Combining unsaturated zone modelling with indirect and direct measurements to quantify solute transport during snowmelt

Protecting groundwater by monitoring the unsaturated zone

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Motivation

Relevant scales and processes

**Scales of relevant processes**

- Transport route: Where? How fast? How to monitor?
- Field scale: Flow and transport, geological heterogeneities
- Lab. and field scale: Flow and transport processes, spatial heterogeneities
- Lab. scale: Bio-geo-chemical interactions

**Contaminant source**

- Bio-degradable
- Surrounded by soil environment

**Bio-geo-chemical interactions influence:**

- pH
- EC (Electrical conductivity)
- Eh (Red-ox potential)
- Microbial community (diversity of bacteria and fungi)
- Plant activity (root development, root exudation)
- Hydraulic properties (Ks, K (unsaturated))
Filipović et al., 2016

Motivation

• Method for monitoring:
• Predictive model
• Electrical resistivity, a method for monitoring and model validation?
Unsaturated zone simulations

Modellering med SUTRA (C. Voss, USGS)

30 målepunkter i umettet sone!

Snowmelt infiltration
10mm/day, 21 days

Surface

Vertical centre of mass (m)

Time, days from application

PGsim
CI-sim
PGobs
CI-obs

(French et al, 2001)
Electrical resistivity (ERT)

• Electrical conductivity of the unsaturated zone is a function of
  – Water content
  – EC of water (Contaminant concentration)
  – Temperature
• Time-lapse: measure changes

How to separate these effects?
• Field experiments
  – Direct measurements, suction cups, tensiometers, temperatures
  – Indirect measurements, ERT
• Numerical modelling

Can we trust indirect monitoring to tell us something about flow and transport in the unsaturated zone?
Characterisation:

Geophysical methods:
- GPR
- Electrical resistivity
  - Ohmmapper
  - Cable:time-lapse
- Radio magnetotellurics
- EM

Soil sampling:
- ”Undisturbed” soil columns 5m long
- Pf- sampling
- Soil – top vegetation
  - Microbial characterisation
  - Remediation tests
Electrical resistivity: Ohmmapper

a) Runway

b) Perpendicular Line 1: Sharp boundary inversion model

c) Perpendicular Line 3: Sharp boundary inversion model
Electrical resistivity: Ohmmapper

3D image of 2D merged resistivity models in both directions

Runway
Time-lapse Electrical resistivity (ERT)
Electrical resistivity timelapse - results

Crossing OSL_48

Crossing OSL_96

Change in el. resistivity

Lower conductivity

Higher conductivity

Accumulated snowmelt + precipitation

Dates
26.02.2009
23.03.2009
17.04.2009
12.05.2009
06.06.2009
01.07.2009
26.07.2009
20.08.2009
14.09.2009
09.10.2009
03.11.2009
28.11.2009
Cross-borehole electrical resistivity tomography (ERT) was used during March-May 2001 to monitor changes in resistivity due to increases in tracer concentration.

Suction samplers accessed in the lysimeter provided point measurements of tracer concentration.

25 electrodes per borehole. Electrodes from ground surface to 3.84 m

(French et al., 2002)
- Suction cups, EC water samples
- Thermistors, soil temperature
- Tensiometers, soil suction
Monitoring tracers – ERT image changes

Changes in conductivity from cross-borehole ERT images

(French et al., 2002)
Monitoring tracers – Br concentration changes

Changes in Br concentration from suction samplers

(French et al., 2002)
Monitoring tracers – comparison of methods

Comparison of ERT and Br sampling results on 24-April-01

(French et al., 2002)
Cross borehole ERT

- Chemicals added March 26, 2010
- Transform to 1D

Day 6  
01.04.2010

Day 12  
07.04.2010

Day 19  
14.04.2010

Day 31  
26.04.2010
Theory unsaturated zone

The van Genuchten model (1980)

\[ \theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^b]^{1-1/b}} \]

\[ S = \frac{1}{[1 + (\alpha|\psi|)^b]^{1-1/b}} \]

- \( S \) is the saturation (-)
- \( \psi \) is the suction pressure (L)
- \( \theta_s \) saturated water content (L^3L^-3)
- \( \theta_r \) residual water content (L^3L^-3)
- \( \alpha \) is related to the inverse of the air entry suction,
- \( b \) is a measure of the pore-size distribution (-)

