Influence of heat storage on biodegradation at contaminated sites

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Heat storage in groundwater will be relevant especially for urban regions:

- climatization of office / industrial buildings, shopping malls, etc.
- temporal storage of renewable energy
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Possible impacts on groundwater contaminations:

- hydraulic impacts:
  - decrease of water viscosity $\rightarrow$ local increase of hydraulic conductivity

- biogeochemical impacts:
  - increased release of DOC from sediments
  - increased solubility of org. contaminants
  - stimulation of microbial growth
Temperature dependence of microbial growth:

- **Mesophile**: 20 °C bis 45 °C
- **Psychro-tolerant**: 5 °C bis 30 °C
- **Psychrophile**: −5 °C bis 20 °C
- **Thermophile**: 40 °C bis 70 °C
- **Extrem Thermophile**: 65 °C bis 90 °C
- **Hyperthermophile**: 85 °C bis 110 °C

Stimulation of microbial growth at increased groundwater temperatures → potential for increased biodegradation?

(Brielmann et al., Grundwasser 2011)
Scope and aims

• First model based investigation of the influence of local heat storage on contaminant biodegradation

• Synthetic scenarios derived from a BTEX contaminated site in northern Germany

• Use of aquifer for cooling of hypothetical facility via BHEs (e.g. office building or mall)

• Simplified model setup to allow identification of key processes and process interactions.

• Focus: plume processes → hydraulic effects and biodegradation
Parameterization based on site data of a BTEX contaminated quarternary aquifer (Brand airfield, Miles et al., GW 2008)

→ synthetic model of reduced complexity:

- homogeneous medium sand: eliminate effects of sediment heterogeneity, uniform flow velocity of 1 m/d

- 1 lumped BTEX compound and 2 degradation pathways: typified “plume fringe” and “plume core” degradation

- 6 microbial groups

  "BTEX": C₈H₁₀

  aerobic degrad.

  psychrophiles
  psychrotolerants
  mesophiles

  (-5 – 25°C)
  (5 – 35°C)
  (15 – 45°C)

  methanogenesis

  psychrophiles
  psychrotolerants
  mesophiles

  (-5 – 25°C)
  (5 – 35°C)
  (15 – 45°C)
Growth of aerobes:

\[
\frac{\partial X_{a,i}}{\partial t} = \mu_{\text{max}}(T) X_{a,i} - \frac{O_2}{M_{O_2} + O_2} \frac{BTEX}{M_{\text{BTEX}} + BTEX} \frac{I_{X_{\text{tot}}}}{I_{X_{\text{tot}}} + X_{\text{tot}}} - \xi X_{a,i}
\]

Growth of methanogenes:

\[
\frac{\partial X_{m,i}}{\partial t} = \mu_{\text{max}}(T) X_{m,i} - \frac{BTEX}{M_{\text{BTEX}} + BTEX} \frac{I_{O_2}}{I_{O_2} + O_2} \frac{I_{X_{\text{tot}}}}{I_{X_{\text{tot}}} + X_{\text{tot}}} - \xi X_{m,i}
\]

\[
\mu_{\text{max}}(T) = \left[ B(T - T_{\text{min}}) \right]^2 \left\{ 1 - \exp \left[ C(T - T_{\text{max}}) \right] \right\}
\]

(Zwietering et al., 1991)

parameters for \(\mu_{\text{max}}(T)\) were derived from review of literature data on T-dependent growth of contaminant degraders.
(1) Vertical cross section

- BTEX degradation in shallow aerobic aquifer
- aerobic plume fringe (mixing controlled) and methanogenic plume core (kinetics controlled) biodegradation
(1) Vertical cross section

- BTEX degradation in shallow aerobic aquifer
- aerobic plume fringe (mixing controlled) and methanogenic plume core (kinetics controlled) biodegradation
- BHE installation within the BTEX plume
(1) Vertical cross section

- Detail model across a plume section
- “Model spin up” of 20 years: plume development and biodegradation simulated at constant temperature of 10°C
(1) Vertical cross section

- Detail model across a plume section
- “Model spin up” of 20 years: plume development and biodegradation simulated at constant temperature of 10°C
- Simulation of 5 years of heat storage: non-isothermal groundwater flow, heat & mass transport, biodegradation

\[ q = 0.25 \text{ m/day} \]

\[ \text{const. } q = 0.25 \text{ m/day} \]

\[ \text{O}_2 = 0.25 \text{ mol/m}^3 \]

\[ \text{BTEX} = 0.11 \text{ mol/m}^3 \]

\[ \text{O}_2 = 0.25 \text{ mol/m}^3 \]

\[ \text{gw-recharge (oxic)} \]

\[ q = 315 \text{ mm/year} \]

