Hydrology
• Inflow of young carbon

• Young carbon drives biochemistry

• Mixture of young and old carbon is not the result of pore water mixing, but mobilization of old organic carbon
Hydraulic Characteristics at Intensive Site

- **Relative Head (mm difference from head at 19m)**
- **δ¹⁸O (per thousand)**
- **Hydraulic Conductivity (m/s)**
- **Depth (m)**
Depth-wise variation of stable water isotopic values at the filed site.
Boro Rice Cultivation and Number of Wells

A: Graph showing the fraction of the total area of Bangladesh covered by Boro Rice, Groundwater Irrigation, and Surface Water Irrigation areas, along with the number of Shallow and Deep Wells over time from 1970 to 2000.

B: Graph depicting the maximum depth to the groundwater level (GWL) per year from 1988 to 1997, with different symbols representing different regions (NW, NC, NE, SW, SC, SE) and a line representing the country average.
Monitoring Rice field

Monitoring Rice field
Pumping
Measured Pumping Rates of 41 (out of 54) Irrigation Wells (1/28 and 2/20 2004)

Mean = 24.1 Litres / Second

Litres / Second
The graph shows the relationship between the normalized aquifer head and the pumping duration. The equation for the relationship is given as:

\[ h(t) = A + Ae^{-Bt} \]

The graph includes data points for different periods:
- January 10-hour days
- February 11-hour days
- All days from January 7 to April 16
River Exchange
Exchange With River
Ponds
Model
Aquifer:

\[ S \frac{dh_a}{dt} = \left( h_f - h_a \right) K_f f_f + \left( h_p - h_a \right) K_p f_p + \left( h_r - h_a \right) K_r f_r + \left( h_v - h_a \right) K_v f_v - q_I - f_{av} \alpha_v ET_0 \]

Village:

\[ S_y \frac{dh_v}{dt} = \left( h_a - h_v \right) K_v - \left( 1 - f_{av} \right) \alpha_v ET_0 + R \]

Field:

\[ S_y \frac{dh_f}{dt} = \left( h_a - h_f \right) K_f - \alpha_f ET_0 + R + \frac{q_I}{f_f} \]

Pond:

\[ \frac{dh_p}{dt} = \left( h_a - h_p \right) K_p - \alpha_p ET_0 + R \]
\( B: \text{ET}_{\text{tree}} \text{ from aquifer} \)
<table>
<thead>
<tr>
<th>Village ET&lt;sub&gt;tree&lt;/sub&gt; from</th>
<th>Case-A</th>
<th>Case-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay</td>
<td></td>
<td>aquifer</td>
</tr>
<tr>
<td>K&lt;sub&gt;f&lt;/sub&gt; (1/d) [conductance for field]</td>
<td>8.9x10-4</td>
<td>8.9x10-4</td>
</tr>
<tr>
<td>K&lt;sub&gt;v&lt;/sub&gt; (1/d) [conductance for village]</td>
<td>6.3x10-6</td>
<td>9.1x10-4</td>
</tr>
<tr>
<td>K&lt;sub&gt;p&lt;/sub&gt; (1/d) [conductance for pond]</td>
<td>9.3x10-3</td>
<td>8.3x10-3</td>
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<tr>
<td>K&lt;sub&gt;r&lt;/sub&gt; (1/d) [conductance for river]</td>
<td>7.7x10-2</td>
<td>8.7x10-2</td>
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<tr>
<td>Objective Function w/ pumping</td>
<td>5.9x10-1</td>
<td>5.7x10-1</td>
</tr>
<tr>
<td>w/o pumping Residence Time (yrs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w/ pumping 19</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>w/o pumping 42</td>
<td>42</td>
<td>22</td>
</tr>
</tbody>
</table>

**Table 1.** The estimated conductance parameter values when the storage coefficients are fixed, the respective objective functions (sum of square errors), and modeled residence times for the aquifer.
### Case A: Village ET out of Clay

<table>
<thead>
<tr>
<th></th>
<th>$K_f$</th>
<th>$K_p$</th>
<th>$K_r$</th>
<th>$K_v$</th>
<th>CV</th>
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<tr>
<td>$K_v$</td>
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<td>0.01</td>
<td>0.09</td>
<td>1</td>
<td>5.45</td>
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</tbody>
</table>

### Case B: Village ET out of Aquifer

<table>
<thead>
<tr>
<th></th>
<th>$K_f$</th>
<th>$K_p$</th>
<th>$K_r$</th>
<th>$K_v$</th>
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</thead>
<tbody>
<tr>
<td>$K_f$</td>
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<td>$K_p$</td>
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<tr>
<td>$K_v$</td>
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<td>0.05</td>
<td>0.00</td>
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<td>0.06</td>
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</table>

### Case A: Village ET out of Clay

<table>
<thead>
<tr>
<th></th>
<th>$K_f$</th>
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<th>$K_r$</th>
<th>$K_v$</th>
<th>$S_y$</th>
<th>$S$</th>
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<td>0.13</td>
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</table>

### Case B: Village ET out of Aquifer

<table>
<thead>
<tr>
<th></th>
<th>$K_f$</th>
<th>$K_p$</th>
<th>$K_r$</th>
<th>$K_v$</th>
<th>$S_y$</th>
<th>$S$</th>
<th>CV</th>
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<tbody>
<tr>
<td>$K_f$</td>
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<td>-0.16</td>
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</tbody>
</table>
A. Planting Season (Nov-Dec, prior to pumping)

Rate of watertable decline = \( \frac{e}{\theta} \)

Silty Clay

Sandy Aquifer

river sediments
B. Pumping and Irrigation

\[ \text{rate of decline} = \frac{e}{t} \]

\[ \text{pumping rate} = p \]

return flow = \( p - e \)

Irrigation Well

Sandy Aquifer

flow from river
Transient Three-Dimensional Flow Model

River cells
Pond cells
Village areas
Irrigated rice areas
Irrigation wells
Drinking wells
Other agriculture area
Area of interest

114 row and columns 15 layers
Estimated Groundwater Age Distribution at 30-m

Median age of 66 years with irrigated agriculture
240 years without irrigated agriculture
Conclusions

- Arsenic concentrations are subject to change and irrigation pumping is sufficient to have significantly changed flow paths, drawing young water and chemicals into the aquifer.

- Geochemical parameters at our site are consistent with a scenario of concomitant arsenic release and organic carbon oxidation.

- Deeper wells have the potential to alleviate the problem, but could also become contaminated.

Tremendous disparity with US groundwater contamination problems

- In the developed world people don’t drink seriously contaminated groundwater when contamination is known.

- Relative to US, efforts to understand the physical and chemical processes are not funded.

Need a serious scientific/engineering program
People

MIT
Chris Swartz
Nicole Keon
Winston Yu
Jenny Jay
Dan Brabander
Peter Oates
Harry Hemond

BUET
Borhan Badruzzaman
Ashraf Ali
Feroze Ahmed
Khandaker Ashfaque

U. Cincinatti
Shafik Islam

Roger Beckie
Volker Niedan
Future directions

• Arsenic in other regions in Asia
  Does Bangladesh indicate the future?

• Arsenic in agriculture and food chain

• Combined surface-water groundwater management pathogens vs. arsenic

Can these be done without a detailed hydro-bio-geo-chemical model?
Field Site

Agriculture Areas
40% boro rice
71% irrigated

Irrigation Wells
Small N$_2$ glove bag at night