Archie's law (1942) Assumed no surface conductivity

\[ \sigma_{bulk} = \frac{1}{\rho_{bulk}} = \frac{1}{F} \sigma_w = \sigma_w \phi^m S^n \]

- \( \sigma_{bulk} \) is the bulk electrical conductivity of the soil,
- \( \rho_{bulk} \) is the bulk electrical resistivity of the soil,
- \( F \) is the formation factor,
- \( \sigma_w \) is the pore fluid electrical conductivity,
- \( \phi \) is porosity raised to Archie’s cementation factor \( m \),
- \( S \) is saturation raised to Archie’s saturation factor \( n \).

\[ \theta_s = \theta_r + \theta_s - \theta_r \]

\[ S = \frac{1}{1 + (\alpha|\psi|)^b} \]

\[ \theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^b]^{1-1/b}} \]

\[ S = \frac{1}{[1 + (\alpha|\psi|)^b]^{1-1/b}} \]

Local
Archie’s law calibration

\[ \log(R_b) = \frac{-1.7361}{S} + 2.4212 \]

(Forquet, 2005)
Combining and comparing

Saturation

EC-water

Measured bulk resistivity

(Bloem et al, in progress)
Conclusion, further work

- ERT can reveal distribution of contaminants in the unsaturated zone
- Time-lapse ERT gives a good idea of how contaminants are moving
- For quantitative use:
  - Consistency in resolution space and time
  - 1D vs 3D – not trivial
  - Uncertainty in parameters of the pedotransfer functions (based on point measurements and lab)
- Global movement: spatial moments most successful so far
- Effects need to be explored further in unsaturated zone processed based model: Hydrus, SUTRA (USGS) with heterogeneous realisations of the soil physical properties.
Takk for meg!
<table>
<thead>
<tr>
<th>Time</th>
<th>Program 14. november</th>
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<tbody>
<tr>
<td>09:15-09:45</td>
<td>Registrering</td>
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<tr>
<td>09:45-11:30</td>
<td>Sesjon 1</td>
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<tr>
<td>09:45-10:00</td>
<td>Velkommen - Helen K. French, Formann IAH-Norge</td>
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<td>10:00-10:30</td>
<td>Introducing: intrinsic hydrogeology. Description of aquifer properties based upon observations from within the aquifer. Fridtjov Ruden, Ruden AS</td>
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<td>10:30-11:00</td>
<td>Jern og mangan i grunnvann – hvordan håndteres det i grunnvannsbaserte vannverk. Per Aagaard, UiO</td>
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<td>11:00-11:30</td>
<td>Pumping Iron. Larse Aaberg Stenvik, NTNU</td>
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<td>11:30-12:30</td>
<td>Lunsj</td>
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<td>12:30-13:30</td>
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<td>12:30-12:50</td>
<td>Overvåkning av norsk grunnvannkjemi – historie, resultater og framtidsbehov. Pål Gundersen, NGU</td>
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<td>12:50-13:10</td>
<td>I hvilken grad kan dagens grunnvannsovervåkning representere ekstreme hydrogeologiske forhold? Heidi Anette Grønsten, NVE</td>
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<td>13:10-13:30</td>
<td>Norge; De 1000 akviferers land og gjennomføring av grunnvannsdirektivet. Atle Dagestad, NGU</td>
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<td>15:10-15:40</td>
<td>Grunnvann og overvannshåndtering. Sylvi Gaut og Sigrun J. Jahren, SWECO</td>
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<td>15:40-16:10</td>
<td>Brønnborer Fastland – ditt beste valg i grunnen! Einar Østhassel, MEF</td>
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<td>16:10-16:30</td>
<td>Asker Panorama ekskursjon 15. november. Fridtjof Ruden, Ruden AS</td>
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<td>16:30-19:30</td>
<td>Middag</td>
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Send en mail til helen.french@nmbu.no
Further work – include ice

- Model infiltration in a frozen soil (SUTRA_ICE beta version) with phase change
- With and without cryosuction, FROST 1D

VALIDATION - Unsaturated flow

comparison with HYDRUS-1D

![Graph showing infiltration over time and depth, with labels for each day and moisture content.](image)

Temper.: 0 deg C
Time: 1 day
Soil: sand
Water cont.: 0.1

(Stuurop, work in progress)
Thank you for your attention!