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WP3 D3.3 D8

Report: Critical assessment of emerging techniques for in situ monitoring of water content and fluxes

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Enigma ITN

WP3 - Quantify temporal changes in subsurface water content and fluxes distributions

D3.3/D8: Report: Critical assessment of emerging techniques for in situ monitoring of water content and fluxes

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Objectives of this Workpackage

The objective of WP3 is the development and field validation of novel techniques for characterizing temporal changes in the spatial distribution of flow and water content in the subsurface. These methods will go beyond classical approaches of static subsurface characterization, explore the potential of emerging techniques, and validate prototype instruments for monitoring temporal fluctuations in the distribution of subsurface fluxes, water content and exchanges with surface water bodies.

Four different techniques are explored, focusing, on the one hand, on the subsurface water content quantification (ESR 5 and ESR 8) and, on the other hand, on the groundwater flux estimation (ESR 6 and ESR 7). Based on existing knowledge, new approaches are developed with the aim of applying the latest technology in order to make in situ data acquisition productive and reliable. The combination of these techniques could allow for a better subsurface water processes understanding, broadening the possibilities in terms of groundwater dynamics monitoring and prediction.

Description of work

The identified activities are (i) investigate the potential of seismic and V_P/V_S methods for monitoring temporal changes in water content distribution (ESR 5), (ii) design quantitative multi-scale thermal imaging techniques for characterizing fluid flow distributions based on passive and active fiber optic distributed temperature sensing (FO-DTS) and unmanned aerial vehicles (ESR 6 and ESR 7), and (iii) validate the first prototype of a portable absolute gravimeter for monitoring water content distributions at different times without the need for a fixed reference (ESR 8).

These activities are carried out independently by the ESRs and their institutions in order to develop and validate the different techniques. At a later stage, all the different tools and approaches can be tested simultaneously, providing insights on how to improve the tools individually but also how they may complement each other.

In terms of using seismic methods for the study of water saturation changes in near surface applications, we investigate forward and inverse approaches for P-wave refraction tomography and surface wave dispersion analysis using rock (or soil) physics relationships. We study and compare the different theories that define elastic moduli and wave propagation velocities with the aim of finding a good method to quantitatively estimate water saturation from the seismic data.

The use of heat as a tracer to estimate groundwater fluxes follows two different approaches. 1) We use Active FO-DTS to estimate the flow velocity inside the porous media and to gain knowledge on the flow field. Then the flow field is used to find an appropriate description of the aquifer properties via inversion. 2) We use Passive FO-DTS, temperature profiling and thermal infrared imaging in order to obtain a thermal characterization of the subsurface water that is then studied and modelled in order to estimate exchange fluxes with the surface.

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Hydrogravimetry aims at observing mass changes caused by subsurface water content changes. The direct, integrative and non-invasive gravity method can contribute as a constraint on storage terms in hydrological modeling and hydrogeophysical inversion. In preparation of the field validation of a new, portable absolute quantum gravimeter, other absolute (iGrav, FG5) and relative (CG5) data as well as surveys of the vertical gravity gradient are combined with hydrological modelling.

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Introduction and literature review

In this section, a review on the most representative studies on our topics is presented. We address each of them focusing on our common goal: monitoring water content and fluxes in situ.

By reviewing the existent knowledge, we expect to get an overview of what and how has been done so far, generating with it a brainstorming process that could lead not only to new ideas to apply to our field sites but also to potential applications of several of our studied methods to combine their strengths.

Although we share a common objective, our methodologies differ substantially both on the way they are applied in the field and on the theoretical background needed to use them. That is the reason why we divide this section in four different parts: Seismic methods, fiber optic distributed temperature sensing methods, thermal imaging methods and gravimetric methods.

1. Seismic methods for monitoring saturation changes in the critical zone

1.1 Introduction

Seismic methods provide information about contrasts in mass densities and propagation velocities in the subsurface. The changes in density and velocity depend on material composition, porosity, state of stress, and degree of saturation. Nevertheless, it is not straightforward to determine how each of these properties contributes to the contrasts solely from the seismic signal. In this regard, rock physics and poroelasticity act as a link to study the relationships between changes in properties and seismic response.

In hydrologic settings, seismic methods have been used for decades to assess the hydrogeologic framework and hydrologic boundaries of aquifers (Haeni, 1988). However, the geophysical observation of fluid distribution had been more difficult because of a poor understanding of how materials respond to saturation (West and Menke, 2000). More recently, the relationships between seismic and hydrological properties have been studied, and they have been helpful for solving the forward problem of predicting the seismic velocities and attenuation from knowledge of porosity, saturation, and permeability (Pride, 2005).

Although the solution to the inverse problem is not fully developed, the use of wave propagation velocities estimated from seismic data has become more popular to characterize the near surface. The behavior of shear (S) and pressure (P) waves in the presence of water is partially decoupled, such that the ratio of their propagation velocities V_P/V_S is strongly linked to water saturation. The use of V_P/V_S, Poisson's ratio or derived parameters seems promising for the estimation of water content variability over decametric spatial scales.

In time-lapse field applications, V_P and V_S profiles retrieved from P-wave refraction tomography and surface wave dispersion analysis have been used to study temporal and seasonal changes in aquifers and earthworks (Pasquet et al., 2015; Bergamo et al., 2016a; Bergamo et al., 2016b; Dangeard et al., 2016). The observations of these studies validate the interest in using seismic data to monitor saturation changes.

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In this section, we explain the methods of interest for retrieving V_P and V_S profiles from seismic data: P-wave refraction tomography and surface wave dispersion analysis. We continue by discussing the link between the mechanical properties of unconsolidated media and propagation velocities.

1.2 Seismic methods in near-surface applications

In P-wave refraction tomography, the travel distance and travel time information from seismic data allow reconstructing a V_P model of the subsurface; the method is based on identifying P-wave first arrival times and tracing the corresponding rays to build the V_P model. Figure 1 shows a basic tomography workflow.

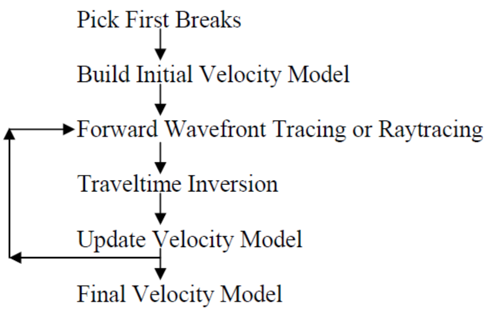

Figure 1. P-wave refraction tomography workflow. (Zhang, 2009).

In surface wave dispersion analysis, the dispersion curves from seismic data can be used to obtain a V_S profile. The procedure for subsurface characterization using surface waves is based on two steps: estimating the experimental dispersion curve from the surface wave propagation, and inverting this experimental dispersion curve to obtain a V_S estimate which is strongly linked to the material's stiffness (Foti and Strobbia, 2002; Socco et al., 2010). Figure 2 shows an example of dispersion curves for a synthetic V_S profile.

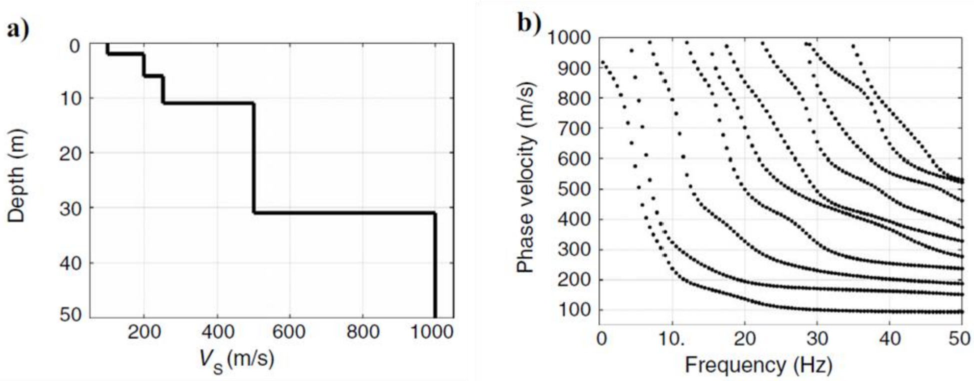

Figure 2. a) Synthetic S-wave velocity profile, b) corresponding modal dispersion curves. (Modified from Socco et al., 2010).

