What happens to the underlying aquifer when you put 1000 meters of ice on top?

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UW System Groundwater Research
Program (project WR09R004)
This kind of study is possible only with the help of:

- The computerized drinking water database maintained by the WDNR
- Regional groundwater modeling efforts (WGNHS; USGS)
- Near universal cooperation from water utilities
Can you tell me why my water is cloudy?

N2 vs Ar Plot

gas concentration normalized to sea level

City of Kaukauna
Wisconsin 2003

Excess Air in cc

Recharge
Temperature in Degrees C.

WEA line ->
Presentation outline

• The set up: regional hydrogeology, glacial history, isotope and noble gas tracers
• Methods – data collected, etc.
• Pleistocene history as expressed in the north transect near Green Bay
• Comparison to Pleistocene history as expressed in the south transect near Milwaukee
• Some insight into the physical mechanisms that generate subglacial recharge water
Bedrock geology of Wisconsin

Modified from WGNHS
Diagrammatic stratigraphy

General hydrogeology of southeast Wisconsin

- Sand and Gravel Aquifer
- Silurian Dolomite Aquifer
- Shallow Aquifer
- Sandstone Aquifer

from Ken Bradbury, WGNHS
timing of Last Glacial Maximum

from Mickelson and Colgan, 2004
Below the “equilibrium line” glaciers are rotten
and melting fast.

from NASA website (they have a neat movie too)
Formation of Glacial Lake Oshkosh

after Hooyer (2007), Late glacial history of east-central Wisconsin
Base map with glacial deposits

Modified from WGNHS
How $\delta^{18}O$ (and $\delta D$) reflect temperature variations

\[ \delta^{18}O = 0.54T - 13.3 \]

Taken from: http://www.iceandclimate.nbi.ku.dk/research/past_atmos/past_temperature_moisture/fractionation_and_temperature/
How noble gases work – CE model

Closed-system equilibration (CE) with entrapped air

$C_i(T, S, P) = C_i^*(T, S, P) + \frac{(1 - F_{CE}) \cdot A_{CE} \cdot z_i}{1 + F_{CE} A_{CE} z_i / C_i^*(T, S, P)}$

from Holocher, 2002
Methodology for tracer study

WHERE:

• Municipal wells screened only in deep aquifer
• Previous chemical history
  • Consistency with numeric flow models (USGS)
• Physical access needed

WHAT:

• Analyzed for
  • Major ions
  • Stable isotopes ($\delta^{32}S$, $\delta^{13}C$, $\delta^{18}O$, $\delta D$)
  • $^{14}$C dates
  • Noble gases (excess air/temperatures/fractionation/pressure factor)
**Glacial history as seen in the aquifer**

**south transect**

**Pre-glacial (3)**
- $^{14}$C > 26Kyr
- NGT warm
- δ$^{18}$O enriched (pre-glacial climate)

**Glacial (2)**
- 14Kyr < $^{14}$C < 26Kyr
- NGT and δ$^{18}$O cold

**Post glacial (1)**
- $^{14}$C < 14Kyr
- $^{14}$C dates match modeled values
- NGT and δ$^{18}$O warm

*from Klump, et al., 2008*
Glacial history as seen in the aquifer

north transect

**Glacial (2)**
- $10 \text{ Kyr} < ^{14}\text{C dates} < 26 \text{ Kyr}$
- Cold $\delta^{18}\text{O temperatures} (< 0^\circ \text{C})$
- High pressure factors ($q$)

**Post glacial (1)**
- $^{14}\text{C dates} < 10 \text{ Kyr}$
- Warm $\delta^{18}\text{O temperatures} (> 0^\circ \text{C})$
- Lower pressure factors ($q$)
What happens along the ice axis?
\( \delta^{18}O \) and noble gas thermometry

south transect

congruent and reasonable temperature records

\[ \Delta = \text{NG temperature} \]

\[ \Delta = \delta^{18}O \text{ temperature} \]

from Klump, et al., 2008
Excess air and pressure factors
north and south transects
$\delta^{18}O$ and noble gas thermometry

North transect

Incongruent and unreasonable temperature records (at least initially)

$\boldsymbol{\text{\textcircled{•}}} = NG$ temperature

$\boldsymbol{\text{\textcircled{◊}}} = \delta^{18}O$ temperature
Excess air and pressure factors
north and south transects
Genesis of recharge water

NGT reflects local climate
δ¹⁸O temp reflects local climate
ΔNe less than 70%
Recharge heads 0.5 - 4 meters
Normal CE fractionation
Genesis of recharge water

NGT reflects local climate
\( \delta^{18}O \) temp reflects local climate
\( \Delta N_e \) less than 70%
Recharge heads 0.5 - 4 meters
Normal CE fractionation

