Hydrology, Geophysics and Geodesy – HG²
A new way to manage water resources

Royal Observatory of Belgium, 23 October 2015

Proceedings

M. Van Camp and M. Vanclooster (eds.)
Introduction

In August 2015 the superconducting gravimeter GWR-C021 will be measuring gravity changes continuously for 20 years at the geophysical station of Membach, eastern Belgium. Those measurements have pioneered the use of surface gravity measurements to elucidate water dynamics in the terrestrial crust. Based on this experience, another superconducting gravimeter iGrav was installed in November 2014 in Rochefort in the framework of the KARAG project (Karst Aquifer Research by Geophysics).

To celebrate this anniversary and the installation of the iGrav in Rochefort, a symposium was organized on the 23 October 2015, aiming to gather hydrologists, hydrogeologists, geologists, geophysicists to discuss advances in geophysical techniques to assess components of the terrestrial water balance at different scales.

This workshop aimed at discussing the potential of new technologies to better assess the water mass balance and dynamics in terrestrial systems, and to foster cooperation between Belgian specialists of different fields. Workshop topics included:

- Advances in the use of geophysical techniques (ground based, airborne and satellite) to assess water balance components of terrestrial ecosystems.
- Use of geophysical techniques to support the modelling of the hydrological balance at different spatial and temporal scale.
- Interaction between hydrology and geodesy.

In these proceedings, we compile the abstracts and proceedings that were developed at this occasion. We aim with these proceedings promoting the diffusion of new specific knowledge in the broad geophysical and geodesic domain as a way to improve the management of water resources. We thank members of the scientific committee for helping evaluating the presentation. We thank ORB for the logistics that were arranged for organizing the meeting. We thank all participants for the interesting and lively discussions that were hold at this occasion.

M. Van Camp
M. Vanclooster
Uccle, Brussels, December 2015
Scientific committee

Prof. Alain Dassargues, ULg
Prof. Marijke Huysmans, VUB
Prof. Olivier Kaufmann, U. Mons
Prof. Frédéric Nguyen, ULg
Dr Michel Van Camp, Royal Observatory of Belgium
Prof. Marnik Vanclooster, UCL
Dr Christophe Frippiat, Institut Scientifique de Service Public ISSEP
Prof. Niko Verhoest, U. Gent
Prof. Kristine Walraevens, U. Gent.
Program

09h30  Van Camp, M.J.; Camelbeeck, T.
       Short historic of Membach

09h40  Van Camp, M.J.; Dassargues, A.; Vanclooster, M.; Watlet, A.; Kaufmann, O.; Crommen, O. (keynote lecture)
       Assessing groundwater mass balance: Keynote lecture: Hydrogeodesy in Membach and Rochefort

10h20  Mikolaj, M; Güntner, A.; Reich, M.; Schröder, S.; Wziontek, H.
       Portable superconducting gravimeter in a field enclosure: first experiences and results

10h40  Watlet, A.; Van Camp, M.J.; Francis, O.; Poulain, A.
       Hydrogeophysics to monitor the vadose zone of a karst system

11h00  Frippiat, C.; Veschkens, M.; Funcken, L.; Pacyna, D.
       Barometric and gravimetric effects on water levels in an abandoned underground coal mine

11h20  Kaufmann, O.; Watlet, A. (keynote lecture)
       Geophysical monitoring to assess underground water distribution and fluxes

13h00  Hermans, T.; Beaujean J.; Nguyen, F. (keynote lecture)
       Integration of geophysical data in hydrogeological models

13h40  Simpson D.; Van Steenwinkel J.; Meyus Y.
       Bottom-towed resistivity survey to support groundwater modelling of potential leakage during the enlargement of the Juliana canal

14h00  Vanclooster, M.; Wiaux, F.; Tran, P.; Lambot, S.
       The added value of high resolution hydrogeophysical monitoring for unravelling hydrological control of C emission along hillslopes

14h20  Walraevens, K.; Vandenbohede, A.; Van Camp, M.
       Salt water intrusion: mapping the interface depth

14h40  Schwartz, N.
       The effect of organic contaminants on the spectral induced polarization signature of soil
Title: Barometric and gravimetric effects on water levels in an abandoned underground coal mine

Authors: C. Frippiat\textsuperscript{1}, M. Veschkens\textsuperscript{1}, L. Funcken\textsuperscript{2} and D. Pacyna (SPW/DGO3)

\textsuperscript{1}ISSeP
\textsuperscript{2}SPW/DGO1
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Abstract:

The abandoned underground coal mine of Péronnes-lez-Binche (Eastern Belgium) is currently undergoing flooding. Water levels are monitored at two former mine shafts equipped with piezometers: Sainte-Marguerite and Saint Albert. Both shafts monitor different parts of the former mine that are not in perfect hydraulic connection with each other. The water level in Saint Albert has raised from about -230 m AMSL in 1998 to about +4 m AMSL in March 2015. Water levels are still increasing at a rate of about 2 m/year. In Saint Marguerite, the water level in 1998 was about -180 m AMSL in 1983 and is current at about +24 m AMSL.

Water levels have been monitored on an hourly basis using automatic probes since end of 2009 in Sainte Marguerite and since 2014 in Saint Albert. The detailed examination of the time series reveals high frequency (i.e. hourly) fluctuations that cannot be caused directly by flooding. Correlation analysis shows that the fluctuations are caused (i) by atmospheric pressure and (ii) Earth tides. Removing both effects yields data series that are much smoother. Obtaining such smooth data series is essential in order to be able to establish a quantitative link between the geometry of the voids being flooded and the water level.

It is also found that barometric efficiency at Sainte Marguerite is about 25\%, while that of Saint Albert is about 40\%, revealing that the underground coal mine behaves as an aquifer with spatially-varying geomechanic and hydraulic properties.
Title: Integration of geophysical data in hydrogeological models

Authors: T. Hermans\textsuperscript{1}, J. Beaujean and F. Nguyen\textsuperscript{3}

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Abstract:

Aquifers constitute essential geological bodies for environmental studies such as contaminated sites remediation, low-enthalpy geothermal energy or groundwater resources. The heterogeneity of these reservoirs governs flow processes and needs to be quantified. A proper description of such complex deposits requires an integrated approach combining geological, geophysical and hydrogeological data. Solving such spatial inverse problems in the Earth Sciences remains a considerable challenge given the large number of parameters to invert for, the non-linearity of forward models and, as a result, the ill-posedness of the problem. A combination of robust measuring technologies and reliable predictions based on numerical models are necessary to estimate better hydrogeological parameters. Sparse and continuous data are increasingly being used conjunctively in hydrogeological modeling and inverse calibration to alleviate extrapolation and subjective interpretation.

We here present two approaches that address the assimilation of spatially distributed data, provided by geophysics, local data such as hydraulic tests in wells, and (hydro)geological data provided by well logs or outcrop description. The first approach is a deterministic one and the second approach a stochastic one.

In the deterministic context, two hydrogeophysical inversion schemes are developed and a thorough comparison of an uncoupled and a coupled quantitative approach based on the use of surface electrical resistivity tomography (ERT) only is performed. The uncoupled hydrogeophysical inversion involves constraining hydraulic parameters using geophysically-derived data and first requires a geophysical inversion, after which the geophysical parameters are converted to hydrologic data through a petrophysical relationship. The inverse hydrological calibration is then performed on these inferred hydrological data. The coupled hydrogeophysical inversion involves constraining hydraulic parameters using geophysical data through a forward hydrogeophysical model in which the hydrologic data are converted to resistivities through a petrophysical relationship. A geophysical forward problem is then solved for the geophysical data. The inverse hydrological calibration is performed on the inferred geophysical observations. In both schemes, we show that an independent geophysical inversion is required to delineate heterogeneous bodies. In this context, we study how to derive informative content of ERT images and therefore ERT-derived hydrologic data and ERT-derived geometry. We show that a quantitative appraisal (the cumulative sensitivity) must be used as a proxy for filtering areas correctly resolved. Our developments are demonstrated on several benchmark SWI models (numerical and analytical), a thermohydrologic model and a field test.

In the second approach, geostatistics is used to specify prior models, more particularly, information to control the spatial features of the inverse solutions. Two-point geostatistical approaches have been developed to describe the heterogeneity of one geological formation but fail to reproduce the heterogeneity of fluvial deposits with multiple facies. Multiple-point statistics (MPS)
introduced the training image (TI) concept to replace the variogram within an extended sequential simulation framework. The use of geophysics to constrain such simulations has been studied in the petroleum industry with wave-based methods (seismic reflection), but little research has been done to assess the use of near-surface potential methods to condition MPS in environmental studies. In this context, we propose to integrate geological (borehole logs), geophysical (electrical resistivity tomography (ERT) profiles) and hydrogeological (hydraulic heads) data within MPS models on the alluvial plain of the Meuse River, Belgium. In this context, we develop a methodology to verify the consistency of independently-built TIs with geophysical data. Our methodology starts by creating subsurface models with each TI. From these models we create synthetic geophysical data and from this synthetic data, synthetic inverted models. These models are now compared with a single inverted model obtained from the field survey, allowing for our definition of what is “consistent”. To that extent, we calculate the Euclidean distance between any two inverted models as well as field data and visualize the results in a 2D or 3D space using multidimensional scaling (MDS). In a second step, we present a cluster analysis on the MDS-map to highlight which parameters are the most sensitive for the construction of TI. Based on this analysis, a probability of each geological scenario is computed through kernel smoothing of the densities in reduced projected metric space. The integration of hydrogeological data is made through a stochastic inversion method: the probability perturbation method (PPM), using MPS constrained with geophysical data to generate models. The PPM algorithm automatically seeks solutions fitting both hydrogeological data and training-image based geostatistical constraints. Only geometrical features of the model are affected by the perturbation, i.e. we do not attempt to directly find the optimal value of hydrogeological parameters (chosen a priori), but the optimal spatial distribution of facies whose prior distribution is quantified in a training image.
Title: Geophysical monitoring to assess underground water distribution and fluxes

Authors: O. Kaufmann¹ and A. Watlet¹

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Abstract:

For more than a century, geophysical methods have been developed and applied to the on-shore and off-shore prospection of fluids in a wide variety of geological contexts and at different scales. Applications include the delineation of reservoirs, their characterization in terms of inferred hydraulic properties, discontinuities, heterogeneities and anisotropies.

Exploration in the oil and gas industry largely relies on the continuous improvement of the seismic reflection acquisition and processing. For applications dealing with the underground water, a large array of techniques may be applied depending on site conditions, scale and desired resolution. However, electrical and electromagnetic methods are in a large range of cases the favored methods. Indeed, soil and rock electrical properties are strongly dependent on the presence and salinity of water in the porosity.

Water distribution in the subsurface is subject to variations not only in space but also in time. In order to detect and track those variations, monitoring methods are needed. Here we focus on the challenges associated with the monitoring of groundwater distribution based on the DC resistivity method.

The first challenges are relative to making reliable electrical resistance measurements and include the definition of the monitoring system, the qualification of the monitoring system, the automation of measurement and reporting, the assessment of measure repeatability and measurement error and the (semi-)automated verification of the system integrity and derive. Other challenges concern the processing and interpretation step and include corrections of external factors (e.g. temperature), choice of a processing workflow (data filtering, inversion strategy, uncertainties ...) and integration with external proxies.