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The joint use of P-wave refraction tomography to retrieve V_P and surface wave dispersion analysis to estimate V_S has become more popular when characterizing the near surface and monitoring temporal saturation changes (Pasquet et al., 2015; Bergamo et al., 2016a; Bergamo et al., 2016b; Dangeard et al., 2016). Pasquet et al. (2015) used both V_P and V_S 1D profiles to detect different water table levels in an aquifer; furthermore, they discuss the usefulness of V_P/V_S and Poisson's ratio in providing more hydrological information from the partially saturated zone. Bergamo et al. (2016a, 2016b) analyzed V_P and V_S 2D sections separately to monitor seasonal changes in a railway embankment; they conclude that the changes they observe in the seismic data are consistent with the seasonal variations and recorded precipitation on the site. Similarly, Dangeard et al. (2016) studied seismic data from two different time periods in a hydrogeological observatory; they analyzed the differences in P-wave traveltime and Rayleigh wave phase velocity to image temporal variations of mechanical properties associated with water content. The observed variations validate the interest in using seismic data to monitor saturation changes.

1.3 Mechanical properties of unconsolidated granular media

The seismic signal is certainly related to mechanical properties that partly depend on porosity and saturation. Therefore, it is important to study and understand the theories that define the elastic moduli of materials.

The effective elastic properties of packings of spherical particles depend on normal and tangential contact stiffnesses of a two-particle combination. For a random sphere packing, effective bulk and shear moduli can be expressed through porosity ϕ, coordination number C (the average number of contacts per sphere), sphere radius R, and the normal and tangential stiffnesses (Mavko et al., 2009). There are several models that describe the effective bulk and shear moduli in terms of these parameters, with the Hertz-Mindlin model being probably the most known (after Hertz, 1896 and Mindlin, 1949).

However, granular media have properties lying somewhat between solids and liquids and are sometimes considered to be a distinct form of matter. Complex behavior arises from the ability of grains to move relative to each other, modify their packing and coordination numbers, and rotate (Mavko et al., 2009). Several authors have shown that this complex behavior causes effective medium theory (EMT) to fail in cohesionless granular assemblies (Goddard, 1990; Makse et al., 2004; Tournat and Gusev, 2010).

The main prediction of EMT is the scaling of the bulk modulus, K, and shear modulus, G, with the stress, P, as $K \sim G \sim P^{1/3}$. However, there is a large volume of experiments for irregular sand grains as well as spherical glass beads (for a comprehensive review see Goddard, 1990, and for a review in the geotechnical literature see Richart et al., 1970) which show anomalous scaling characterized by exponents varying between 1/3 and 1/2 (Makse et al., 2004; Pride, 2005).

Different approaches have been proposed to try to overcome the discrepancies between EMT and observed behavior. As EMT usually treats the coordination number C as a constant, Goddard (1990) proposed a C dependent on stress. Pride (2005) then used this definition within the Walton model

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(similar to the Hertz-Mindlin model, c.f. Walton, 1987) to define the effective moduli. Makse et al. (2004) found that the bulk modulus is reasonably well defined with the simple EMT, but it is inadequate in describing the material's response under shear perturbations, suggesting a new scaling behavior with stress. In their laboratory experiments, Jacob et al. (2008) also estimated different stress dependence than that of EMT and expressed wave propagation velocities as a combination of a coefficient depending mainly on the elastic properties of the grains, porosity and coordination number, and the stress to the power-law exponent found with their experiments.

Until now we have only discussed dry cases. Complexity arises with the presence of water since the moisture amount affects the cohesion of the material, resulting in changes of stiffness and, consequently, of wave propagation velocities (West and Menke, 2000; Cho and Santamarina, 2001).

To estimate the elastic moduli and the wave propagation velocities of a partially saturated and saturated medium, we have to explore the fluid substitution problem. Generally, when a medium is loaded under an increment of compression, such as from a passing seismic wave, an increment of pore-pressure change is induced, which resists the compression and therefore stiffens the material (Mavko et al., 2009). The low-frequency Gassmann-Biot (Gassmann, 1951; Biot, 1956) theory predicts the resulting increase in effective bulk modulus of the saturated medium and considers the shear modulus as fluid-independent. Furthermore, the presence of fluid increases the material's density which also affects the propagation velocities.

In the geotechnical community, authors usually study the changes in shear strains with varying saturation. Several studies have highlighted the sensitivity of seismic velocities to changes in soil suction (Cho and Santamarina, 2001; Mancuso et al., 2002; Donohue and Long, 2010) and present empirical relationships for shear modulus or shear wave velocity.

In more recent applications of seismic methods in near surface applications, Pasquet et al. (2016) used a rock physics model based on Hertz-Mindlin contact theory to estimate porosity and saturation of a shallow hydrothermal system from V_P and V_S calculated from seismic data (Figure 3). Using the model, they predicted V_P and V_S for a mineral composite over a range of possible porosities and saturations, and then found the porosity and saturation values that produced a better match with the seismic velocity profiles. Finally, they discuss the consistency between the changes observed in the seismic data and the estimated parameters.

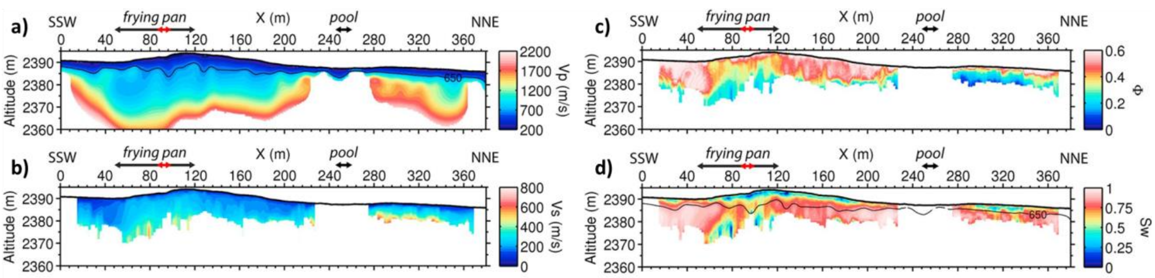

Figure 3. a) VP model from P-wave refraction tomography, b) VS model obtained from surface-wave dispersion analysis, c) porosity (ϕ) and d) water saturation (Sw) models calculated from the seismic data using a rock physics model. (Modified from Pasquet et al., 2016).

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2. Fiber-Optic DTS methods to monitor subsurface flow dynamics

2.1 Introduction

Adequate understanding of groundwater flow direction and magnitude at both regional and local scale can lead to more advanced management of groundwater resources, Aquifer Thermal Energy Systems (ATES), remediation sites and other subsurface infrastructures. Introducing Distributed Temperature Sensing (DTS), that allows to measure the temperature both in time and space along the fiber optic, has opened a new horizon in the use of heat as a tracer to discern groundwater flow. Optical fibers are harmless to the environment and suffer low losses over great distances which leads to the applicability for large area distributed network sensing. Even though DTS system employment is rapidly evolving, the application of DTS for hydrogeology is still in the development phase and requires further investigation especially in terms of quantitative interpretation of water flow. Active Fiber-Optic DTS, in which heat is also added to the DTS system, has proven to be a successful substitution of passive heat tracer that uses normal DTS especially for flux and velocity measurements. This feature allows us to better understand the heterogeneity of sedimentary aquifer systems. Understanding groundwater flow helps to detect well clogging and to cope with sediment heterogeneity especially in fluvial deposited sediments. This can be achieved by measuring groundwater flow in detail and in real-time using Active Distributed Temperature Sensing (A-DTS).

2.2 Passive and Active DTS

Distributed temperature sensing (DTS) systems rely on an optoelectronic device that can measure temperature at regular intervals over meters to kilometers based on the change of temperature-dependent light transmission characteristics in a fiber optic (FO) cable. Optical fiber (OF)-based sensors have been intensively investigated for a wide variety of applications (e.g., temperature, strain, pressure, rotation, displacement, refractive index (RI), polarization, ultrasound, pH, CO2, O2, cells, proteins, and DNA). The working principle is based on sending short laser light pulses and recording shifted frequencies of the backscattered lights as shown in figure 4. The location of the backscattered light, which also convey its temperature information, can be found considering the speed of the light (constant even in a fiber), the time at which the light pulse was emitted and the returning time of the backscatter lights. Continuous monitoring of backscattered light allows construction of the distributed temperature measurement along the length of a cable (Smolen et al., 2003).

