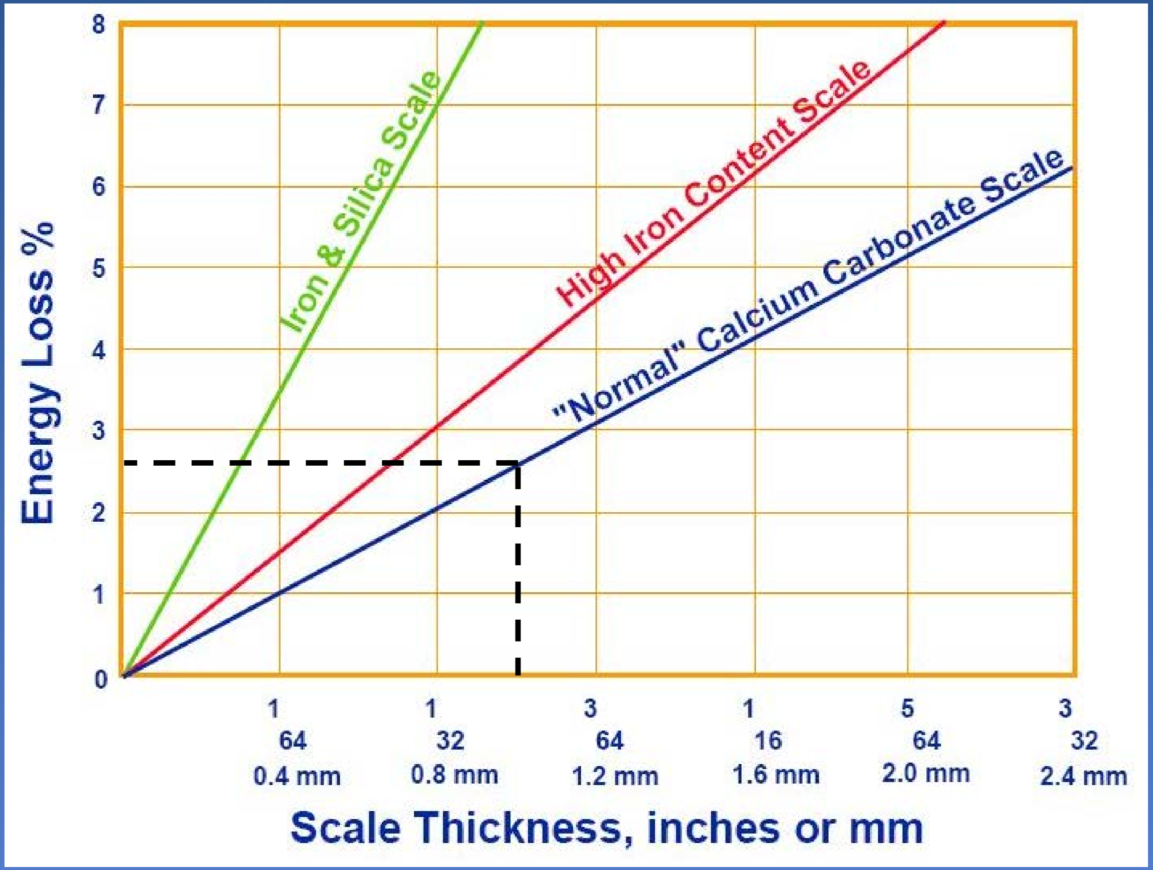


Phelan (1975)

Calcium Carbonate Solubility

- Depends on Ca, Alkalinity, pH, T
- Calcium carbonate gets less soluble as temperature increases
- Fouling is an issue for cooling, not heating