In recent years, ERT monitoring systems have been installed and operated in Membach and at the Rochefort Cave Laboratory in order to track groundwater content changes in the vadose zone on a daily basis. We illustrate with these experiments how to face these challenges.
Title: Portable superconducting gravimeter in a field enclosure: first experiences and results

Authors: M. Mikolaj¹, A. Güntner¹, M. Reich¹, S. Schröder¹ and H. Wziontek²

¹Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Potsdam, Germany

²Federal Agency for Cartography and Geodesy (BKG), Branch Office Leipzig, Germany

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Abstract:

The inherent high precision and low drift of superconducting gravimeters (SGs) predetermines these instruments for unique continuous and integrative observations of water storage variations occurring in the area surrounding the point of installation. Nevertheless, the exploitation of gravity time series for hydrological purposes is often hindered due to the location of SGs inside observatory buildings. Such settings is accompanied by many unknowns and disturbances such as non-natural flow paths or umbrella effects. To minimize these negative impacts, a SG of the latest generation, i.e., iGrav, has been installed in a small field enclosure with a footprint smaller than 1 metre squared in Wettzell, Germany. In this contribution, we present the technical layout and discuss the emerging challenges in running such gravimeter system. We report on the quality of the acquired time series and show the direct comparison to the recordings of a nearby SG (SG030). In addition, we present the first comparison to traditional hydrological instrumentation, i.e., different types of soil moisture sensors, groundwater variations and lysimeter time series.
Title: The effect of organic contaminants on the spectral induced polarization signature of soil

Authors: N. Schwartz

1 UCL

Corresponding author: Nimrod Schwartz, UCL, nimrod.schwartz@uclouvain.be

Abstract:

In recent years, there is a growing interest in using geophysical methods in general and spectral induced polarization (SIP) in particular as a tool to detect and monitor organic contaminants within the subsurface. The general idea of the SIP method is to inject alternating current through a soil volume and to measure the resultant potential in order to obtain the relevant soil electrical properties (e.g. complex impedance, complex conductivity/resistivity). Currently, a complete mechanistic understanding of the effect of organic contaminants on the SIP response of soil is still absent. In this work, we combine laboratory experiments with modeling to reveal the main processes affecting the SIP signature of soil contaminated with organic pollutant. We investigate the effect of several organic contaminants on the SIP signature of porous media and identified the main mechanisms governing the SIP response. For polar organic compounds, an exchange process between inorganic and organic compounds was found to be a major factor affecting the SIP response. For non-polar organic compounds changes in the micro-geometry of the fluid phase, resulted from the introduction of the organic contaminant, are the main process affecting the SIP signal. In this talk we will discuss about the relations between these processes and the SIP signature of porous media.
Title: Bottom-towed resistivity survey to support groundwater modelling of potential leakage during the enlargement of the Juliana canal

Authors: D. Simpson¹, J. Van Steenwinkel¹ and Y. Meyus¹

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Abstract:

The Juliana canal in the south-east of the Netherlands will be enlarged to allow larger transport ships to pass through. The canal was dug out as an open excavation in mostly dry conditions in the 1930ies. As its water level and even its bottom level are mostly higher than the groundwater level and in some canal sections above the terrain level, an artificial clay layer of 60 cm thick was laid out over the bottom to keep the water in the canal. During the enlargement of the canal, the clay layer will be removed and replaced by bentonite mats. Between the removal and replacement, the canal water will temporarily leak to the groundwater system, of which the discharge is largely determined by the permeability of the formation underneath the canal bottom. Particularly important is the presence of Pleistocene gravel layers (“Maasgrind”) with a high permeability. In order to estimate the leakage and its effects on the groundwater system, detailed groundwater models were run with different scenario’s. Apart from point-like observations such as drillings and cone penetrations tests, a bottom-towed electrical resistivity survey was conducted on the canal to have a continuous image of the spatial variability of lithology under the canal bottom. The resistivity values were correlated with the drillings and electromagnetic inductions measurements in piezometers just next to the canal. The results showed large variations in the formation resistivities along the canal length, which could be explained by the local geological knowledge. The interpretation of the resistivity values in depth was however not straightforward. One of the reasons was that electrical resistivities of the gravel layer were very similar to the underlying sand (“Zand van Breda”), which made it difficult to distinguish the gravel from the sand.

Acknowledgements

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Title: Hydrology and gravimetry

Authors: M.J. Van Camp¹, A. Dassargues², M. Vanclooster³, A. Watlet⁴, O. de Viron⁵, O. Kaufmann⁴, and O. Crommen⁶

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Abstract:

For the 10 last years, terrestrial and satellite (GRACE) gravity measurements have reached such a precision that they can be of interest to better monitor underground water masses.

First, we show that terrestrial measurements provide high-precision information about the time evolution of mass changes in the few kilometres square around the gravimeter.

Then, examples of the possibilities and limitations of terrestrial measurements are given in Membach, close to Eupen, and in the Rochefort karst system. In Membach, we show that the evapotranspiration can be directly inferred from continuous gravity measurements: as water evaporates and transpires from terrestrial ecosystems, the mass distribution varies through the system, changing its gravity field at the level of, or smaller than 10-10 g per day. This corresponds to 2.0 mm of water over an area of 50 ha. The strength of this method is its ability to ensure a direct, traceable and continuous monitoring of actual ET for years at the mesoscale (~50 ha) with a precision of a few tenths of mm of water. In Rochefort, gravity measurements at the surface and in the cave allows separating the water contained in the unsaturated zone from the saturated one and therefore monitoring groundwater content changes that occur in the unsaturated zone only.
Title: The added value of high resolution hydrogeophysical monitoring for unravelling hydrological control of C emission along hillslopes.

Authors: M. Vanclooster\textsuperscript{1}, F. Wiaux\textsuperscript{1}, P. Tran\textsuperscript{1}, and S. Lambot\textsuperscript{1}

\textsuperscript{1}UCL

Corresponding author: Marnik Vanclooster, UCL, marnik.vanclooster@uclouvain.be

Abstract

Soils play an important role in the carbon (C) cycle. They constitute an important part of the global C pool, by storing C in de forms of organic matter and carbonates. The soil micro-organisms respiration transforms organic carbo (OC) into CO\textsubscript{2}. Two considerable concerns exist in relation with this: the global climate change due to the greenhouse gas warming potential of CO\textsubscript{2} and the decrease of soil quality.

Soil C distribution is very heterogeneous in soils and the respiration is strongly controlled by soil hydrological variables. We consider the hillslope as an elementary unit to provide a detailed mechanistic understanding of the soil hydrological processes which regulate C respiration at the landscape scale.

By means of a process based empirical and modelling study for a hillslope in the loamy belt of Belgium, we show how different geophysical techniques (TDR, GPR) can be deployed for monitoring soil hydrological processes at the hillslope scale, how soil hydrology is distributed in space and time along the hillslope and how this distribution is linked to C emission from soils.
Title: Salt water intrusion: mapping the interface depth

Authors: K. Walraevens¹, A. Vandenbohede¹, and Marc Van Camp¹

¹ Ghent University

Corresponding author: Kristine Walraevens, U. Gent, Kristine.Walraevens@UGent.be

Abstract:

Geophysical campaigns can contribute very useful information about the presence of saltwater intrusion and the interface depth, both at the local and the regional scale, the latter being especially targeted by airborne methods.

The recent trend towards airborne geophysical campaigns is based on their fast data acquisition. However, caution should be paid when mapping the depth of the fresh/salt-water interface from these data, because the strategy followed for deducing this depth determines the result, which may not necessarily correspond with the depth based on former 1D geoelectrical prospection. Conclusions in terms of changes with respect to the interface depth by comparing results from both campaigns, may then well be incorrect.

The example of the depth of the interface between fresh and salt water in the Belgian coastal plain will be discussed.
Title: Hydrogeophysics to monitor the vadose zone of a karst system

Authors: A. Watlet¹, M.J. Van Camp², O. Francis³, A. Poulain⁴

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Abstract:

The vadose zone of karst systems plays an important role on the water dynamics. In particular, temporary perched aquifers can appear in the subsurface due to changes of climate conditions, diminished evapotranspiration and differences of porosity relative to deeper layers. It is therefore crucial, but challenging, to separate the hydrological signature of the vadose zone from the one of the saturated zone for understanding hydrological processes that occur in the vadose zone.

Although many difficulties are usually encountered when studying karst environments due to their heterogeneities, cave systems offer an outstanding opportunity to investigate vadose zone from the inside. We present results covering two years of hydrogeological and geophysical monitoring at the Rochefort Cave Laboratory (RCL), located in the Variscan fold-and-thrust belt (Belgium), a region that shows many karstic networks within Devonian limestone units.

Hydrogeological data such as flows and levels monitoring or tracer tests performed in both vadose and saturated zones bring valuable information on the hydrological context of the studied area. Combining those results with geophysical measurements allows validating and imaging them with more integrative techniques.

A microgravimetric monitoring involves a superconducting gravimeter continuously measuring at the surface of the RCL. Early in 2015, a second relative gravimeter was installed in the underlying cave system located 35 meters below the surface. This set up allows highlighting vadose gravity changes. These relative measurements are calibrated using an absolute gravimeter. 12 additional stations (7 at the surface, 5 in the cave) are monitored on a monthly basis by a spring gravimeter.

To complete these gravimetric measurements, the site has been equipped with a permanent Electrical Resistivity Tomography (ERT) monitoring system comprising an uncommon array of surface, borehole and cave electrodes. Although such an unconventional ERT setup is challenging in terms of data processing and interpretation, it provides valuable data for inferring variations of the vadose zone saturation rate.
Plateau of Uccle/Ukkel

Avenue De Fré laan

Dieweg

Chaussée de St-Job/Steenweg op St-Job

Alt. ~103 m

You are here
1823 Adolphe Quetelet proposes to build an observatory.
1827 Starting construction in Saint-Josse-Ten-Node.
1833 Starting meteorological observations
Belgium is one of the first countries officially involved in meteorological observations
« L’Observatoire de Bruxelles »
« De Sterrenwacht van Brussel (Saint-Josse ten Noode) »
Idea given in 1876 by Jean-Charles Houzeau, then director of the ROB
1913 Royal Meteorological Institute (RMI) becomes independent

1964: Creating the Belgian Institute for Space Aeronomy
Why an observatory?