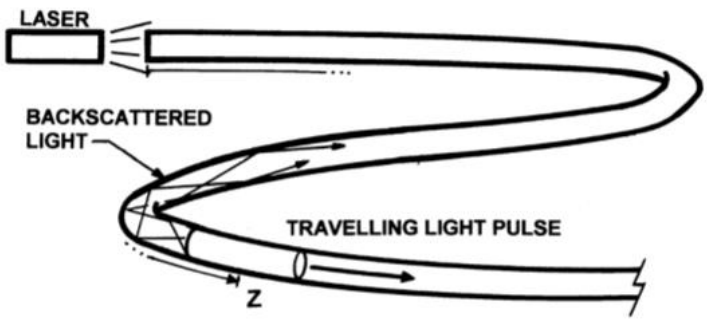

Figure 4. Working Principle of DTS (Smolen et al. 2003).

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Three types of DTS systems have been presented for applications in soil/hydrological sciences:

- active-DTS, sometimes called actively heated fiber optic-DTS (AHFO-DTS), which uses a heated fiber optic cable and monitors the thermal response during the heating and/or subsequent cooling period;
- passive-DTS, the standard DTS method for collecting temperature data along an OF without artificially heating the fiber optic cable; and
- combined active and passive DTS (i.e., independently measuring actively heated and passive FO cables).

2.3 Methods and Applications

2.3.1 Groundwater velocity

Greswell et al. (2009) were some of the first to suggest the use of temperature for underground water velocity detection in soft formations. In their work, they used thermistors for temperature measurement in a designed configuration (shown in Figure 5) in which a heater is surrounded by four thermistors. Their apparatus is capable of measuring the low groundwater velocity in a good range of accuracy as well as understanding the direction of the flow.

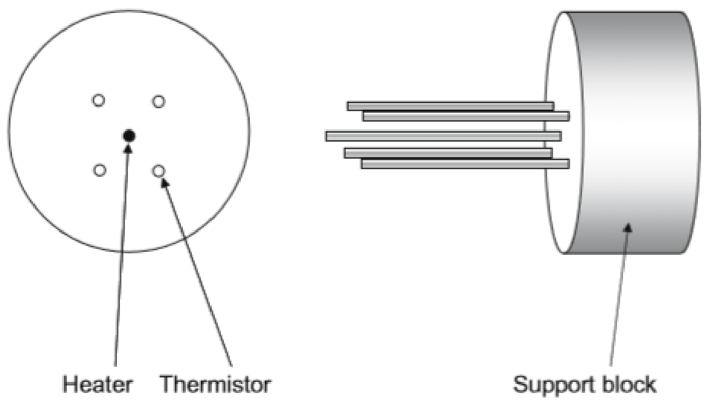

Figure 5. Probe design showing central heater surrounded by four equally spaced temperature sensors (Greswell et al. 2009).

In one of the most recent works, Tombe et al. (2018) presented an approach to estimate specific discharge of groundwater using a heating cable and FO-DTS simulating a heat pulse experiment. They used the direct push method to insert the heating and FO cables in an unconsolidated aquifer to minimize the installation disturbance. They monitored the change in temperature for a few days and fitted two-dimensional analytical solutions to estimate the specific discharge profile with depth.

Banks et al. (2018) proposed a setup to measure the flow direction as well as the flow magnitude. They used a 56-sensor with three heat pulse sources and analyzed the breakthrough curves for each of the sensors using heat transfer equations. They discovered that the use of short-duration heat pulses can provide a rapid, accurate assessment of multi-directional flow fields.

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Coleman et al. (2015) suggested a technique in which FO-DTS with active heating is installed in sealed boreholes to identify the short interval depth of active water flow in fractured media. The principle is simple: the active water flow intervals lead to more heat dissipation which can be understood by high resolution recorded temperature data.

In another work, Bakker et al. (2015) performed an active heat tracer experiment to estimate horizontal groundwater velocity. They employed six FO-DTS and one heating cable with spacing of one meter and monitored the temperature change in four days while heating and cooling the aquifer. An analytical solution along with measured temperature at the heating cable were used to estimate water velocity while the direction of velocity and solid thermal conductivity were estimated by monitoring the temperature changes in another FO-cables.

2.3.2 Surface water groundwater flux exchange

Vogt et al. (2012) used FO cable wrapped around a tube to measure the vertical temperature profile in the unsaturated zone in a shallow riparian field site in northeastern of Switzerland. They used a two-dimensional heat transfer model to estimate the groundwater flow velocity. Their results indicated that uniform flow could not explain the recorded temperature distribution. They also tracked diurnal temperature variation in the ground and analyzed it by the dynamic harmonic regression to estimate the amplitude and phase change. They concluded that the heat transfer from the unsaturated zone due to oscillation of diurnal temperature can lead to underestimation of subsurface water velocity.

In another work, Briggs et al. (2012) employed DTS to quantify the spatial variation of vertical fluxes in the hyporheic zone. A custom fiber-optic high resolution temperature sensor (HRTS) was designed. They deployed their apparatus and monitored the temperature data continuously for one month which also allowed them to monitor the temporal variation of fluxes. Next, they applied the one-dimensional conduction-advection-dispersion equation to their temperature data to quantify the vertical component of the hyporheic flux. They found contrasting temporal trends at different points yielding an adequate description of morphology-driven hyporheic system using HRTS.

Lowry et al. (2007) used DTS to estimate groundwater discharge into wetlands. They concluded that discrete zones of groundwater discharge in a stream within a peat-dominated wetland were identified on the basis of variations in streambed temperature.

Westhoff et al. (2011) used DTS to quantify the hyporheic exchange measuring in-stream water temperature. They claimed that using temperature instead of conventional tracer test has two advantages: exchange parameters can be determined and also the depth of hyporheic zone can be estimated.

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3. Thermal imaging of groundwater upwelling

3.1 Introduction

Temperature has been widely used in hydrology for the past decades both to assess water quality issues and process understanding problems. Theis (1935) and Lubin (Freeze, 1985) noted that *"Darcy's law is analogous to the law of flow of heat by conduction, hydraulic pressure being analogous to temperature, pressure-gradient to thermal gradient, permeability to thermal conductivity, and specific yield to specific heat. Therefore, the mathematical theory of heat-conduction developed by Fourier and subsequent writers is largely applicable to hydraulic theory"*. The similarities between the flow of fluid and the conduction of heat allow us to combine both processes in order to better understand groundwater-surface water interactions.

Groundwater has a relatively constant temperature over time while the earth surface and the surface water bodies are affected by the changes of the atmospheric temperature and the sun radiation in a stronger way. Therefore, it is possible to locate groundwater discharge areas in surface water bodies (streams, rivers, lakes) by looking for cold spots in summer and hot spots in winter.

3.2 Methods

3.2.1 Temperature profiling

The temperature of the subsurface normally increases 1°C per 20-40 m of depth, following what is known as the geothermal gradient. These conditions can be altered by several processes such as thermal variations of the temperature at the surface, affecting especially the near-surface zones, or groundwater flow, among others.

When water recharges from the surface or discharges from the subsurface, the temperature profile of the groundwater deviates from the geothermal gradient thus allowing us to study this deviation to infer the value of the recharge or discharge flows, see Figure 6.

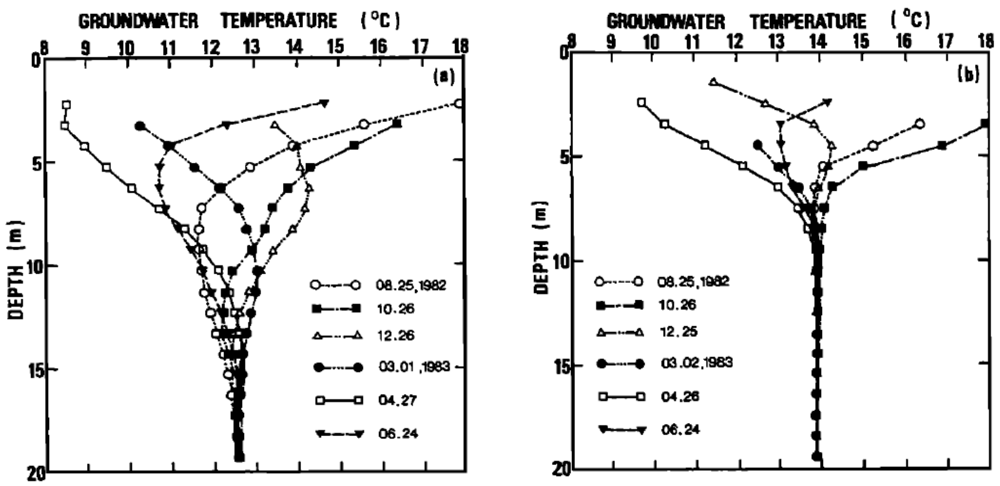

Figure 6. Temperature profile in recharge area (left) and discharge area (right) (Taniguchi, 1993).