**Conceptual Model**

- Vertical cross section
- Heat (line) source term 70W per meter BHE
- Constant pressure
- Oxygen concentration: \( 0.25 \text{ mol/m}^3 \)
- BTEX concentration: \( 0.11 \text{ mol/m}^3 \)
Plume after 20 years of biodegradation
plume is at quasi steady state
BHE heat injection: max. +5°C over 5 years
plume reaches a new stationary state
BHE heat injection: max. +45°C over 5 years
plume reaches a new stationary state
Increase in norm. biodegradation rate $R^*$ over time

$$R^* = \frac{R_{BHE}}{R_0} - 1$$

max. +5°C

max. +45°C
Increase in norm. biodegradation rate $R^*$ over time

$$R^* = \frac{R_{BHE}}{R_0} - 1$$

**Scenario 1 – vertical cross section**

**Increase in biodegradation:**

<table>
<thead>
<tr>
<th></th>
<th>max. + 5 °C</th>
<th>max. + 45 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>aerobic</td>
<td>+ 2 %</td>
<td>+ 12 %</td>
</tr>
<tr>
<td>methanogenic</td>
<td>+ 12 %</td>
<td>+ 87 %</td>
</tr>
<tr>
<td>total</td>
<td>+ 8 %</td>
<td>+ 52 %</td>
</tr>
</tbody>
</table>

- BTEX degradation [\(\cdot\)]:
  - Methanogenesis
  - Aerobic
  - Methanogenic
  - Total

- Time [days]:
  - 0 to 1825
  - Seasonal injection
  - Permanent injection

(2) Horizontal cross section

- Detail model of fringe and plume core zone

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**scenario 2 – horizontal cross section**

BTEX, anoxic

fringe: mixing contr. deg.

plume core degradation

source

oxic
(2) Horizontal cross section

- Detail model of fringe and plume core zone
- “Model spin up” of 20 years: plume development and biodegradation simulated at constant temperature of 10°C
(2) Horizontal cross section

- Detail model of fringe and plume core zone
- “Model spin up” of 20 years: plume development and biodegradation simulated at constant temperature of 10°C
- Installation of ground heat pumps, simulation of 5 years of heat storage: non-isothermal groundwater flow, heat & mass transport, biodegradation

const. conc. $O_2 = 0.25 \text{mol/m}^3$

const. conc. $\text{BTEX} = 0.11 \text{mol/m}^3$

const. groundwater flux $q = 0.25 \text{ m/day}$

heat source term (point source)
(2) Horizontal cross section

- Detail model of fringe and plume core zone
- “Model spin up” of 20 years: plume development and biodegradation simulated at constant temperature of 10°C
- Installation of ground heat pumps, simulation of 5 years of heat storage: non-isothermal groundwater flow, heat & mass transport, biodegradation

const. conc. \( O_2 = 0.25 \text{mol/m}^3 \)

const. conc. \( \text{BTEX} = 0.11 \text{mol/m}^3 \)

const. groundwater flux \( q = 0.25 \text{ m/day} \)
Plume after 20 years of biodegradation
plume is at quasi steady state
BHE heat inj.: max. +45°C in plume fringe over 5 years
plume reaches a new quasi steady state
Increase of mixing (reactor ratio) with temperature

normalized flux related dilution index for conservative transport:

\[ M_Q(x) = \exp \left[ \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} p_Q(x, y) \ln(p_Q(x, y)q_x(x, y)) \, dy \, dz \right] / Q \]

(Rolle et al., JCH 2009)

\[ \Rightarrow \text{increase in mixing is only small.} \]
Increase in norm. biodegradation rate $R^*$ over time

$$R^* = \frac{R_{BHE}}{R_0} - 1$$

**BHE in fringe, max. +45 °C**

**Increase in biodegradation:**

<table>
<thead>
<tr>
<th></th>
<th>BHE in fringe</th>
</tr>
</thead>
<tbody>
<tr>
<td>aerobic</td>
<td>+ 19 %</td>
</tr>
<tr>
<td>methanogenic</td>
<td>+ 75 %</td>
</tr>
<tr>
<td>total</td>
<td>+ 50 %</td>
</tr>
</tbody>
</table>
scenario 2 – horizontal cross section

**BHE heat inj.: max. +45°C in plume core over 5 years**

plume reaches a new quasi steady state
Increase in norm. biodegradation rate $R^*$ over time

$$R^* = R_{BHE} / R_0 - 1$$

**scenario 2 – horizontal cross section**

Increase in norm. biodegradation rate $R^*$ over time

$$R^* = \frac{R_{BHE}}{R_0} - 1$$

<table>
<thead>
<tr>
<th></th>
<th>BHE in fringe</th>
<th>BHE in core</th>
</tr>
</thead>
<tbody>
<tr>
<td>aerobic</td>
<td>+ 19 %</td>
<td>+ 16 %</td>
</tr>
<tr>
<td>methanogenic</td>
<td>+ 75 %</td>
<td>+ 50 %</td>
</tr>
<tr>
<td>total</td>
<td>+ 50 %</td>
<td>+ 35 %</td>
</tr>
</tbody>
</table>
Hydraulic effects of BHE heat storage:

- local increase of hydraulic conductivity
  - focusing of contaminant plume along the T-plume
  - shift or focusing of plume fringes, depends on positioning of BHE
  - mixing is only slightly increased

Influence on degradation kinetics:

- shift in dominant bacterial groups near BHE: psychrophiles → mesophiles
- plume fringe controlled degradation:
  - availability of electron acceptors remains the main limiting factor
- highest potential for stimulation of biodegradation in plume core
This work was performed within the joint project “ANGUS+” with funding by the Federal Ministry for Education and Research, BMBF.

THANK YOU FOR YOUR ATTENTION!