- positional astronomy (sailors) & time
- Meteorology (Quetelet presiding the 1st international conference on sea meteorological observations, 1853, Brussels)
- Tides, magnetism
- Fundamental research

- 1836 Great meridian installed by Quetelet, Cathedral of Brussels
  + meridians in 40 cities (A.R./K.B. 1836)

- From 1870: obsolete due to telegraph

Solar Physics and Space Weather
1983 Liège (Ms = 4.7)

In Saint-Nicolas:

**CHIMNEYS**
813 interventions

**FACADES**
356 shored up

**INHABITABILITY**
93 houses

**DEMOLITION**
15 houses

→ 1000 Homeless
→ Total estimated cost: 250 \(10^6\) EUR
→ Disaster Fund: 100 \(10^6\) EUR (current val.)
Seismicity in Belgium: an elevator pitch

- A nationally destructive earthquake occurs on average every 300 years (M~6)
  - 1382 (Southern North Sea)
  - 1580 (Strait of Dover)
  - 1692 (Verviers)
- A small, locally destructive earthquake occurs on average every 10-30 years
  - Liège 1965 & 1983,
The « pavillon » (1908)
Early years 1898-1911

- 1909 : horizontal Wiechert pendulum 1000 kg
- 1910 : vertical Wiechert pendulum 1300 kg
Belgian seismic network

Het Belgisch seismisch meetnet
Le reseau seismique belge
1971: Height increase of the La Gileppe dam
Membach, August 1995: superconducting gravimeter

Absolute Gravimeter

Seismometers

Superconducting Gravimeter
Portable superconducting gravimeter in a field enclosure:
First experiences and results

M. Mikolaj¹, A. Güntner¹, M. Reich¹, S. Schröder¹, H. Wziontek²

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²Federal Agency for Cartography and Geodesy (BKG), Leipzig, Germany
Motivation

- Superconducting gravimeters (SGs) for hydrological monitoring
  - State: Water storage variations
  - Fluxes: Groundwater recharge, Evapotranspiration
  - Products: Derivation of drought or flood indices

- Limitations of observatory gravimeters
  - Disturbed local hydrology in the near-field
  - Reduced hydrological mass variation due to umbrella effect
Motivation

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  - Disturbed local hydrology in the near-field
  - Reduced hydrological mass variation due to umbrella effect
Gravimeter

- Requirements from the hydrologist's perspective
  - Field-deployable: water-/dust-proof, high temperature range
  - Small footprint: minimal umbrella effect
  - High precision: resolve small gravity changes
  - Long-term stability: low drift and no/minimum steps

- Employed gravimeter: **iGrav-006**
  - Compact design: diameter 55 cm, height 1 m, weight 40 kg
  - High precision and low drift: latest generation GWR SG
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Field enclosure

- Field enclosure (iGFE) design:
  - Fits a pillar with 1 m diameter
  - Housing: iGrav, PC, heating and cooling grills, temperature sensors
Peripheral hardware

- Peripheral hardware enclosure (iBox)
  - Distance to iGFE $\sim 15\,\text{m}$, footprint $\sim 2\,\text{m}^2$
  - Housing: compressor, water chiller, PC, power supply + UPS, He-gas bottle, controllers, temperature sensors
Overall layout
Overall layout

- iGFE+iGrav
- iBox
- groundwater well and SM cluster
- topsoil sensors
Overall layout
Installation site

- Wettzell, Germany (Bavaria)
  - Present gravimeters
    - SG029: since 1999, distance to iGrav-006: $\sim 200$ m
    - SG030: since 2010, distance to iGrav-006: $\sim 40$ m
  - Hydro-meteorological instrumentation:
    - groundwater wells, lysimeter, soil moisture TDR clusters, snow pillow and height sensors, meteo station
Calibration and step removal

- No co-located measurements with FG-5 currently possible
  - iGrav-006 calibrated against SG030
- Step removal
  - Visual inspection: steps occurring during invariable ambient conditions
  - Comparison to hydrological model: steps triggered by inclement weather (power outage)
Calibration and step removal

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- Step removal
  - Visual inspection: steps occurring during invariable ambient conditions
  - Comparison to hydrological model: steps triggered by inclement weather (power outage)
Emerging technical issue

- Spurious temperature effects in gravity residuals
  1. Steps in gravity time series if board temperature exceeds threshold
  2. Marked diurnal variations, related to ambient temperature
Hydrological effect: forward modelling

- Soil moisture (SM)
  - 0 – 10 cm: topsoil TOMST sensors
  - 10 – 225 cm: TDR soil moisture vertical profiles
- Vadose zone (VZ)
  - 225 cm — Groundwater (∼ 6 m depth): extrapolation of TDR profile
- Groundwater (GW)
  - Groundwater variation observed at the near-by well
- Global hydrological effect (GHE)
  - GLDAS/NOAH 0.25 degree, for variations beyond 11 km
Hydrological effect: forward modelling vs iGrav residuals

- iGrav residuals:
  - Corrected for tides, atmosphere and polar motion effect
  - Not corrected for drift
Hydrological effect: forward modelling vs iGrav residuals

- iGrav residuals:
  - Corrected for tides, atmosphere and polar motion effect
  - Not corrected for drift

- Hydrological effect:
  - Sum off all compartments (SM, VZ, GW, GHE)
Hydrological effect: forward modelling vs iGrav residuals

- **iGrav residuals:**
  - Corrected for tides, atmosphere and polar motion effect
  - **Corrected for drift**
    - Manufacturer (GWR) estimation: $15 \text{ nm.s}^{-2}$ per month

- **Hydrological effect:**
  - Sum off all compartments (SM, VZ, GW, GHE)
  - **Fitted linear drift: $32.1 \text{ nm.s}^{-2}$ per month**
Field deployment vs. observatory SG

- Comparison of iGrav-006 residuals to SG030 and hydo-meteorological time series
Field deployment vs. observatory SG

- Footprint difference (field enclosure vs. building): 0.8 vs 88 m²
- Theoretical umbrella effect: 1 m deep, 10% soil moisture difference: 1 vs 22 nm.s⁻²
Field deployment vs. observatory SG

- Topographic effect: height difference 4.1 m
- Theoretical effect of a soil layer (10\%, radius 100 m,–umbrella effect):
  \[0 - 1\,\text{m} = 39\,\text{vs}\,6\,\text{nm.s}^{-2}\]
Outlooks

- Calibration and drift estimation
  - Allow for co-located observation with absolute gravimeter
- Improve temperature control
  - Water chiller and heater (one unit)
- Analysis of gravity differences/gradients (with respect to hydrological variations)
  - Differences between iGrav-006 and SG030/SG029
  - Utilizing additional iGrav in a field enclosure
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Eric Brinton (GWR)
Hydrology and gravimetry

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M. Vanclooster - A. Watlet - O. Kaufmann
G. Pajot-Métivier - F. Casenave
O. Crommen - A. Dassargues
Let us take a gravity time series from a superconducting gravimeter.

E.g. the superconducting gravimeter measuring continuously at Membach, since 1995.
Gravity time series 2004-2012

Membach

Observed signal

1000 nm/s²
or $10^{-7}$ g

Modeled tide

After correcting for Earth tide

1000 nm/s²

X10
Gravity time series 2004-2012

Membach

Atmospheric pressure

100 nm/s²
or $10^{-8} \, g$

Newtonian:
-4 nm/s²/hPa

Loading:
+1 nm/s²/hPa

After correcting for tide and pressure

X2.5

Loading:
+1 nm/s²/hPa

Atmospheric pressure

X2.5

Loading:
+1 nm/s²/hPa
Gravity time series 2004-2012

Membach

- Observed signal
  - tide
  - pressure

- Polar motion

- After correcting for tide, pressure, pole

From Chen et al., GRL 2013
Gravity time series 2004-2012

Membach

40 nm/s² or $4 \times 10^{-9}$ g

We work at this level

Observed signal - tide
- pressure
- polar motion
Hydrological model: The Membach station and the gravimeters

Superconducting gravimeter: Continuously since 1995

Absolute gravimeter: since 1996: ~1 measurement/month

+seismometers
Repeated absolute gravity measurements

Advantage: does not depend on the reference system, long term traceability: important when measuring slow phenomena
Repeated absolute gravity measurements: Results

150 nm/s² or 15 \times 10^{-9} g

Slow oscillation? Hydrological effect?
How to get rid of long periodic hydrological effects???

1) Patience : Wait till it’s smoothed...but how long?
Why should patience be rewarding?

Bath integrates drought and rainfalls ➔ random walk

BUT:
Long-term stabilization: limited capacity (0 to 100% water)

Long term=????
1 year? 100 years?
Gravity rate of change as a function of measurement time

➡️ Membach: after 15 years: $2\sigma \sim 0.5 \text{ nm/s}^2/\text{a} \Leftrightarrow 0.25 \text{ mm/a}$

➡️ Repeated $g$ measurements are appropriate to monitor slow deformations
How to get rid of long periodic hydrological effects???

1) Patience: Wait till it’s smoothed... but how long?

2) Application of hydrological models (I am not optimistic)
Data from the superconducting gravimeter

Seasonal variations! (g lower during winter because water is above the gravimeters)
Geological and geophysics investigations, Water content measurements

48 m

Non saturated weathered zone

Digital elevation model:

→ 200*200 m above the station
→ 1600 rectangular prisms, thickness between 1 and 8 m.

4 probes (depth 30-60 cm)
→ measure soil moisture in the weathered, unsaturated zone, 48 m above the station

Volumetric water content

Low porosity bedrock
Vintage picture:
December 3, 2012: 48 m above the station
Applying the local hydrological model

Stdv:
- SG (before): 13.4 nm/s² (after): 10.1
- AG (before): 16.4 nm/s² (after): 12.6
→ Dynamics: desaturation in the model: probes surrounded by soil/humus
Water contained in pores/voids may be drained more quickly
→ When the weathered zone is unsaturated (summer-fall), the model tends to overestimate the gravity effect (and conversely);
→ Due to the hydraulic conductivity (depends a.o. on the degree of saturation, e.g. in winter water may penetrate deeper → more water actually stored?)
Performs well during “dry summers”. Why? “Wet summers”: upper layer dries up (measured by the TDR), whilst lower zones remain wet (no TDR)?

However the transport of water through the soil is complex due to:

- The topography,
- The forested canopy architecture inducing redistribution of the incident rainfall,
- The 3D configuration of the root system inducing spatially variable root water uptake.

Details: Van Camp et al., JGR, 2006
Gravity time series 2004-2012

Diurnal evapotranspiration

We work at a few $10^{-11}$ g level
Ground water content: diminishing during sunny days
Ground water content and gravity
(stacked gravity data)

0.8±0.1 nm/s² ↔ 2.0±0.3 mm water
Ground water content and gravity
Examples on shorter series

0.7 ± 0.3 nm/s² ⇐⇒ 1.8 ± 0.8 mm water

0.5 ± 0.4 nm/s² ⇐⇒ 1.3 ± 1.0 mm water
Ground water content and gravity: winter case

- GWC (2005-2014, 279 days, January)
- Gravity
Converting gravity changes into ground water changes

- 75% of gravity effect from soil water in a radius of 160 m
- 90% for a radius of 410 m \( \Leftrightarrow 53 \text{ ha} \)
Error assessment on the daily gravity change

Error as a function of number of days.

- Precision of 0.2 nm/s²
  - 0.51 mm of water after 70 days (June & July)
We have a direct measurement of evapotranspiration

- Important to
  - Improve hydrological models
  - Better assess water resources

- Important for climate dynamics
  - Mass fluxes
    (e.g. Amazon deforestation could mean droughts for western U.S.)
  - Energy fluxes

Poorly known, not easy to measure
Comparisons

GRACE-superconducting gravimeters

2 sources of information on gravity changes: GRACE & Superconducting Gravimeters

Added value by combining them?
The reality
What GRACE sees
What a land-based gravimeter “sees”

1 point is 1 km x 1 km (in the best case)
How to compare Gravimeters and GRACE?