First Suzuki (1960) and later Stallman (1965) presented analytical solutions for one-dimensional transient heat-flow equations using temperature profiles in the subsurface. Bredehoeft and

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Papadopulos (1965) also used the same approach, in this case using the Peclet number to compute groundwater velocity from matching measured temperature profiles to their analytical steady-state heat transport model. It is important to note that these analytical solutions rely on strong assumptions (e.g. strictly vertical flow), making them only suitable under certain conditions.

A similar methodology has also been applied to estimate exchange between aquifers and surface water bodies (Hatch et al., 2006; Constantz, 2008; Jensen and Engesgaard, 2011). In the same way, temperature profiles in streambeds and lakebeds are modified based on infiltration or exfiltration processes. In this case, probes with several temperature sensors are installed into the streambed/lakebed, providing time series temperature data at different depths as shown in Figure 7. The depth these systems reach is on the order of a few tens of centimeters, providing temporal evolution of the near surface temperature beneath the surface water body.

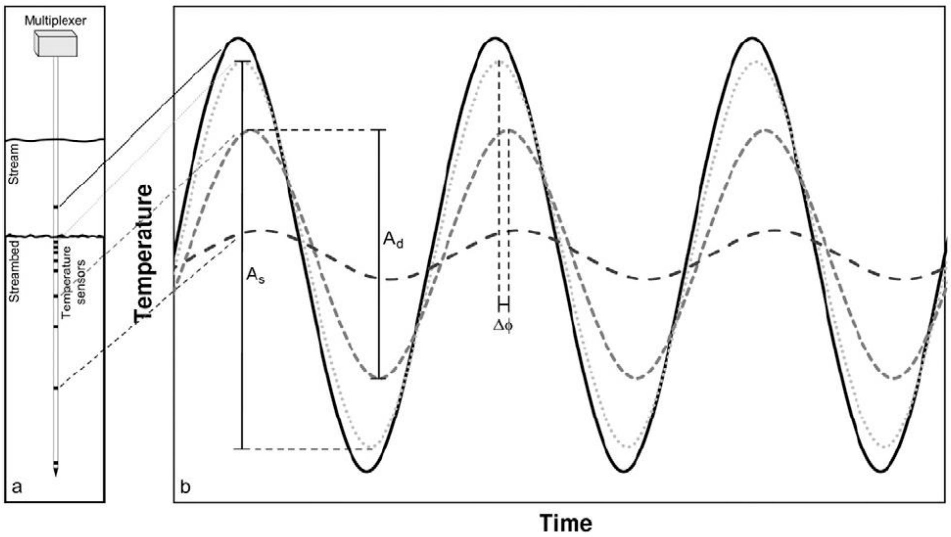

Figure 7. Temperature probe (a) and temperature signal at different depths (b) (Jensen and Engesgaard, 2011).

3.2.2 Distributed temperature sensing

The distributed temperature sensing (DTS) method most commonly applied to obtain temperature data in hydrology consists on sending a laser pulse through a fiber optic (FO) cable and measuring the return time of the reflecting pulse. Different reflections occur, and the ratio between the longwave reflection (Stokes) and the shortwave reflection (Anti-Stokes) allows us to measure the temperature everywhere along the cable (Selker et al., 2006a).

This methodology has been used in many different environments with the aim of obtaining temperature data of both surface water and groundwater. Selker et al. (2006b) used this approach to measure lake bottom temperatures along the bed of Lake Geneva, using preexisting FO cable from telecommunications infrastructure. They also measured the air-snow interface temperature profile above a glacier with a spatial resolution of 5 mm by wrapping a FO cable around a PVC pipe; this same system was also used to measure the air-water interfacial temperature in an Alpine lake. The results

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of this work showed that FO-DTS is a reliable tool to obtain thermal data in hydrologic systems with both a high precision in the measurements and within a wide range of temporal and spatial scales.

Recently, Sebok et al. (2015) applied FO-DTS to map sedimentary processes and spatio-temporal variations of groundwater discharge in a stream in Denmark. By fixing a FO cable to the streambed bottom with nine parallel loops, the temperature of the whole width of the streambed was monitored along the study reach. This layout provided a 2D map for streambed temperatures. Their results show (Figure 8) that FO-DTS captures the differences in the streambed temperature caused by erosion and sedimentation processes and that it is possible to locate potential high-discharge sites by means of studying the temperature anomalies in the DTS data.

A similar approach was used to measure lake water temperature at multiple levels and to map groundwater discharge zones (Sebok et al., 2013). In this case, the discharge was measured using seepage meters and indirectly calculated by fitting an analytical solution to the measured vertical lakebed temperature profiles. The high-discharge areas located with the FO-DTS data were confirmed by both the seepage meters measurements and the results of the vertical lakebed temperature profiles analysis, which generally agreed in the groundwater fluxes discharging to the lake.

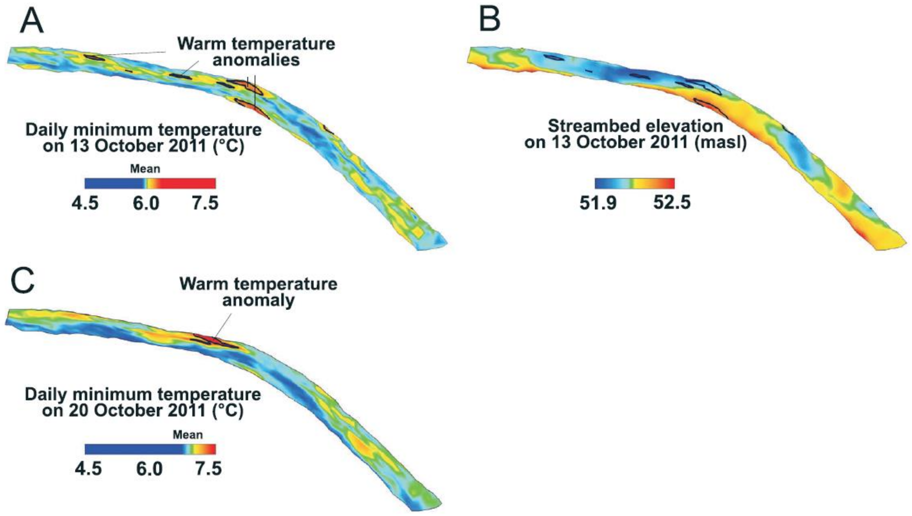

Figure 8. Temperature distribution (A, C) and streambed elevation (B) on different dates. The potential high-discharge zones can be observed as warm temperature anomalies (Sebok et al., 2015).

3.3.3 Thermal infrared imaging

In some cases it is impossible to locate the groundwater discharge areas with the naked eye, thus making the measurement of exchange fluxes between groundwater and surface water very complicated and time consuming. A relatively new approach to solve this issue is the use of thermal infrared (TIR) cameras. By obtaining thermal images of the field site, it is possible to locate potential areas of groundwater discharge based on the groundwater – surface water temperature differences. This method is capable of locating small-scale groundwater discharge spots due to the good resolution of the thermal cameras and at the same time, it allows us to cover big areas in a reasonable amount of time by the use of remote sensing equipment.

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Cardenas et al. (2008) used this technology to study the differences in temperature in a stream with algae communities and how this varied during low and high discharge seasons. A handheld thermal camera was used to obtain real-time high resolution data and showed how the fast flowing sections of the stream had lower temperatures than the slower sections and how the sandbars were heated up by solar radiation. This thermal data may have an impact on biogeochemical models as most of them are temperature dependent.

Röper et al. (2015) also showed that the use of TIR imagery can be useful to locate groundwater discharge areas above the low water line in a coastal area in Germany. They used a handheld thermal camera that allowed them to observe fresh water springs with a diameter of 1-2 cm from which groundwater is constantly draining out.

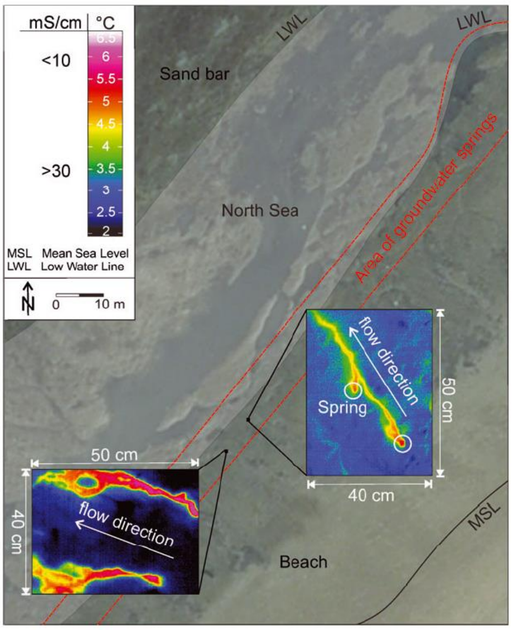

Figure 9. Example of thermal pictures of groundwater springs at a Sopiekeroog Island (Röper et al., 2014).