Fouling and Heat Transfer Efficiency



4 gal min^{-1} Median Mason Co. ppt

⋮

~1 mm deposit in 4 months

GSHP Installations

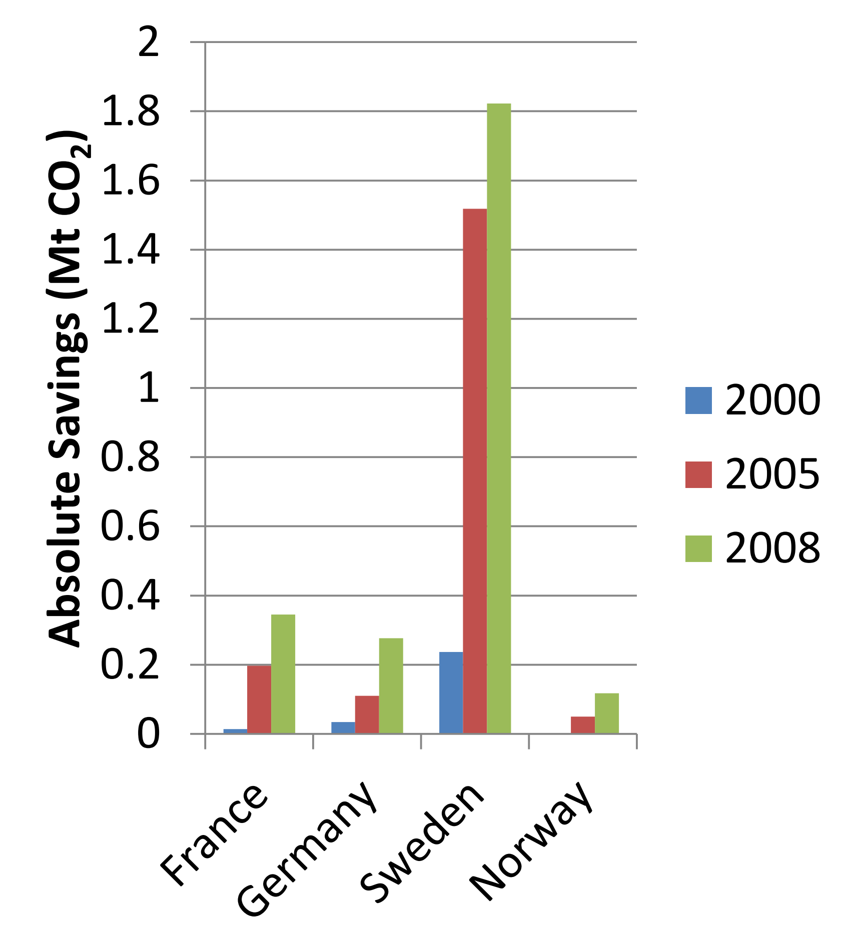
- 600,000 systems in U. S. as of 2010
- <0.5% of single-family houses

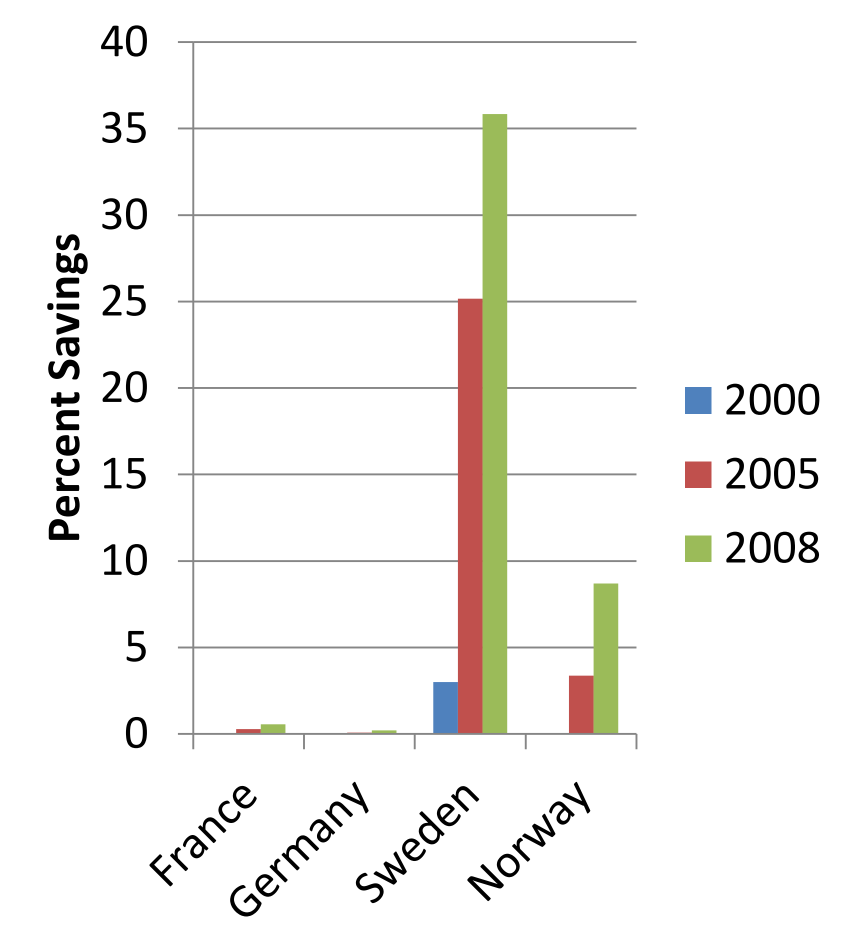
GSHP Potential Benefits

- Retrofitting 20% of single-family houses with GSHPs would reduce
  - Primary energy use by 9.0%
  - CO_2 emissions by 9.1%
  - Summer peak electrical demand by 11.2%

Liu (2010)

Greenhouse Gas Savings of GSHPs





Bayer et al. (2012)

Cooling with groundwater, commercial scale

Flow rate 150 gal/min

Hoover (2010)