In both cases: annual signal (not a surprise in geodesy)

- 40 nm/s² ⇔ 4 µGal

Here: superconducting gravimeter in Bad Homburg (DE)

→ Coherent between the gravimeters?
→ Coherent between gravimeters and GRACE?
To compare annual signals: phasor

Maximum within 74 days
(for stations experiencing large amplitude)

What do we learn?

→ Winters are wetter!

Notice: even worse if the sign of underground stations is not inverted
What about Gravimeters & GRACE?
Annual component

No agreement on annual:
- Neither between SGs
- Neither between SGs and GRACE

If agreement: so what?
Annual removed:
Let us look at the interannual

11 on 45 pairs significantly correlated
(anticorrelated if underground-surface pairs)

 совершен
Only little common signal
What can we do with it?
We find Nothing Is this strange?

Similar Forcing (let us assume!)

Complicated transfer function

Annual

Disparate phases & amplitudes

Inter-annual

10 on 45 gravimeter pairs significantly correlated

Details: Van Camp et al., GJI, 2014
Conclusions

We find the case that surface gravity and GRACE data are seeing the same signal to be weak.

Poor correlations between the gravimeters themselves:
→ True for the annual period
→ True for the inter-annual periods

Possible common, long period climate effects?
→ Longer time series & More stations needed

✓ Land-based gravity great for **local** hydrogeological investigations

✓ GRACE great for **large scale** hydrogeological phenomena
Hydrogeophysics to monitor the vadose zone of a karst system

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HG2 workshop
Uccle, 23 October 2015
Why do we study karst systems?

Not only because they are nice places to work in...
They also provide drinking water to 25% of world population

Improve the management of their resources is crucial in a changing world

BUT complicated due to their complex structural heterogeneities
GEOCONTEXT
GEOCONTEXT

Gerny Anticline
Lorette Cave
Rochefort Syncline

Geological Layers
- Trois Fontaines Fm.
- Terre d’Haus Fm.
- Mont d’Haus Fm.
- Fromelennes Fm.
- Nismes Fm.
- Eprave
- Nou Maulin

Lomme
Wamme
GEOCONTEXT
\[
\Delta S = P - ET - R - I
\]

\(\Delta S\) = Epikarstic reservoir variations

\(P\) = Précipitations

\(ET\) = Evapotranspiration

\(R\) = Run off

\(I\) = Infiltration

**Porosity contrast expected**

- Discontinuous Perched Saturated Zone
- Temporary Saturated Zone
- SATURATED ZONE

---

**Highly heterogeneous**: micro- and macroporosity

Consists in sub-systems:

- Caves & conduits (drains, transmissivity)
- Fissures & porous matrix (capacitive)

Unknown connections

Highly **non-linear dynamics**, geometry is **time-dependent** (depends as the degree of saturation)
**Borehole Description**

- **C:** Consolidated limestones
- **P:** Porous limestones

Rapid variation in porosity.
HYDROGEOPHYSICAL APPROACH

Geoelectrical Monitoring

Gravimetric Monitoring

Hydrogeological Data

Groundwater storage variations in the vadose zone (epikarst)

Better understanding of the contribution of the epikarst and unsaturated zones on the water dynamics

Moisture Probes

Drip Counters

Piezometers

Direct measurements for calibration
What is the area of influence of the gravimeters?
Bouguer reduction or plate effect:

\[ \Delta g = 2\pi \rho G H \]

- \( G \): Gravitational Constant
- \( \rho \): Density of water
- \( H \): Variation of water

Cone below (and above) the gravimeter where a certain percent of the plate effect is effective:

\[ r = \sim 10d \]
GRAVIMETRIC AREA OF INFLUENCE

- 90% Bouguer Depth of the watertable (low) at JTR12
- 95% Bouguer Depth of the watertable (low) at JTR12

Geological Layers:
- Trias Fontaines Fm.
- Terre d'Huurs Fm.
- Mante d'Huurs Fm.
- Fromeennes Fm.
- Nimes Fm.

Geosites:
- Eprave
- Nou Maulin
- Piezometers
- Lomme
- Wamme

Aquifers:
- Geny Plateau Aquifer

Legend:
- GF5
- JTR12

Scale:
- 0 200 400 600 800 1,200 1,600 Meters

Orientation:
- N
GRAVIMETRIC AREA OF INFLUENCE

The permanent gravimetric monitoring covers efficiently the studied site and whole the Rochefort karst system (Lorette cave)

The area of influence represents $\pm 22.10^6$ m$^3$ in the vadose zone

The Gerny Plateau aquifer influates poorly (less than 5%) the gravity signal recorded at RCL
GRAVIMETRIC MONITORING RESULTS
GRAVIMETRIC MONITORING RESULTS

Flash Flood
Flash Flood
Flash Flood
Flash Flood
GRAVIMETRIC MONITORING RESULTS

Before

Flood

The saturated zone was flooded
GRAVIMETRIC MONITORING RESULTS
GRAVIMETRIC MONITORING RESULTS

Gravity measurements of all stations show high increases during the flood.

Before

2014-07-09

After

2014-07-11

Flood

2014-07-10

90% Bouguer
Depth of 2 meters

90% Bouguer
Depth of 8 meters

Gravity difference to the gravity mean of a station (nm/s²)
Seasonal gravity variation

Not visible in saturated zone level datasets

Related to vadose zone hydrodynamics
### Seasonal gravity variation

Not visible in saturated zone level datasets

Related to vadose zone hydrodynamics

\[ \Delta g = 80 \text{ nm/s}^2 \]

IF \( \phi = 5\% \) => \( H = 1.35 \text{ m} \)

IF \( \phi = 20\% \) => \( H = 0.33 \text{ m} \)
ERT MONITORING

Borehole for ERT monitoring

Electrical Resistivity Tomography (ERT) Profile

Temperature sensors
Permanent surface profile 48 electrodes – 1 meter spacing

Daily measurements (dipole-dipoles, gradient)


Feb 2015 – up to date: Iris Syscal Pro

Borehole – 31 electrodes – 1 meter spacing

Daily measurements (dipole-dipoles, surface to borehole)

Feb 2015 – up to date: Iris Syscal Pro
Inversion using BERT (Günther & Rücker 2006)

- Robust inversion (L1 norm)
- Rms > 10% (due to high heterogeneities)
- Data converged to $\chi^2 \approx 1$ showing that error model is well fitted
- Corrected for temperature

Shows high heterogeneities in resistivity

- High conductive layer in the surface
- High resistive patterns follow bedding orientation
- Conductive area next to the sinkhole may be related to
  - Clayish layers between limestones beds
  - Infiltration pathways
  - Anisotropy induced by the topography through the bedding orientation
ERT MONITORING RESULTS

Change in resistivity with regard to humid conditions (20 Mar)
Increase in resistivity in the first layers correlated to decrease of gravity
High heterogeneity of the karstic subsurface shown by borehole surveys

Gravimetric monitoring covers efficiently the area of the Rochefort Cave Laboratory

A gravimetric monitoring is able to follow changes in groundwater content of both the saturated and the vadose zone in a karst system

Surface ERT measurements have monitored drying processes of the epikarst in correlation with gravity data
Development of the gravimetric monitoring

Relative gravimeter permanently installed in the cave underneath surface laboratory since Spring 2015

Isolating vadose zone gravity signature

Development of the ERT monitoring

Additional electrodes installed since Summer 2015

- Borehole and cave electrodes (surface-to-borehole and borehole-to-cave arrays)
- Surface electrodes lateral to the surface profile (minimizing subsurface 3D effects)

Integration of direct measurements

- Drip counters already provide useful information on transmissivity
- Moisture sensors and conductivity sensors will help calibrating the data

Rock/soil samples analysis

- Challenging due to high heterogeneity
- Help in fitting parameters for interpreting the data in terms of saturation
Acknowledgments:
We are particularly thankful to V. Hallet, G. Rochez, C. Barcella, Y. Quinif, Ph. Meus, L. Funcken, the Royal Meteorological Institute, M.Vandiepenbeeck, P. Vuylsteke, and all the Lorette Cave’s staff.

THANK YOU FOR YOUR ATTENTION
Barometric and gravimetric effects on water levels in an abandoned underground coal mine

Christophe FRIPPIAT, Mathieu VESCHKENS, Luc FUNCKEN, and Daniel PACYNA
Site location
Péronnes-lez-Binche, Hainaut, Belgium

Coal mines of Ressaix, Leval, Péronnes, Mariemont et Houssu.

Used as an underground gas storage facility from 1975 to 1992.


Now fully decommissioned.
Geology and global structure of the coal field

Coal field divided in two separate areas: Massif de Masse and Massif du Centre Poirier, separated by a faulted zone (Plat Crain)
Groundwater levels in the upper coal field
Shafts equipped with piezometers
Bulk WL measurements (full history)

- Pump initially at -417 m in St Albert
- Pump moved at -222 m in St Albert in 1982
- Pumping stopped in 1998

Questions:
When will the WL reach that of the shallow aquifer?
When will the WL stabilize?
Where will the WL stabilize?
...
Bulk WL measurements (full history)

- Pump initially at -417 m in St Albert
- Pump moved at -222 m in St Albert in 1982
- Pumping stopped

Questions:
- When will the WL reach that of the shallow aquifer?
- When will the WL stabilize?
- Where will the WL stabilize?
- ...
Bulk WL measurements (recent data)

Ste Marguerite

Automatic measurements at time steps ranging between 15” to 2 hours

St Albert

Pressure transducers with vented cables for automatic barometric compensation
Bulk WL measurements (high freq. fluctuations)

What are these fluctuations linked to?

Is it important to take them into account when analyzing the GW rebound?
Sample measurement period – S\textsuperscript{te} Marguerite shaft

Bulk WL fluctuations
Sample measurement period – S\textsuperscript{te} Marguerite shaft

**Bulk WL fluctuations**

**Variations of P\textsubscript{atm}**
Sample measurement period – Ste Marguerite shaft

Bulk WL fluctuations

Variations of $P_{\text{atm}}$

Bulk WL data + effect of filtering for $P_{\text{atm}}$ only
Sample measurement period – S\textsuperscript{te} Marguerite shaft

Bulk WL fluctuations

Variations of $P_{\text{atm}}$

Bulk WL data + effect of filtering for $P_{\text{atm}}$ only

Bulk WL data + effect of filtering for $P_{\text{atm}}$ and Earth tides

BE = 25.1%
Barometric efficiency:

\[ BE = -\rho g \frac{\Delta h}{\Delta P_{atm}} \]

- **Gravity** [m/s²]
- **Density of water** [N/m³]
- **Variation in atmospheric pressure** [Pa]
- **Variation in water level** [m]

**Mechanism:**

A variation of atmospheric pressure is a distributed constraint applied to:

- the surface of water in the piezometer
- the top of the confined aquifer in the subsurface

The variation of pressure is counteracted by:

- the water column only in the piezometer
- partly by the soil/rock matrix and partly by the liquid phase in the aquifer

This change in force equilibrium results in a variation in WL in the piezometer
It can be shown that

\[ BE = 1 - \left( n\beta_w + b\beta_f \right) \]

\[ \beta_f \]

Water compressibility [-]

Soil/rock matrix compressibility [-]

Coefficient related to grain and matrix compressibility [-]

Porosity [-]

If \( BE \to 1 \) : deep aquifer, rigid and poorly compressible aquifer material

It can also be shown that barometric efficiency is linked to aquifer specific storage \( S_s \)

\[ S_s = n \frac{\rho g \beta_w}{EB} \]
In reality, water level response is not instantaneous but time-dependent. Water storage mechanisms in the piezometer cause a delay in response.