If the TIR cameras are mounted on an unmanned aerial vehicle (UAV) it is possible to obtain thermal images from a vertical view of large areas in a relatively small amount of time.

Several authors have used this methodology to locate groundwater discharge areas in lakes (e.g. Lewandowski et al., 2013), rivers (e.g. Wawrzyniak et al., 2013; Bingham et al., 2012; Cardenas et al., 2011) and coastal areas (e.g. Kelly et al., 2013), proving that the thermal imaging with the use of UAVs is a powerful tool for hydrology science.

The next step in the use of this approaches is to be able to not only obtain qualitative data from the TIR images but to also quantify the amount of water that is exchanged from the ground to the surface. In this direction, Mundy et al. (2017) studied groundwater seeps using thermal imagery in fractured rocks over a two years period. They noted that although it is possible to assess whether the seepage flow is higher or lower in comparison to other seeps in the vicinity area, it is not yet possible to obtain a quantitative relationship between the thermal data from the TIR cameras and the groundwater flux seeping out of the ground.

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4. Gravimetry to monitor water storage changes

4.1 Introduction

The gravitational attraction experienced on the surface due to the mass of the Earth is in the order of 9.81 m/s² (referred to as *g*). Modern gravimeters allow for measurements in the order of 10e-9 g. A commonly used unit in gravimetry is the Gal (0.01 m/s²). Hydrological signals are typically in the range of the several microGals (1 microGal = 10e-8 m/s²) and can be described as the remaining residuals after corrections for known effects have been applied. These effects are e.g. temporal variations to the Earth's gravity field due to solid Earth tide and ocean loading tides caused by the attractions of the Sun and the Moon or local effects due to atmospheric pressure effects to which gravity measurements are highly sensitive (Van Camp et al., 2016).

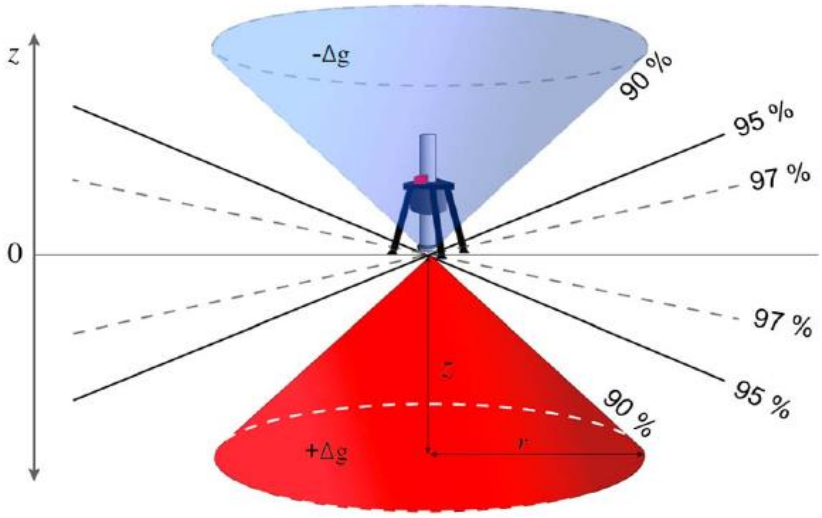

Figure 10. The cone of sensitivity is symmetrical above and below the instrument. About 90% of its sensitivity is found in a cone with a depth of about 10 times its radius. From Van Camp et al., 2017.

Hydrological changes lead to gravitational changes not exclusively related to the mass variations. Volume changes and displacement due to saturation and leaking of aquifers should be taken into account through measurements of tilt, inclination and strain (e.g. Longuevergne et al., 2009). At scales of a few square kilometers aquifer mass changes have been reported as dominant compared to deformation by deep Earth mass changes (Llubes et al., 2004). Gravity variations caused by hydrology were originally regarded as noise in geodetic and geodynamical applications. Long-term gravimetric observation series conducted with superconducting gravimeters (SG) at the geodetic station Strasbourg showed seasonal variations that can be partially attributed to hydrological mass changes (Amalvict et al., 2004). These observations at such typically highly instrumented study sites at e.g. the long-term geodetic observatory in Moxa, Germany (Krause et al., 2009) provide hydro-meteorological observations that aid determining the influence of soil moisture, snow and groundwater on the gravity signal. Even relatively small fluxes as 1.7 mm of evapotranspiration on a 50 km² area could successfully be detected using high-precision gravimetry (Van Camp et al., 2016).

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In the last years, hydrogravimetry has progressed significantly. Hydrological fluxes can show high spatial variability, which limits the information gained from point informations such as observation wells. However, gravimetry acts as a direct, integrative and non-invasive contribution to constrain storage changes in hydrology. A recent, comprehensive and extensive review on gravimetry by Van Camp et al. (2017) discusses the state-of-the-art of applications in various disciplines as well as available absolute and relative gravimeters.

4.2 Translating water content changes into gravity anomalies

Regarding the interpretation of gravity signal or potential field data, in general there are three approaches to follow: For simple cases forward-modelling is applied which generates the expected gravity anomalies caused by mass distributions of known dimensions and density that can hence be compared to the data. A second approach is solving the inverse problem. Due to the non-uniqueness of the inverse solution, gravity alone is of most benefit to hydrological applications when coupled with additional data in a joint inversion. Furthermore, there are techniques that could be referred to as transformation as they aim at signal enhancement, such as up- and downward continuation or procedures from analytical signal processing (Blakely, 1996).

Calculation of the gravity response caused by simple geometric shapes such as spheres, infinite or semi-infinite slabs, dykes and cylinders can be easily achieved with available analytical solutions (Blakely, 1996). For most hydrogeological applications such simplified assumptions won't hold. In the simplest representation of the impact water level change has on the gravitational attraction, a flat water table as the change in thickness of an infinite extent is assumed. Hence a Bouguer slab approximation can be applied that considers the change of water table height as the change in thickness of an infinite plate. A layer of 10 mm water causes a difference in gravity of 4.2 nm/s^2 or 0.42 microGal. High precision instruments such as superconducting gravimeters reach precisions that make it possible to measure water layers of sub-mm thickness (Van Camp et al., 2017). However, for extensive field studies that require a portable gravimeter the achieved precisions are much lower. Jacob et al. (2010) reported a survey error range of 2.4 and 5.5 microGal in the terrain using a Scintrex CG5 relative gravimeter which enabled them to detect water storage changes of 0.25 m.

Leiriao et al. (2009) developed a code that calculates gravity changes as saturation changes in incremental prismatic cells of hydrological models to aid hydrological simulations. According to the distance between measurement and mass changes, different approaches need to be chosen between the prism formula, the MacMillan formula and the point-mass approximation. The published code switches from between these three formulas to the adequate formula as a function of distance (Leiriao et al., 2009).

4.3 Aiding hydrological modelling through joint inversion

The investment in integrating complementary (hydro-) geophysical variables into the same modelling framework is worth the effort. Hydrological models benefit the most from geophysical data when applying coupled inversion (Hinnell et al., 2010; Linde, 2014). Parameter correlation can be a useful constraint in hydrogeological model calibration. Christiansen et al. (2011) combined time-lapse gravity data with hydraulic head data in a coupled hydrogeophysical inversion that performed better at

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estimating evapotranspiration and conductivities in the riverbed than head data alone. Numerous combinations of the gravity method with other observations have been modeled or applied in joint inversions. Daily evapotranspiration estimation from high precision gravity observations and eddy covariance measurements still face uncertainties but are in progress (Reich et al., 2018; a, b). Total water storage has been derived from gravity and tree-ring records (Creutzfeldt et al., 2015). Pfeffer et al. (2013) applied relative and absolute gravimetry combined with local PGS measurements and magnetic resonance soundings.