NGT reflects moulin air temp
\( \delta^{18}O \) temp reflects glacial ice
\( \Delta N_e \) between 70% and 110%
Recharge heads 2.5 – 8 meters
Normal CE fractionation
Genesis of recharge water – a suggestion

NGT reflects local climate
\( \delta^{18}O \) temp reflects local climate
\( \Delta N_e \) less than 70%
Recharge heads 0.5 – 4 meters
Normal CE fractionation

NGT reflects moulin air temp
\( \delta^{18}O \) temp reflects glacial ice
\( \Delta N_e \) between 70% and 110%
Recharge heads 2.5 – 8 meters
Normal CE fractionation

\( \delta^{18}O \) temp reflects glacial ice
\( \Delta N_e \) of several hundred %
Very little fractionation
NGT indefinable by CE model
Recharge heads indefinable
Conclusions about that 1000 m of ice

- Identifiably distinct packets of water exist within a stratigraphically continuous aquifer
- Aquifer was not sealed off Last Glacial Maximum (LGM)
- Source of LGM recharge varies as a function of distance from terminus
- Large amounts of LGM water exist in the aquifer (universally true in northern hemisphere basins?)
- Possible technique for determining the provenance of basal water in modern ice sheets
Thanks for inviting me
What does the SE Wisconsin regional model say about travel time?
After whining for more porosity

1) Particle are traced in reverse from St. Peter to water table for flow conditions stretching from Year 2000 to predevelopment
2) Deep SEWI wells are black crosses
3) Color flood is time of travel from water table to St. Peter (assuming HIGH porosity values)

TIMES OF TRAVEL FROM WATER TABLE  (max=10,136 years)

HSTseSPh

SEWI - St. Peter - High Porosity

Effective Porosity:
- Unlithified: 0.2
- Carbonate/Shale: 0.01
- Sandstone: 0.1

Maquoketa Subcrop
After even more whining on my part

“I still think 10% porosity for the deep sandstone is too high -”

“- even perhaps for you, given the ages well in excess of 20,000 yrs in Milw/Racine/Kenosha counties.”

“A porosity of 5% might be more bearable.”
Study Area Basemap

Center transect
Fond du Lac, Washington, and Ozaukee Counties

Problem!
Why this area is a problem...

- elevation of basement
- aquifer thickness

from John Skalbeck

from Nate Magnusson
**Simplified hydro-stratigraphic column**

<table>
<thead>
<tr>
<th>Stratigraphic Nomenclature</th>
<th>Hydraulic Conductivity (K_h (m/d))</th>
<th>Lithology and Generalized Hydrostratigraphy</th>
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</thead>
<tbody>
<tr>
<td>Group</td>
<td></td>
<td></td>
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<tr>
<td>Quaternary</td>
<td></td>
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<tr>
<td>Devonian</td>
<td></td>
<td></td>
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<tr>
<td>Silurian</td>
<td></td>
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<tr>
<td>Maquoketa</td>
<td>9E-5 - 0.09</td>
<td>Quaternary and Silurian aquifers: sand &amp; gravel, till, dolomite</td>
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<tr>
<td>Sinnipee</td>
<td></td>
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<tr>
<td>Galena</td>
<td>0.012 - 0.09</td>
<td>Maquoketa aquitard: shale and dolomite</td>
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<tr>
<td>Platteville</td>
<td></td>
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<tr>
<td>Ancell</td>
<td>0.36 - 1.8</td>
<td>Cambrian-Ordovician aquifer system: sandstone and dolomite, with interbedded shale and siltstone (leaky aquitards)</td>
</tr>
<tr>
<td>Prairie du Chien</td>
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<td>Glenwood</td>
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<tr>
<td>St. Peter</td>
<td>0.07 - 0.7</td>
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<tr>
<td>Trempealeau</td>
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<tr>
<td>Jordan</td>
<td>0.7 - 2.6</td>
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<tr>
<td>St. Lawrence</td>
<td>0.18 - 1.1</td>
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<td>Tunnel City</td>
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<td>Elk Mound</td>
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<tr>
<td>Wonewoc</td>
<td>0.36 - 1.8</td>
<td>Precambrian: igneous and metamorphic</td>
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<td>Eau Claire</td>
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<tr>
<td>Mt. Simon</td>
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</tr>
</tbody>
</table>

Modified from Feinstein, et al., 2004
Stable isotope constraints

\[ \delta^2H = 8 \cdot \delta^{18}O + 10 \]
Late Wisconsin Glaciation

from Mickelson and Colgan, 2004
Isotope transect to the south
Information gathered in Waukesha county

- Basic geochemistry
- Numeric modeling
- Stable isotope data
- Noble gas data
- $^{14}$C dates