Barometric effects also take place in unconfined aquifers. They are linked to the compressibility of the column of air.
Estimation of BE

Clark's method (1967)

\[ \sum W_j = \sum W_{j-1} + W_j \]

\[ W_j = |\Delta h_j| \]

\[ \sum B_j = \sum B_{j-1} + B_j \]

\[ B_j = |\Delta P_{atm,j} / \rho g|. \]

Regression deconvolution method (Toll and Rasmussen 2007)

Implemented in BETCO

(or can be easily coded e.g. in Matlab)

\[ \Delta h(t) = \sum_{i=0}^{m} \alpha(i\Delta t) \frac{\Delta P_{atm}(t - i\Delta t)}{\rho g} \]

Response function

\[ A(\tau = i\Delta t) = \sum_{j=0}^{i} \alpha(j\Delta t) \]
Example application: confined aquifer

- Aquifer response: confined aquifer with piezometer storage
- Most of observed fluctuations are linked to atmospheric pressure
- Filtering highlights long-term smooth trend (recharge)
Earth tides

Earth tide is the periodic upward and downward displacement of the solid Earth's surface caused by the variation in the gravitational attraction forces of the Moon and Sun.

Order of magnitude: 40 cm!

Complex phenomenon:
• Depends on Lunar and Solar position
• Depends on the elasticity of the Earth’s crest
• Depends on the shape/thickness of the Earth’s crest
• Linked to oceanic tides, causing additional periodic loading on the Earth’s crest

Direct consequence: cyclic temporal variations of the Earth’s gravity field
What if there’s no gravimeter near my piezometer?

There are mathematical models for predicting Earth tides...
Results: St Albert
Results: Ste Marguerite
Results: Ste Marguerite (2)
Results: Ste Marguerite (3)
GW rebound – need to filter data
Remaining mysteries…

- Pumping?
- Imperfect filtering of Earth tides?
- Earthquake
- Works around the piezometer
Take home messages

Barometric and gravimetric effects on groundwater levels mostly take place in deep confined aquifers

They are NOT linked to sensor technology (all sensors used here are compensated sensors).

Ignoring these effects can lead to
errors in pumping test analysis
disastrous effects in correlation analyses
biased estimation of recharge mechanisms

more specifically here… biased analysis of groundwater rebound in abandoned mine works

…

They can provide information on aquifer compressibility
Geophysical monitoring to assess underground water distribution and fluxes

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Exploration geophysics
Underground water

- Water distribution, fluxes, pathways
Fields and Topics

- Soil science
  - Soil moisture changes
  - Water fluxes in soil-plant-atmosphere system
- Geotechnics
  - Saturation
- Subsurface hydro(geo)logy
  - General hydrogeologic setting (boundaries, lateral heterogeneities of moisture in the vadose zone, monitoring infiltration...)
  - Groundwater flowpaths
  - Groundwater flows

Large range of scales (space, time)!
Geophysical Tools

- Direct point measurement techniques
  - TDR
  - Neutron probe
- Indirect geophysical techniques
  - In boreholes
    - Electrical conductivity or resistivity logging tools
    - NMR logging
    - Gamma-gamma logging
  - Between boreholes or Surface and boreholes
    - ERT
    - GPR
  - From ground surface
    - ERT
    - GPR
    - MRS
    - SP
- Remote sensing

Focus on ERT
Why ERT?

- Link between water content and electrical properties

- Time-lapse ERT can be used to monitor changes in electrical resistivity linked to groundwater flows when they create variations in water content and/or water conductivity.

- ERT system setup then operated remotely

- Imaging at scales m ⇒ hm (2D/3D)

- Imaging changes within h ⇒ year
General idea

- Soil/Rock samples
- Petrophysical relationship
- Repeated resistivity measures
- Imaging changes in resistivity
- Conversion to changes in water content
- Imaging changes in water conductivity
Water in soils and rocks

- **Porosity**
  \[ \phi = \frac{V_a + V_w}{V_{tot}} \]

- **Saturation**
  \[ S_w = \frac{V_w}{V_a + V_w} \]

- **Water content**
  \[ \theta = \frac{V_w}{V_{tot}} \]

\[ \Rightarrow \theta = S_w \cdot \phi \]
Electrical properties

Conductive and capacitive properties represented by $\sigma^*$, $\rho^*$ or $\varepsilon^*$:  
$$\sigma^* = \frac{1}{\rho^*} = i\omega\varepsilon^*$$

- The electrical property information can be used to qualitatively characterize the rock/soil type as well as the pore fluid properties.

- Petrophysical models can often be used to make more quantitative predictions about rock/soil properties ($\theta$, $\rho_w$, $\phi$, clay content...)

- Underground electrical conduction types (electrolytic, electronic, dielectric)
Water and electricity...

In most of soils/rocks at low freq.: electrolytic conduction

Empirical law for porous, non clayey rocks or soils (Archie’s law):

\[ \rho_b = a S_w^{-n} \phi^{-m} \rho_w = S_w^{-n} F \rho_w \]

Extension to account for surface conductivity (Waxman & Smits)

\[ \rho_b = S_w^{-n} F \rho_w \left( \frac{1}{1+\rho_w \frac{BQv}{S}} \right) \]
ERT Monitoring

- Resistivity related to moisture content (simplest relation based on Archie’s law)
  \[ \rho = \rho_0 \theta^m \]

- Tracking changes in resistivity through time for detecting temporal changes in the moisture content in the vadose zone
  \[ \ln \Delta \rho = -m \ln \Delta \theta \]

rem : \( \rho_0 \) and \( m \) may change through time and even with \( \theta \)!

Pore-water composition (electrolytic solute in both the mobile and immobile domains) has an influence on bulk resistivity
In short...

Vadose zone:
- time-lapse ERT sensitive to changes in $S_w$

$\rho \searrow$: infiltration
$\rho \nearrow$: evapo-transpiration or deep percolation

Saturated zone:
- time-lapse ERT sensitive to changes in $\rho_w$

$\rho \searrow$: increase in ionic concentration of the groundwater
$\rho \nearrow$: dilution of groundwater

Saline tracer experiments are based on imaging a decrease in resistivity on the tracer flowpath.
Dependence on temperature

\[ \rho \uparrow \text{ when } t \downarrow \]

- Simple linear approximation: (Keller & Frischknecht)

\[ \rho_t = \frac{\rho_{25^\circ C}}{1 + \alpha(t - 25^\circ C)} \]

temperature slope compensation commonly used:
\[ \alpha = 0.025 \, ^\circ C^{-1} \]

Not valid when freezing!
Model example

Ex: fitted model from tests on fine grain samples

\( S_w \) [10 – 100%]

\( T \) [5 – 45°C]

\( \rho_w : 26 \ \Omega. \ m \)
ERT – Back to basics

- Image subsurface electrical resistivity distribution
ERT – Measuring R

- Usually quadruple array: 2 Tx electrodes, 2 RX electrodes

\[
R = \frac{\Delta V}{I}
\]

\[
\rho_a = k \frac{\Delta V}{I}
\]
Electrodes Arrays

- Conventional arrays

**WENNER** \( \alpha \)

\[
C \quad a \quad P \quad a \quad P \quad a \quad C
\]

\[k = 2 \pi a\]

**WENNER** \( \beta \)

\[
P \quad a \quad P \quad a \quad C \quad a \quad C
\]

\[k = 6 \pi a\]

**WENNER** \( \gamma \)

\[
C \quad a \quad P \quad a \quad C \quad a \quad P
\]

\[k = 3 \pi a\]

**WENNER SCHLUMBERGER**

\[
C \quad n.a \quad P \quad a \quad P \quad n.a \quad C
\]

\[k = \pi n (n+1) a\]

**DIPOLE-DIPOLE**

\[
P \quad a \quad P \quad n.a \quad C \quad a \quad C
\]

\[k = \pi n (n+1) (n+2) a\]
ERT – Sequence

- Measure $R(\rho_a)$ with different electrode arrays
- Pseudosection
ERT – Inversion

- Discretization

- Look for an effective resistivity model that would have a response similar to measures
ERT inversion

regularisation parameter

- Minimize

\[ \Phi = \Phi_d + \lambda \Phi_m. \]

- Iterative resolution with Damped Least-Squares formulation

\[
(S^T D^T D S + \lambda C^T C) \Delta m_k = S^T D^T D (d - f(m_k)) - \lambda C^T C (m_k - m_0)
\]

with

\[
S_{i,j}(m) = \frac{\partial f_i(m)}{\partial m_j}
\]

- \( m_k \): current model vector
- \( d \): the data vector
- \( f(m_k) \): forward response of the current model
- \( m_0 \): starting or reference model
- \( D \): data weighting matrix
- \( C \): model smoothness matrix
Monitoring

- Site
  - Site description & characteristics
  - Definition of monitoring objectives and principles
  - Site preparation

- Equipment
  - Equipment selection
  - Equipment setup / wiring / electrodes (in place or not, buried or not...)
  - Integrity checks

- Strategies
  - System control
  - Measures : sequences, frequency...
  - Data collection, data quality assessment and data management
  - Data filtering and inversion
  - Interpretation
ERT Monitoring

- Generation of large datasets
  - e.g. 3000 measures/day * 365
  - Gives more than 1 million of measures/year for processing on daily basis
- Necessity to optimize and automatize data processing workflows
Electrodes & Layouts

Electrodes materials (inox, graphite, ...)

- Electrodes laid out along a profile on the surface
- Electrodes spread out on the surface (regular grid or not)
- Electrodes set in boreholes (in the saturated zone or not)
- Electrodes in underground cavities
- Combination of the above layouts
Sequences

$n$-electrode deployment enables the implementation of

\[ n_{4p}^{\text{compr}} = \frac{n \cdot (n-1) \cdot (n-2) \cdot (n-3)}{8} \]

different and non-reciprocal quadrupoles (Xu and Noel, 1993)

\[ \Rightarrow 48 \text{ electrodes : } > 500,000 \text{ arrays} \]
\[ \Rightarrow 96 \text{ electrodes : } \sim 10 \times 10^6 \text{ arrays} \]
Sequence optimization

**Speed up data acquisition**
- Reordering for multichannel systems (parallel or multiplexed systems)

**Design better sequences**
- Sequential design procedures (e.g. Stummer, Wilkinson)
  - Adding sequentially arrays to a base dataset given resolution improvements
  - Removing sequentially arrays from a comprehensive dataset
- Complete dataset (e.g. Blome)
  - Creating a dataset from which a comprehensive dataset can be reconstructed
ERT Monitoring

- Overall sequence measurement time may induce motion blur if rapid changes in resistivity distribution
  - reduce the number of electrodes;
  - reduce single measurement time;
  - reduce number of arrays in sequence (cf. sequence optimization).
ERT acquisition

- Acquisition parameters
  - Waveform (shape, frequency ...)
  - Repetition
  - Tx I, V
  - Rx V
  - Batteries (V, T)
  - ...