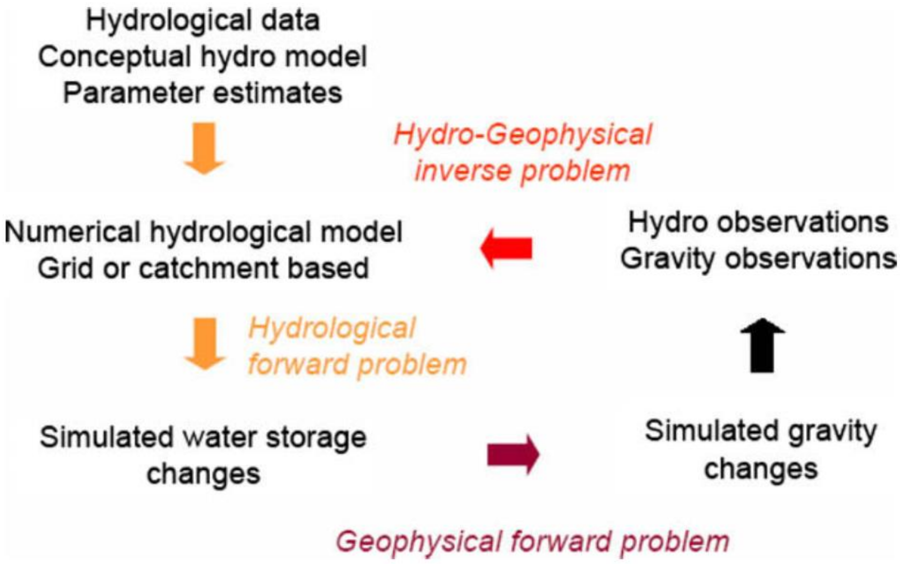

Figure 11. Flowchart from Leiriao et al. (2009): Conceptual steps in joint hydro-gravimetric model development.

Time-lapse gravity monitoring offers the possibility to detect reservoirs that show gravity changes corresponding to seasonal hydrological signals. Creutzfeldt et al. (2012) showed that storage-discharge relationships can be determined by including local high-precision gravimetry at different catchment scales. Landscape-scale water balance monitoring has been conducted with high precision, stationery gravimeters in a field enclosure (Güntner et al., 2017).

Piccolroaz et al. (2015) successfully applied time-lapse gravity monitoring to small, alpine catchment with complex topography gaining uncertainty reduction from a gravity and streamflow than from streamflow alone.

Discrepancies between modelled and observed gravimetrical responses suggest that further storage components and delays need to be considered. Especially the unsaturated areas play a role. In a field study in Niger Pfeffer et al. (2013) observed fast water table drop at the beginning of the dry season that is followed by a slower decrease and accompanied by decrease of the root zone storage. Capillarity effects hold water in the root zone and show different timescales of retention and release than the groundwater table. Krause et al. (2009) observed gravity decline when the interception or canopy storage above the gravimeter is filled which is later followed by an increase in gravity. Evapotranspiration sets on after the precipitation event stops and hence reducing the gravity drop. The gravity signal is later a superposition of the effects of water mass loss to the atmosphere and percolating soil water which causes an increase of gravity once it reaches beneath the gravimeter.

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Kennedy et al. (2016) used time-lapse gravity data for monitoring and modeling an artificial recharge facility with a deep groundwater table and showed that gravimetry can serve in estimating infiltration rates. They discussed the advantage of gravity to react to mass changes without delay and respond to infiltration processes whereas groundwater levels show a delayed response and are prone to noise from well operation.

Monitoring and modelling hydrological responses in Karstic catchments comes with its specific challenges (uncertainty of storages, cavities, conduits) (Hartmann et al., 2014) to which gravimetry can be of interest. Jacob et al. (2010) applied time-lapse gravity in a 100 km² Karstic catchment monitoring using movable, relative gravimeters and stationary, absolute gravity data as references. This study revealed horizontal heterogeneities distributed over the catchment area. With depth-to-surface gravimetry (Jacob et al., 2009) vertical distinction of storage contributions is investigated using surface and cave measurements to study the role of the epikarst in between. Further studies have focused on increasing the vertical resolution with two gravimeters at different heights such as the variable baseline method (Kennedy et al., 2014). One benefit of this approach is the increase in signal-to-noise ratio since temporal signals observed in both gravimeters such as tides can be effectively removed without the shortcomings of location-dependent tidal parameters. Single gravimeter surveys are more sensitive to storage changes than to the velocity of a wetting front which can be overcome by operating two instruments simultaneously. With two gravimeters Kennedy et al. (2014) could estimate the wetting front velocity at shallower depth. As the depth of a wetting front increases more of this mass moves into the cone-shaped area of sensitivity of the gravimeter inducing a stronger signal. With even further increasing depth, however, the signal is reduced. They further were able to better distinguish the change from infiltration to horizontal redistribution once the water table is reached.

4.4 Gravity's contribution to hydraulic parameter estimation in pumping/injection tests

The aim of pumping tests is to estimate aquifer parameters, mainly hydraulic conductivity and specific yield. To obtain the parameters sufficient drawdown data is needed which requires a sufficient number of (costly) observation wells and drawdown data with a sufficiently low noise level. The interest in improving observation and simulation of the gravity response to pumping tests has increased over the last years due to its non-invasive and integrative nature. The added value of gravimetry to sites where drawdown data of sufficient quality is too difficult or costly to be obtained should be further investigated.

Howle et al. (2003) investigated the feasibility of artificially recharging a 300 ft deep ground-water system in California. Injection was monitored using time-lapse microgravity surveys and specific yield was obtained. Results showed a good match between injected volumes and observed gravity anomalies, however, close to the injection wells gravity change was less; local heterogeneities of the aquifer, or noise by the injection process itself were discussed as possible causes. Gehman et al. (2008) conducted pumping tests and came to the conclusion that gravimetric responses match the specific yield estimates. Head changes from gravity agree within ±0.45 m.

Damiata and Lee (2006) developed a mathematical model to simulate the gravitational response to the hydraulic tests of unconfined aquifers. Blainey et al., 2007 extended this numerical experiment and compared the use of high- and low-quality drawdown and gravimetric data to estimate the aquifer

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properties, hydraulic conductivity and specific yield. Already mentioned Leiriao et al. 2009 prismatic gravity forward-model has been applied to simulate pumping test related mass changes. Specific yield and hydraulic conductivity were found to be only imprecisely described by gravity changes alone. However, low quality drawdown data would only perform well concerning hydraulic conductivity and not specific yield, whereas the combination of low-quality drawdown and gravimetric data lead to precise estimates of both.

The mentioned studies consider idealised conditions such as aquifer testing with a fully penetrating well and isotropic and homogeneous conditions. Herckenrath et al. (2012) followed this further and extended the model for the more common case of partially penetrating pumping wells in anisotropic aquifers, delayed drainage effects, and possible data errors. They conclude that gravity data's performance is slightly improved by a coupled-inversion with magnetic resonance tomography. However, signal-to-noise ratios were estimated as relatively large.

González-Quirós and Fernández-Álvarez (2014) presented a coupled hydro-gravimetric model to simulate gravity changes caused by pumping of unconfined aquifers. Drawdown was modelled as a 2D-steady-state flow model obeying the Dupuit assumption. Since the gravimetric response requires a 3D model, a joint model is proposed that modifies the existing electrostatic potential field code provided in COMSOL to its analogy as the gravitational field.

Tsai et al. (2017) extended the focus from individual wells to larger test sites and conducted a numerical experiment of injection tests. While basing their calculation on the model by Leiriao et al. (2009), they calculated the drawdown by applying the analytical solution developed by Mishra and Neuman (2011) to describe saturated-unsaturated flow to a well with storage in a compressible unconfined aquifer. The aim was to investigate how time-lapse gravity survey could serve hydraulic tomography which refers to the estimation of the spatial variability of hydraulic conductivity and specific yield. The joint inversion of gravity data and head data outperformed hydraulic tomography based on head data alone.

Maina and Guadagnini (2018) presented a global sensitivity analysis of the probability distribution of gravity changes caused by well operation focusing on the first four statistical moments. Uncertainty in gravity changes showed to be statistically highly influenced by parameters governing unsaturated flow which suggests gravity's contribution to hydraulic parameter estimation which should be further investigated. However, they discussed that while gravity performs well regarding aquifer storage terms and water retention curve parameters its contribution to the estimation of saturated and unsaturated hydraulic conductivity appeared to be limited.

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Achieved and on-going activities, results and challenges

The four ESRs involved in this Workpackage apply different methodologies to different sites. Although it is planned to perform some shared experiments in common sites to test the combination of the different methods, the work done so far is only representative of the individual experiments and monitoring campaigns performed by the ESRs with their institutions.

In the following paragraphs we explain these field work campaigns, stating the location at which they are being performed and the details on the field instrumentation and the data acquisition process.

1. Seismic experiments

In September 2018, a time-lapse infiltration test was carried out at the Ploemeur Hydrological Observatory. We performed the infiltration during two consecutive days and acquired both seismic and electrical resistivity data along two orthogonal lines crossing the infiltration area (Figure 12). We did 11 acquisitions for each line, both using seismic and electrical resistivity, where the first and the last acquisitions were performed before the first infiltration and after the last infiltration, respectively. In total, 3.3 l of water was infiltrated. Adjacent to the infiltration area, there was a pit equipped with TDR probes and the water content was monitored in real time. The next steps are to process the data; we have started with the electrical resistivity to produce time-lapse ERT images. After this, we will process the seismic data to obtain V_P and V_S profiles. Finally, we plan to perform clustering and joint inversion of the data.

Figure 12. Acquisition set-up for the infiltration test at the Ploemeur Hydrological Observatory. The wood planks delimit the infiltration area.

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2. Thermal imaging experiments

The thermal characterization techniques are being applied to a lowland stream valley system in central Jylland, Denmark. The aim of the study is to thermally characterize the field site and to use thermal data to evaluate the groundwater upwelling processes as well as the groundwater – surface water interactions.

The temperature profiles are acquired by introducing a temperature and pressure sensor in boreholes drilled around the stream, obtaining a map of the groundwater temperature. By locating areas with thermal anomalies, it is possible to identify potential groundwater discharge. This data can also be used to obtain groundwater upwelling fluxes by fitting an analytical 1D solution to the measured vertical temperature profiles.

A FO-DTS system is deployed in a double loop of FO cable. The cable is placed 20 cm below and on top of the surface along a transect perpendicular to the stream. Thus, both the surface temperature and the near surface temperature are recorded with an spatial resolution of 1 m during 7 to 10 days periods throughout the year. This data shows the thermal evolution of the upper part of the ground, which varies from saturated to unsaturated conditions depending on the location and the season of the year.

Temperature probes are installed in the streambed following the FO cable transect. By measuring the streambed temperature at 10 different depths it is possible to indirectly obtain the groundwater flux to the stream through the streambed.

Several drone flights with a TIR camera have been performed in order to obtain thermal images of the whole study area. Anomalies in the ground temperature may indicate potential locations of groundwater seeps. By acquiring TIR data in different field campaigns through the year, we aim to understand the dynamics of the groundwater upwelling processes at the study site.

The use of integrated surface and subsurface hydrological models allows us to model both the hydrological processes occurring in the stream and the groundwater flow and heat transport. This will lead to a more detailed understanding of the stream – aquifer system as well as to quantify the fluid exchange between both water bodies. The differences between the results of these models under different thermal conditions (e.g. winter and summer conditions) could provide insights on how the effect of temperature affects hydraulic parameters in such systems. The comparison between the integrated model results and the TIR images could potentially allow us to go one step further in using TIR imagery as a quantification tool of groundwater – surface water exchanges.

3. FO-DTS experiments

A temperature model and inversion approach has been developed which uses distributed temperature data to calculate the flow rate inside the wellbore. This sheds light on the benefits of installing passive DTS as a permanent downhole monitoring tool that can provide useful information about the temporal and spatial values of the temperature all along the wellbore. Using this model and distributed temperature data, other useful information such as the flow rate of the fluid in different section of the wellbore can be extracted. This is very informative in fractured media in terms of real time contribution of each fracture crossing the wellbore on the total production of the wellbore. This model and approach has been numerically validated using a COMSOL numerical model.

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In October 2018 a series of distributed temperature measurement inside the wellbore using DTS was performed on the fractured Ploemeur site in Brittany, France. The temperature measurements are performed in two ambient conditions as well as during pumping. In addition to temperature measurements, flow measurements were also conducted which aim at the verification of the flow measurement model by recorded distributed temperature inside the wellbore. It is worth to note that temperature measurements have been conducted for a period of 36 hours to cover a complete and half tide cycle. The tidal temperature data will be analyzed to discern the effect of tide on production from each fracture.

Figure 13. Temperature profile monitoring using DTS and flow measurement on study wellbore PZ-26 in Ploemeur-Brittany (October 2018).

4. Gravimetry experiments

A vertical gravity gradient survey inside a geodetic observatory in a karstic environment (GEK) in L'hospitalet-du-Larzac about 90 km northwest of Montpellier has been conducted. This survey aims at investigating the contribution of time-lapse monitoring of the vertical gravity gradient to an improved estimation of small-scale soil moisture changes and infiltration processes. The gradient has been estimated by conducting gravity surveys on different heights on tripods on three close-by concrete pillars using a relative gravimeter, the Scintrex CG5 Autograv. Monthly gradient data has been collected since November 2017 that show small variations between pillars and among survey months. Several tests have been conducted to assess the uncertainty of this method.

Numerical simulations that correct for specific mass asymmetries caused by the placement of the concrete pillars within the building have been applied to account for differences in gradient (curvature) between the pillar positions. This assessment is essential for the interpretation of gravimeter intercomparison within the GEK building (typically conducted at different heights due to different instrument heights, hence transfer is needed).

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Figure 14. Vertical gravity gradient survey inside GEK-observatory, L'hospitalet-du-Larzac, France. Left: Relative gravimeters measure gravity placed on tripods of different heights. (Photo: Cooke, 2017) Right: Observatoire Géodésie en Environnement Karstique (GEK). (Photo: Le Moigne, 2011)

Besides the data acquisition the development of a hydrological model for the conditions at the GEK site has been started, based on *Pflotran* (Hammond et al., 2014). This model will be calibrated with precipitation, AET and borehole data available for the site. Efficient coupling of hydrological model and calculation of the gravimetric response are in progress. In preparation of the more elaborate soil water change estimates, simple simulations have been conducted that account for the expected difference in vertical gravity gradient caused by given heterogeneities such as the rainfall shadow or umbrella effect of the building. For certain soil moisture changes the differences in vertical gravity gradient caused by such an umbrella are certainly in the same order of magnitude as the observations. After a year of measurements has been completed (which will be the case by November 2018) and the hydrological model has been calibrated and applied, conclusions can be drawn from this study. The study will be based on a year of gradient measurements, an understanding of the error budget and uncertainty of the method as well as an insightful comparison with the hydrological model output.

Additional techniques such as an ERT or MR studies have been suggested to determine soil moisture. Soil moisture TDR probes have been dismissed due to the high heterogeneity and very thin (or absent) soil cover on the Karstic bedrock. The results suggest that heterogeneous soil moisture patterns could hence be detectable with a relative portable gravimeter despite its susceptibility to tares, non-linear drift and other error sources. A repeatability study in June of several consecutive days suggests that measured variations are larger than the day-to-day variations with the same instrument. Further tests were aimed at a comparison of acquisition protocols, instruments (two CG5 and one CG6) as well as at the variability in between measurement loops. While however being relatively small the largest observed temporal differences are larger than the estimated errors and occurred about half a year later. Differences between pillars and their interpretation have to be merged with insight gained from the hydrological model output. While preparing for the field validation of the AQG these surveys and numerical studies aim to increase understanding of the possibilities and pitfalls. More accurate surveys are planned upon instrument delivery. This opens the discussion on the possibilities provided by the AQG or further in future, the potential of high-precision gradiometers for hydrological monitoring.

This study will be followed up by a more general feasibility study to assess the influence of measures of spatial heterogeneity of soil moisture distributions on expected gravity and vertical gravity gradient signals.

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Innovations of the emerging techniques for in situ monitoring of water content and fluxes

The innovative value of our joint project lies in applying methods that have not been combined before for the purpose of water flux and storage estimation. The innovative character of the gravimetric approach described in this document is on the one hand the utilization of a new gravimeter with considerable new possibilities and improvements. On the other hand, the investigation of the vertical gravity gradient as an additional source of information and model constraint aids reducing the non-uniqueness of the solution bears potential and extends the information content of the gravity signal on its own. Last but not least joint inversion in hydrological applications of gravity data and the methods described in this document is likely to offer new insights, especially joint studies with thermal methods is to our knowledge unprecedented.

Seismic methods have been widely used in hydrological settings but their potential to quantitatively describe the critical zone still remains limited. The major contribution of this project lies in estimating mechanical parameters from seismic data to quantify the temporal and spatial evolution of subsurface water content, allowing to better understand both mechanical and hydrological processes in the near surface. Moreover, with emerging techniques such as seismic noise interferometry and distributed acoustic sensing, seismic could become an effective passive and non-intrusive method to monitor the critical zone.