- Data error estimation
  Very important for inversion:
  - over-estimation of noise ⇒ over-smoothed images
  - under-estimation of noise ⇒ inversion artefacts
  Error model from reciprocal arrays (e.g. Slater et al.)
ERT Pre-processing

- Data filtering (filter on acquisition parameters)
- Data error analysis, (from reciprocal error)
- System integrity check
- Gap filling (geostat)
System integrity check

Identify problematic electrodes (Bayesian approach)

Threshold on Q

Reliability grid
Example on synthetic data

Faulty

Unreliable

Faulty

Unreliable
Membach monitoring experiment

Site
Forested, on a slope
0-8m of unconsolidated silty cover with blocks over clayey sandstones

Layout
48 stainless steel electrodes
2 m spacing

Acquisition
D-D arrays
twice a day for two years
Membach monitoring experiment

Soil Temp. [°C] @ .6 m

Soil Gravimetric Water Content [%]
ERT Monitoring Inversion strategies

- Independent time slices inversion
- Difference inversion
- Time-lapse inversion (fixed reference model, cascade inversion)
- 4D inversion (Kim, Karaoulis)
ERT Monitoring RCL

Permanent surface profile 48 electrodes – 1 m spacing
- Daily measurements (dipole-dipoles, gradient)

Borehole – 31 electrodes – 1 m
- Daily measurements (dipole-dipoles, surface to borehole)
ERT Monitoring measures RCL
Imaging temporal changes

- Plotting ratio, differences...

- Variable transform to image in terms of saturation (refs.)...
Time-lapse inversion

![Graph showing Tmax and Tmin temperatures over time with X and Y-axis labels for Resistivity/Ratio and X-Axis respectively. The graph includes data points for dates from 11/01/2014 to 3/05/2014.]
Temperature correction

- Subsurface seasonal temperature variation (1D approx.):
  \[ T(z, t) = T_{\text{mean}} + Ae^{-\left(\frac{z}{d}\right)} \sin(\omega t + \phi - \frac{z}{d}) \]

- Parameters fitting from T sensors buried along the profile

- Apply temperature correction on effective resistivities

  \( 1^\circ \text{C results in } \sim 2\% \text{ in resistivity (linear approx.)} \)
Imaging resistivity changes

Surficial drying

% of change in resistivity

Distance [m]

Distance [m]

Distance [m]

Distance [m]

Distance [m]

Distance [m]
ERT Monitoring Inversion

- Very strong contrasts leading to artefacts ⇒ mask deeper infiltration or resistivity changes
- Densify measurement in the upper part of the section (more electrodes)
- Decoupling shallow cells (as suggested by Clement et al. 2009)
Limitations/difficulties

**Petrophysical relationships**
- On samples
- Simplifications
- Several influent variables (hypothesis, external data)

**ERT imaging**
- Time dependent data error and coverage
- Smoothing, artefacts
- Partial recovery of parameters
- Fast changes difficult to track
Integration of geophysical data in hydrogeological models

Thomas Hermans\textsuperscript{2}, Jean Beaujean\textsuperscript{1}\textdagger, Frederic Nguyen\textsuperscript{1}

\textsuperscript{2} appliedgeophysicsulg.wordpress.com

\textsuperscript{1}\textdagger,(* formerly)
Different possibilities to integrate geophysical data

Geophysical images

Mod from Binley et al., WRR, (2015)
Data integration workflows from a deterministic POV

Straightforward, strongly dependent on resolution
Beaujean et al., WRR, 2014

Consistent with process, CPU intensive
A seawater intrusion problem

(Michael et al., *Nature*, 2005)
SWI benchmark

True values
$K \ (\text{m/s}): \ 9.09 \times 10^{-3}$
$\alpha \ (\text{m}): \ 45.7$

Calculated equivalent $K$

Low $K$ facies

True values
$K_h \ (\text{m/s}): \ 9.18 \times 10^{-7}$
$\alpha_L \ (\text{m}): \ 4.5$

$h$

$L$
Uncoupled
Strong dependency on resolution

Error
ERT-derived SMF

Simulated SMF isoline
ERT-derived SMF isoline

Distance perpendicular to the shoreline (m)

-5.9 -5.3 -4.8 -4.2 -3.7 -3.1 -2.5 -2.0 -1.4 -0.8 -0.3

log scale cumulative sensitivity
Calibration results (no conceptualization error)

**Parameters**

- **Poorly estimated Parameters**
  - \( K_{h1} \) (m/s) \((\times 10^{-7})\): 9.18 \(80\)
  - \( K_{h2} \) (m/s) \((\times 10^{-3})\): 9.09 \(8.3\)
  - \( \alpha_{L1} \) (m): 4.5 \(43.7\)
  - \( \alpha_{L2} \) (m): 45.7 \(175.7\)

**Graphs**

- **ALL**: RMS: 26
- **Filtered**: RMS: 4
- **Filtered+BH**: RMS: 13

**ERT-derived Salt mass fraction**
Coupled
Strong dependency on conceptualization

Model error

No model error

Actual conceptualization
Calibration results

ERT data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{h1} ) (m/s) (( \times 10^{-7} ))</td>
<td>( 9.18 )</td>
<td>( 9.18 )</td>
</tr>
<tr>
<td>( K_{h2} ) (m/s) (( \times 10^{-3} ))</td>
<td>( 9.09 )</td>
<td>( 9.09 )</td>
</tr>
<tr>
<td>( \alpha_{L1} ) (m)</td>
<td>( 4.5 )</td>
<td>( 4.5 )</td>
</tr>
<tr>
<td>( \alpha_{L2} ) (m)</td>
<td>( 45.7 )</td>
<td>( 45.7 )</td>
</tr>
</tbody>
</table>

ERT data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{h1} ) (m/s) (( \times 10^{-7} ))</td>
<td>( 11 )</td>
<td>( 11 )</td>
</tr>
<tr>
<td>( K_{h2} ) (m/s) (( \times 10^{-3} ))</td>
<td>( 12.9 )</td>
<td>( 12.9 )</td>
</tr>
<tr>
<td>( \alpha_{L1} ) (m)</td>
<td>( 21.3 )</td>
<td>( 21.3 )</td>
</tr>
<tr>
<td>( \alpha_{L2} ) (m)</td>
<td>( 31.2 )</td>
<td>( 31.2 )</td>
</tr>
</tbody>
</table>
A first conclusion

Geophysics can be used quantitatively if:
- Resolution (images)
- Conceptualization
- Petrophysics

Geophysics should be used 2x for conceptualization and calibration
Uncertainty in Training-Image Based Inversion of Hydraulic Head Data Constrained to ERT Data: Workflow and Case Study

Thomas Hermans\textsuperscript{1}, Frederic Nguyen\textsuperscript{1}, Jef Caers\textsuperscript{2}

\textsuperscript{1}University of Liège, Belgium
\textsuperscript{2}Stanford University, Energy Resources Department
Data integration problem from a probabilistic POV

Pump test

Well data

Geophysical data
Workflow

- Stating of prior geological uncertainty from previous studies
- Probabilistic falsification of stated geological prior with geophysical data
- Inversion and conditioning with falsified prior

Hermans et al., WRR, 2015
Geological prior uncertainty

Study of similar systems

Geological and Hydrogeological studies of the Meuse alluvial aquifer

(Gouw and Erkens, 2007)

Statement of prior uncertainty using training images

Sc1  Sc2

Sc3  Sc4

Sand  Gravel  Clay
Falsification with ERT data

12 profiles were inverted using standard regularization techniques.

Histograms of electrical resistivity per facies can be obtained from borehole information.
Forward modeling by inversion

Model 1

Model 2

Standard geophysical forward/inversion workflow

Inversion Model 1

Inversion Model 2

Field Model – \( D_{ERT} \)
How well does the falsification work? 
synthetic experiments

- What if the scenarios are very different?
- What if the scenarios have only different geometries?
- What if the “reference scenario” (true TI) is not included in the set?
- What if the reference scenario is completely inconsistent with proposed set of TIs

**Monte Carlo experiment**: generate many different true Earth models, verify the average probability of retaining the true scenario
Example MDS plots for 4 “what if” cases

Confusion matrix (%)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SC/SL</th>
<th>SC/BL</th>
<th>MC/SL</th>
<th>MC/BL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC/SL</td>
<td>93</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>SC/BL</td>
<td>11</td>
<td>88</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MC/SL</td>
<td>29</td>
<td>10</td>
<td>51</td>
<td>10</td>
</tr>
<tr>
<td>MC/BL</td>
<td>8</td>
<td>6</td>
<td>19</td>
<td>67</td>
</tr>
</tbody>
</table>
## Included true scenario vs not included

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SC/SL</th>
<th>SC/BL</th>
<th>MC/SL</th>
<th>MC/BL</th>
<th>BL1</th>
<th>BL2</th>
<th>BC</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Classification</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with SC/SL</td>
<td>70</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>without SC/SL</td>
<td>4</td>
<td>32</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>63</td>
</tr>
</tbody>
</table>
Results for the actual field case
## Updating of prior uncertainty

| Scenario | Gravel geometry   | $P(Sc_i)$ | $P(Sc_i|D_{ERT}) - 2D$ | $P(Sc_i|D_{ERT}) - 5D$ |
|----------|-------------------|-----------|------------------------|------------------------|
| Sc$_1$   | Small channels    | 0.25      | 0.2                    | 0.29                   |
| Sc$_2$   | Medium channels   | 0.25      | 0.18                   | 0.14                   |
| Sc$_3$   | Small bars        | 0.25      | 0.27                   | 0.27                   |
| Sc$_4$   | Big bars          | 0.25      | 0.35                   | 0.30                   |
Pre-posterior uncertainty

Pre-posterior probability based on wells and updated uncertainty for prior scenario

Pre-posterior probability based on wells, updated uncertainty for prior scenario and ERT data
Pump test: probability perturbation method

1. Initialization with prior model constraints
   - Generate initial model with MPS
   - Run flow simulation with HGS

2. Outer loop to ensure the convergence
   - \[ \sum_{i=1}^{N} (h_{i}^{\text{ref}} - h_{i}^{\text{calc}})^2 \leq \varepsilon \]

3. Inner loop to optimize the perturbation
   - Choose a value of \( r_0 \), the perturbation parameter
   - Generate a model with MPS
   - Run flow simulation with HGS

- Yes
- Change the random seed to generate new random numbers

- No
- Converge to best \( r_0 \)?