In terms of thermal characterization of hydrological systems, a lot of effort has been put into studying flux exchange between surface water bodies (rivers, lakes) and groundwater. In our case, the methodology is applied to study on-land groundwater upwelling, that is the amount of groundwater seeping from the ground to the surface of the study site. This is by itself a new way of applying the already used field techniques and aims to test the feasibility of using tools such as DTS and groundwater temperature profiling to estimate the seepage fluxes that escape the groundwater system. Furthermore, the combination of groundwater temperature profiling and the unsaturated zone thermal characterization using DTS, allows us to monitor the behaviour of the entire shallow subsurface, giving insights of the measurable temperature signal on the surface. The use of TIR mounted on unmanned aerial vehicles extends the coverage of this knowledge so that it is possible to locate the groundwater upwelling in a wider range of locations.

The application of DTS for monitoring subsurface media is applicable for two different subsurface category, fractured and porous media. In first part, we aim to extract fractured media properties by continuous monitoring of passive temperature recorded by DTS inside the wellbore. Here, the innovative part would be to understand the hydromechanical properties of fractured media induced by tidal signals which affect the production rate in ambient condition just by using passive temperature data and change in the flowrate. For the porous media, knowing about the heterogeneity of porous media is of great interest especially when it comes to transport problems. Usually, the permeability field is imaged thanks to hydraulic tomography but this is based on pressure variations most of the times. Since the challenge is to model field heterogeneity to solve transport issues, tracer tomography has been developed but it is not obvious to achieve tracer tests in the field (it has also some limitations). The innovative part of our work would be a new measurement like flow velocities with a great spatial resolution and performing inversion based on the measured velocities in the field.

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Limits/issues of the emerging techniques for in situ monitoring of water content and fluxes

Each of our methodologies relies in a set of assumptions that constrain their use to some specific locations or characteristics. In this section we highlight the limitations we have been able to detect to hopefully find a combination of methods to decrease uncertainty and to broaden the possibilities of data acquisition and monitoring.

The spatial variability of dry near-surface materials is frequently of greater influence on seismic-wave velocities than the variations of water content. Therefore, discerning between spatial variability or fluid responses still remains a limitation when solely using seismic methods. Our research is currently trying to overcome this limitation by performing controlled experiments and comparing the seismic response with a geophysical method that is not sensitive to mechanical properties (refer to *Achieved and on-going activities, results and challenges*). Another possible limitation is the need of having control on the elastic moduli and porosity of the soil in question; this will not be an issue for a well-known site, however, if these parameters are not known, it might be necessary to take soil samples and perform laboratory tests, compromising the versatility of the technique.

Non-uniqueness of the gravity interpretation remains an issue. The mentioned studies of joint inversion combining gravimetry and other geophysical methods came to the conclusion that gravity alone performed poorly but improved parameter estimation when applied together with other data, often outperforming them. The necessity of stationary, absolute gravimeters and the uncertainty of relative gravimeters are serious limits to gravimetric applications. In view of the development of a portable, absolute quantum gravimeter numerous joint studies could be feasible in the near future.

The biggest challenge regarding the use of heat as a tracer to study groundwater upwelling is the reliability of the flux quantification. It is relatively easy to locate upwelling zones by studying the temperature contrast in the groundwater system but estimating the amount of water that actually seeps out of the ground poses a lot of uncertainties. Analytical solutions to indirectly obtain the groundwater flux rely on strong assumptions that can barely be met due to, for instance, the heterogeneity of any natural geological system. In this regard, integrated hydrological modelling may be a useful tool to better constrain this assumptions, allowing us to obtain more reliable results.

The use of TIR imagery is still relatively new and the quality of the images one can obtain is not as good as desired. When studying groundwater upwelling in stream valleys we encounter localized small scale processes and well founded technologies are needed. Moreover, thermal cameras do not directly measure temperature but radiance. This values are converted and uncertainty arises in this process both from possible interferences in the image (e.g. solar radiation and reflective bodies) and from parameters needed for the conversion process.

The greatest challenge in employing DTS for characterization of porous media is installing Active Fiber optic DTS in soft media. The installation must be done so as to minimize the geological interference. Furthermore, the number of measuring points, arrangement and their location is of great importance which we will try to respond during the development of inversion approach.

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Added value of the network

The network provides us with possibilities to collaborate that extend beyond the work package framework. A possible joint pumping test experiment including ESR 8 and ESR 3 at the Emme site in Switzerland is currently in discussion and preparation for four weeks in January/February 2019. The earlier described advantages and challenges of gravimetric monitoring of pumping tests will be investigated applying simulations and field observations. To deepen the investigations aimed at the vertical gravity gradients, the additional information gained from gravity gradient monitoring during these hydrological experiments will be assessed in simulations (and possibly) during surveys. Additional to the constraints on total mass anomalies caused by the drawdown cone in the aquifer, vertical gravity gradients could aid when quantifying anisotropy of flow. ESR 7 will also be involved. This activity exploits the possibilities and opportunities achieved.

For ESR 8 a secondment at UPCH (HOBE site) is planned where such studies could be conducted. The Larzac, HOBE and Emme site provide different environments as well as groundwater and soil moisture dynamics that offer the possibilities to assess and test joint methods in field studies as well as to evaluate the usefulness of these approaches in different environments.

For ESR 7 two secondments are planned. One at UFZ Leipzig in which the field techniques applied in the lowlands in Denmark could be tested in a different environment, potentially adding knowledge to improve them. A second secondment at University of Neuchatel will provide modelling training and expertise to the project, leading to increasing the chances of correctly representing and quantifying the natural environment in which the thermal characterization has been done and the processes occurring in it.

For ESR 5 a secondment in UNIL (University of Lausanne) will take place from May to August 2019. The goal is to work together with Niklas Linde and part of his team on clustering and joint inversion of the data from the Ploemeur experiment (September 2018). Further on, a seismic experiment is planned at the Äspö Hard Rock Laboratory (SKB, Sweden) to study a fractured-rock context and analyze the effects of fracture density on the seismic signal. This work will be done in cooperation with ESR 9, who has acquired GPR data at the site.

For ESR6, two different periods of three month secondment is planned at University of Lausanne. The first secondment period starts in beginning of 2019 and the work will be about proposing a novel inversion approach based on the underground fluid velocity measurement. This inversion will be tested on several synthetic cases. The second period of secondment in University of Lausanne will take place after the acquisition of field data to used the developed inversion approach on real data.

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Dissemination activities

ESR 05: Lara Blazevic, CNRS

AGU 100th Fall Meeting, 2018. Poster presentation with the title *"Finding appropriate rocks physics models to interpret seismic data in hydrogeophysics applications"*.

4th Cargèse Summer School: Flow and Transport in Porous and Fractured Media, 2018. Poster presentation with the title *"Monitoring spatio-temporal water redistribution in the subsurface with seismic methods"*.

Oral presentation at doctoral school days at MINES ParisTech:

> 05/04/2018 Paris: Journées des Doctorants - École Doctorale Géosciences, Ressources Naturelles et Environnement

ESR 06: Behzad Pouladi, CNRS, University of Rennes.

4th Cargèse Summer School: Flow and Transport in Porous and Fractured Media, 2018. Poster presentation with the title *"Temperature as a powerful tool in understanding the subsurface process and properties"*.

ESR 07: Joel Tirado-Conde, University of Copenhagen.

33rd Nordic Geological Winter Meeting, 2018. Poster presentation with the title "*Temperature profiles to measure groundwater discharge to Ringkøbing Fjord"*.

Computational Methods in Water Resources XXII, 2018. Oral presentation with the title *"Benchmarking the use of heat as a tracer by the use of integrated surface and subsurface hydrologic models"*.

4th Cargèse Summer School: Flow and Transport in Porous and Fractured Media, 2018. Poster presentation with the title *"Heat as a tracer to study groundwater upwelling: field data and benchmarking integrated hydrological modelling"*.

ESR 08: Anne-Karin Cooke, MuQuans, Talence, and University of Montpellier

Poster presentation at two doctoral school days at the university of Montpellier:

> 22/03/2018 Montpellier: Journée de Doctorants: Institut Montpelliérain de l'Eau et de L'Environnement (IM2E)
> 18/05/2018 Montpellier: Journée des Doctorants Géosciences Montpellier

Presence and oral presentation : 8-13/04/2018, Vienna, Austria: General Assembly of the European Geoscience Union 2018 (EGU) : Titel: "*Potential impact of ground-based gravity gradiometer for subsurface reservoir monitoring"*

Abstract: https://meetingorganizer.copernicus.org/EGU2018/EGU2018-14372.pdf

4th Cargèse Summer School: Flow and Transport in Porous and Fractured Media, 2018. Poster presentation with the title *"On the potential of vertical gravity gradient monitoring for hydrological signal detection"*

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End of deliverable WP3 D3.3 D8

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