Training Image

- \( r = 0 \)
- \( r = 0.1 \)
- \( r = 0.2 \)
- \( r = 0.3 \)
- \( r = 0.4 \)
- \( r = 0.5 \)
- \( r = 0.6 \)
- \( r = 0.7 \)
- \( r = 0.8 \)
- \( r = 0.9 \)
Matching pump test data
Posterior uncertainty

Posterior

Classification

Probability of gravel

Elevation (m)

X (m)

Y (m)

Elevation (m)

X (m)

Y (m)

Sand  Gravel  Clay
Summary

- Workflow in three steps:
  1) Construction geologically informed spatial prior with multiple scenarios
  2) Validation/falsification of the prior with geophysical data
  3) Inversion of dynamical data using ppm

- Geophysical data is used twice: validation & conditioning

- Future work: extend falsification of scenarios to other types of data or data combinations
Thanks

- Publications may be found at
- orbi.ulg.ac.be

and more info at
- appliedgeophysicsulg.wordpress.com
Bottom-towed resistivity survey to support groundwater modelling of potential leakage during the enlargement of the Juliana canal
Eye-witness report 1933-1935

“Toen wij over een weggetje liepen dat loodrecht op de lengterichting van het kanaal ligt zagen wij reeds op grote afstand van het kanaal aan alle kanten het water uit de grond borrelen en naarmate wij het kanaal naderden des te talrijker werden de kwellen en des te krachtiger werden de waterstralen.

Tenslotte werd het zo dat het er veel van had als was er eenvoudig een goot gelegd, dwars door de kanaalwand. Het lekwater gutste in inderhaast aangelegde sleuven, welke hier en daar dwars de weg doorploegde.”

6 TEST PROGRAM
DELTARES:
• Seismic ‘Chirp’,
• Multibeam echosounder,
• Side Scan Sonar,
• Ground Penetrating Radar.

DEMCO: electric resistivity tomography: bottom-towed.
MAPPEM: electric resistivity tomography: sub-bottom.

AGT: electromagnetic induction/gamma logging in piezometers.
9 RESISTIVITY
12 SURVEY-LINES
13 RESISTIVITY PROFILES

Electric conductivity (mS/m)
14 NAP +37
15 EM/GAMMA-LOGGING
The added value of high resolution hydrogeophysical modelling for unravelling hydrological control of C emission along hillslopes

M. Vanclooster, F. Wiaux, P. Tran, S. Lambot and K. Van Oost

Uccle 23 Octobre 2015
Outline

• Rational of the study.
• The hydrogeophysical and respiration modelling of a hillslope.
• Some lessons learned.
Rational of the study

SOC is major C stock (3 x more than in terrestrial biomass and 2 x more than atmospheric C)
Rational of the study

Source: Andrews (2000)
Rational of the study

1) Soil temperature
2) Soil water content
3) SOC quantity
4) SOC quality

\[ \frac{\partial C_x}{\partial t} = C_x (-K_x \sum_j f_j) \]
Rational of the study
Specificity of hillslopes

- Is this buried OC really stored?
- How is it stabilized?
- How would it behave under changing climatic conditions?
Rational of the study
Specificity of hillslopes

Uncertainty on pools and fluxes!!!

Source: Van Oost (2012)
Rational of the study
Research questions

• General: What are the controlling processes determining C emission variation along a hillslope and how can this be integrated in improved C emission models?

• Specific: What is the spatial variation of soil moisture along a hillslope?

• Specific: How does this spatial variation of soil moisture influences soil respiration?
Methodology

• Experimental (hillslope and laboratory)
  – Pedogenetic – geomorphologic approach
  – Hydrologic – hydrogeophysic approach

• Modelling
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study

Transect le long d’une pente (vue de profil)
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study

<table>
<thead>
<tr>
<th>Summit</th>
<th>Convex shoulder</th>
<th>Backslope</th>
<th>Toesl.</th>
<th>Footslope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Antenne radar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Datalogger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Points de mesure des flux de ( \text{CO}_2 ) en surface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chambre de mesure des flux de ( \text{CO}_2 ) en surface</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Capteurs pour les mesures de profil (TDR, \( T^\circ \) et [\( \text{CO}_2 \)])
Methodology: The hillslope study

[Diagram showing a cross-section of a hillslope with various measurement tools and instruments.]
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study
Methodology: The hillslope study

(a) DGPS antenna
  GPR antenna
  ZVNA
  Laptop

(b) Plot showing response with distance and time.
Methodology: The hillslope study

SOC turnover
\[ \frac{\partial C_x}{\partial t} = C_x (-K_x \prod_{i} f_i) \]

Heat transport model
\[ C_p(\theta) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[ \lambda(\theta) \frac{\partial T}{\partial z} \right] - C_w q_w \frac{\partial T}{\partial z} \]

Hydrological model
\[ \frac{\partial \theta}{\partial t} - \frac{\partial}{\partial z} \left[ k(h) \left( \frac{\partial h}{\partial z} - 1 \right) \right] - Q \]

CO₂ transport model
\[ \frac{\partial C}{\partial t} = -\frac{\partial}{\partial z} \left( J_{da} + J_{dw} + J_{ca} + J_{cw} \right) + S \]
Physical control on soil respiration

Source: Wiaux et al., 2014
Physical control on soil respiration

Source: Wiaux et al., 2014
Physical control on soil respiration

Source: Wiaux et al., 2014
Spatial structure of soil respiration

Source: Wiaux et al., 2014
Spatial structure of soil respiration

Source: Wiaux et al., 2014
Spatial structure of soil respiration

Summit

Footslope

Source: Wiaux et al., 2014
Spatial structure of soil respiration

Summit

Footslope

Source: Wiaux et al., 2014
Spatial structure of soil respiration

Measured soil moisture

Source: Wiaux, 2014
Spatial structure of soil respiration

Calculated diffusivity

Source: Wiaux, 2014
Spatial structure of soil respiration

Source: Wiaux, 2014
Improved monitoring of soil moisture along the hillslope

Source: Tran et al., 2015
Improved monitoring of soil moisture along the hillslope

Date: 13/04/2011

Source: Tran et al., 2015
Improved monitoring of soil moisture along the hillslope

Source: Tran et al., 2015
Improved monitoring of soil moisture along the hillslope

Source: Tran et al., 2015
Improved monitoring of soil moisture along the hillslope

Source: Tran et al., 2015
Take ahome message

• The hillslope is a very interesting scale for studying hydro-geo-eco-physical processes (e.g. soil respiration).

• Hydro-geo-physical and pedogenetic controls on soil respiration could be quantified (basic modelling equations were revisited).

• New approaches (data fusion) could be implemented for improving the monitoring of hydrological controls on soil respiration.

• ERT was not working for elucidating hydrological control on soil respiration.
References

- Wiaux, François; Cornelis, Jean-Thomas; Cao, Wei; Vanclooster, Marnik; Van Oost, Kristof, 2014. Combined effect of geomorphic and pedogenic processes on the distribution of soil organic carbon quality along an eroding hillslope on loess soil. Geoderma, 216: 36-47.
Salt water intrusion:
Mapping the interface depth

Kristine Walraevens, Alexander Vandenbohede, Marc Van Camp
MAPPING THE FRESH-SALT INTERFACE BY GEOPHYSICAL PROSPECTION

DC resistivity electrical method: used since late 1930s (e.g. Belgian coastal plain: De Breuck et al., 1974, 1989)

New methods, e.g. Airborne electromagnetic surveys

HOWEVER: how to compare both results?
Hypothetical salinity profile and the resulting pore water and bulk resistivity as a function of depth for a range of values of $F$, $\rho_m$ and $f_{ll}$.

Transition zone in terms of $\rho$ is shifted upwards compared to TDS! (more with increasing $\rho_m$, decreasing $F$ and increasing $f_{ll}$)
Measuring $\Delta V$ and $I$:

$$\rho = \frac{\Delta V}{I} G$$

Archie’s law (1942) (for non-conductive rock matrix):

$$F = \frac{\rho_b}{\rho_w}$$

Patnode & Willie (1950) (when $1/\rho_m$ becomes important):

$$\frac{1}{\rho_b} = \frac{1}{\rho_m} + \frac{1}{F\rho_w}$$

Relation TDS (g/l) – pore water conductivity:

$$TDS = \frac{10f_{11}}{\rho_w}$$

**VES:** interpretation as discrete layers, each with constant $\rho_b$, while true resistivity profile has gradually changing $\rho_b$

**VES-interface:** in general, in middle of transition zone of $\rho_b$
Hypothetical salinity profile and the resulting pore water and bulk resistivity as a function of depth for a range of values of $F$, $\rho_m$ and $f_{ll}$.

Transition zone in terms of $\rho$ is shifted upwards compared to TDS! (more with increasing $\rho_m$, decreasing $F$ and increasing $f_{ll}$)
Measured pore water resistivity and calculated TDS and bulk resistivity as a function of depth. VES interface at 17 m.

VES data and interpreted geological model for field example: interface was found at 17 m. (above: $\rho_b$ is 45 $\Omega$m; below $\rho_b$ is 1.6 $\Omega$m)
Plot of bulk resistivity below interface mapped by De Breuck et al. (1974) as a function of bulk resistivity above interface.
Table 1 The range of bulk resistivity for different natural materials (after De Moor and De Breuck, 1964, Marechal et al., 1957 and Marechal et al., 1970).

<table>
<thead>
<tr>
<th>natural material</th>
<th>bulk resistivity $\rho_b$ (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry sand</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>sand with fresh pore water</td>
<td>40 - 100</td>
</tr>
<tr>
<td>loam with fresh pore water</td>
<td>25 - 40</td>
</tr>
<tr>
<td>arenaceous clay with fresh pore water</td>
<td>15 - 30</td>
</tr>
<tr>
<td>clay with fresh pore water</td>
<td>6 – 15</td>
</tr>
<tr>
<td>sediments with saline pore water</td>
<td>1 - 10</td>
</tr>
</tbody>
</table>

$< 6 \ \Omega m$: clearly salinized sediments  
$< 3 \ \Omega m$: highly salinized sediments

However, do not take 6 Ωm (or any resistivity value) as value for the interface!!!
CONCLUSIONS BASED ON COMPARISON
OF RESULTS OF BOTH METHODS
↓
MAY WELL BE MEANINGLESS
Depth of the interface Dar es Salaam (Mtoni, 2013)

- 107 available VES (DDCA)
- 177 EC measured on GW
- 8 new VES
- 6 horizontal electrical profiles
- Vertical water resistivity logging in 13 boreholes
Interface deduced from VES at 9.31 m depth (above: 27 Ωm, below 2 Ωm)
Water resistivity logging in borehole B1

interface at 10 m depth
Horizontal resistivity profiling from sea shore inland
Delimitation of salt-water intruded zone

Mapping of interface depth
Spectral Induced Polarization Response of Soil Contaminated with Organic Pollutants

Nimrod Schwartz
Motivation for SIP (and geophysical) methods

- To obtain a spatiotemporal map of the subsurface properties.

- To monitor, in a non invasive fashion, process occurring within the subsurface.
Induced Polarization principle
frequency domain

Applying oscillating electric field and measuring current.

\[ E = E_0 \exp(i\omega t) \]

\[ \sigma^* = \sigma' + i\sigma'' \]

\[ = |\sigma^*| e^{i\phi} \]

\[ J_t = J_c + J_d \]

\( \sigma' \) related to dissipation processes (related to \( J_c \))

\( \sigma'' \) related to energy storage (related to \( J_d \))
Electrical conductivity (in-phase, $\sigma'$) in porous media

- Related to
  - Water content
  - Pore water salinity
  - Geometry
  - Surface conductivity relevant for high clay content

\[
\sigma' = \frac{\sigma_w}{F} S_w^a + \sigma_s^{DC}
\]
Polarization of porous media (quadrature conductivity, $\sigma''$)

- Frequency dependent
  - Low frequency range (mHz – KHz) – Electrochemical polarization
  - Medium frequency range (KHz to hundreds of MHz) – Interfacial polarization (also known as Maxwell-Wagner polarization)
Electrochemical Polarization

- Related to the polarization of the electrical double layer
- Stern layer polarization (Revil and colleagues)
- Membrane Polarization (Marshall & Madden, Titov)

Revil & Florsch (2010)
Stern layer polarization

- Application of an external electric field resulted in a displacement of charge in the direction of the field

Governing equation (PNP)

\[
\frac{\partial \Gamma}{\partial t} = \nabla \cdot (D \nabla \Gamma + \Gamma \beta \nabla \psi)
\]

Solution

\[
\Gamma = -\frac{e\Gamma_0}{(1+i\omega\tau)kT} \psi \quad ; \quad (\tau = \frac{r^2}{2D})
\]

\[
J = e\nabla \Gamma \quad \Rightarrow \quad \sigma^* = \frac{J}{E} = \frac{2\beta e\Gamma_0}{r} \left( \frac{i\omega\tau}{1+i\omega\tau} \right)
\]
Membrane polarization

✧ Polarization due to accumulation of charge at pore throat
✧ Does not distinguish Stern and diffuse layers
✧ Length scale related to the pore size
✧ Does not explicitly consider the chemistry of the surface.

\[ m = \frac{4(\Delta T)^2}{\left(\frac{l_1}{S_1} + \frac{l_2}{\alpha_2 S_2}\right)\left(\frac{S_1}{l_1} + \frac{S_2}{l_2}\right)} \]
Outline

✧ Determine the impact of organic contaminants on SIP response (especially polarization)

✧ Three sets of experiments: mixture, organic cation & free phase

✧ Water-wet surface

✧ Saturated and unsaturated condition

✧ Stern layer and membrane polarization mechanism
Mixture of Contaminants

✧ Unsaturated soil with diesel fuel

✧ Increase in $\sigma'$ despite the addition of non-conductive liquid

✧ Decreases in $\sigma''$, despite the increase in $\sigma'$. 

Schwartz et al, GJI (2012)
Organic Cation

✧ Method

✧ Sodium homo-ionic saturated soil
✧ Flow through experiment with organic cation
✧ Electrical and chemical measurements
✧ Stern layer polarization model

Schwartz et al, JGR (2013)
In-phase conductivity

In-phase conductivity

Solution conductivity

✧ Real part increase with increasing EC at the outlet
✧ CV concentration at the outlet = 0
✧ EC increase as a result of exchange process between Na and CV
Polarization

✧ Significant decrease in polarization at the relaxation frequency
Modeling

✧ Chemical complexation model

\[\begin{align*}
\text{XO}^- + \text{H}^+ & \Leftrightarrow \text{XOH}, \quad K_1 \\
\text{XOH} + \text{H}^+ & \Leftrightarrow \text{XOH}_2^+, \quad K_2 \\
\text{XO}^- + \text{Na}^+ & \Leftrightarrow \text{XONa}, \quad K_3 \\
\text{XO}^- + \text{CV}^+ & \Leftrightarrow \text{XOCV}, \quad K_4
\end{align*}\]

✧ Calculating surface site density of Na and CV

\[
\sigma_s^* = \frac{2}{r_0} \left( \sigma_d + \left( 1 - \frac{1}{1 + (i\omega\tau_0)\alpha} \right) \sum_i e^{\beta_i} \right) \sum_i \sum_i \frac{e^{\beta_i}}{\Gamma_i}
\]

\[\beta \text{ ??}\]
Modeling

✧ Ionic mobility – a key factor in the polarization response.

✧ Sodium form outer-sphere complex with the surface

✧ Organic molecule expel water from the surface, forming a strong inner-sphere complex with the mineral surface

✧ Mobility of organic molecule on the surface is lower than common inorganic cation

Adopted from Chorover and Brusseau (2009)
Conclusion

✧ Exchange process between inorganic and organic significantly impact polarization

✧ Inner-sphere complexes of organic compounds at the Stern layer resulted in a low mobility

✧ Decrease in mobility resulted in a decrease of the soil polarization

✧ Exchange process also affect the in-phase conductivity.
Free Phase NAPL

✧ Method

✧ Mixing water-wet soil (unsaturated) with decane

✧ Constant water content

✧ Electrical and chemical analysis

Shefer et al, WRR (2014)
Free Phase NAPL

✧ Results

✧ No change in real part of conductivity

✧ Decrease in polarization and relaxation time

✧ No change in chemistry (inorganic)
Free Phase NAPL

- Organic phase effect the distribution of the conductive fluid (water)
- Decrease in relaxation time and polarization can be explained by the narrowing of the pore bottleneck
Summary

- Polarization is affected by the presence of organic contaminants (mixture, adsorbed, free phase)

- Two main mechanisms were identified:
  - Exchange process between inorganic and organic compounds
  - Changes in the geometry of the conductive (water) phase

- The results suggest that both Stern layer and membrane polarization need to be considered

- A unified model is needed
Hydrogeological dynamic variability in the Lomme Karst System (Belgium) as evidenced by dye tracing and monitoring data (KARAG Project)
Study site

- Rochefort → South Belgium
- Givetian limestones (Middle Devonian, 385 Ma)

One of the longest karst hydrosystem in Belgium (~10 Km)

Geological background: Blockmans and Dumoulin, 2013
Barchy, Dejonghe and Marion, 2014.
Lomme Karst System
Rochefort - Belgium

- Givetian karst aquifer (limestone)
- Impervious shales
Lomme Karst System
Rochefort - Belgium
Lomme Karst System
Rochefort - Belgium

800 liters/sec

Eprave Resurgence

WAMME RIVER

LOMME RIVER
Lomme Karst System
Rochefort - Belgium
Lomme Karst System
Rochefort - Belgium

Sinkhole
Clayey layer

Epraye Resurgence

WAMME RIVER

LOMME RIVER
Lomme Karst System hydrogeological dynamic – A. Poulain

Confluence

Nou Maulin cave

LOMME RIVER

Lorette underground river

Pré au Tonneau cave

Rochefort cave

Fault zone

Northern River

Southern River

Thier des Falizes cave

Confluence

Lorette river
**Lomme Karst System**

Rochefort - Belgium

- Sinkhole
- Clayey layer

**Organization of underground streams?**
**Karst aquifer dynamic?** **Floods?** **Compartment?**

**Relationship between rivers and karst aquifer?**
Methodology

Lomme Karst System
Rochefort - Belgium

- CTD-Diver (24)
- Gauging station (6)
- Meteo station

Eprave Resurgence

WAMME RIVER

LOMME RIVER

N
Methodology

Lomme Karst System
Rochefort - Belgium

- Injection point (6)
- Field fluorometer (4)

Pré au Tonneau cave

Wamme sinkhole

Northern river

Eprave Resurgence

South. river

Lorette river

Albillia Switzerland
Results – Tracer tests

September 2014 – Low flow conditions (1-2 m³/sec) → 6 tracer injections (uranine & sulpho-B)
Results – Tracer tests

**September 2014** – Low flow conditions (1-2 m³/sec)

→ 6 tracer injections (uranine & sulfo-B)

The **South « connection »**
Results – Tracer tests

**September 2014** – Low flow conditions (1-2 m³/sec)
→ 6 tracer injections (uranine & sulpho-B)

The North « connection »
Results – Tracer tests

- Compartments 1: Northern connection Wamme
- Compartments 2: Southern connection Lomme

Water dynamic in both compartments?
Results – Monitoring

Water level, temperature and electrical conductivity to precise groundwater dynamic
Results – Floods

15m³/sec < Lomme River discharge < 25m³/sec
Surface river overflows compartment 1
Results – Floods

Lomme River discharge $> 25 \text{ m}^3/\text{sec}$
Surface river overflows compartments 1 + 2
Results – Monitoring

Lomme Karst System hydrogeological dynamic – A. Poulain
Results – Monitoring

- Lomme Karst System hydrogeological dynamic – A. Poulain

Graph showing monitoring data from October 2013 to September 2014.
Results – Monitoring

Jan 14  Feb 14

- Electric conductivity (µS/cm)
- Temperature (°C)
- Water level (m.a.s.l.)
- Lomme Riv. discharge (m³/sec)

Surface River  Lorette River
Nou Maulin cave  Pré au Tonneau cave
Val d'Enfer  Grand Bleu
Northern River  Southern River
Results – Monitoring

Jan-Feb 2014 – High flow conditions

- Floods into southern compartment highlight the groundwater organization
- Same °T and EC variations for Lorette River and Southern River
- Northern River shows a different signal
## Results – Monitoring

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**Elect. conductivity (µS/cm)**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Temperature (°C)**
- Oct 13: 5°C
- Nov 13: 10°C
- Dec 13: 15°C
- Jan 14: 20°C
- Feb 14: 25°C
- Mar 14: 10°C
- Apr 14: 15°C
- May 14: 20°C

**Water level (m.a.s.l.)**
- Oct 13: 160 m
- Nov 13: 165 m
- Dec 13: 170 m
- Jan 14: 175 m
- Feb 14: 180 m
- Mar 14: 165 m
- Apr 14: 170 m
- May 14: 175 m

**Lomme Riv. discharge (m³/sec)**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Lorette River**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Nou Maulin cave**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Pré au Torneau cave**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Val d’Enfer**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Grand Bleu**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Northern River**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

**Southern River**
- Oct 13: Low
- Nov 13: Moderate
- Dec 13: High
- Jan 14: Moderate
- Feb 14: High
- Mar 14: Low
- Apr 14: Moderate
- May 14: High

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Lomme Karst System hydrogeological dynamic – A. Poulain
Results – Monitoring

Lomme Karst System hydrogeological dynamic – A. Poulain
Jun-Sept 2014 – Low flow conditions
- Same $T^\circ$ and EC variations for Northern River and Southern River
- Lorette River shows a different signal
Related problematic

- **Gerny Plateau** (20 km²)
- No surface drainage
- **Outlet = LKS** (5 km²)
- Huge hydrogeological potential

**Annual recharge**

= 6 millions m³

- Relationship with LKS?
- Under syncline flow?
Conclusions

- 10 km long karst system with several observation points
- Opportunity → Data from the entire system (not only the final spring)
  - Tracer tests and monitoring highlight a complex internal dynamic
  - Opportunity to understand the components of spring signals
- Takes time and implication on the field
  - Cave surveys, probe installations, fluorometer installation
  - Data collection: good compromise between frequent survey /loss of data because of technical problems
Acknowledgements

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Visit us online!
www.KARAG.be

Thank you for your attention!
Any questions?

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