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WP3 D3.2 D7

Field test of novel techniques for quantifying water content spatial distributions and temporal fluctuations

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Enigma ITN

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

D3.2/ D7: Report: Field test of novel techniques for quantifying water content spatial distributions and temporal fluctuations

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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 by exploring the potential of emerging techniques for monitoring temporal fluctuations in the distribution of subsurface fluxes, water content and exchanges with surface water bodies.

In this report, we explore techniques based on fiber optics distributed temperature sensing (FO-DTS) and seismic methods, focusing on subsurface water content quantification (ESR 5) and on groundwater flux estimation (ESR 6 and 7). Based on the already existing knowledge, new approaches are used with the aim of applying the latest developed technology in order to make in situ data acquisition productive and reliable.

Treating the surface water – groundwater system as a continuous is a more realistic approach than the usual distinction between domains and as their interactions are still challenging to evaluate, we employ these non-intrusive methods that study both environments. Moreover, the combination of these techniques could allow for a better understanding of these interactions, 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), and (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).

These activities are developed independently by the ESRs and their institutions in order to validate the different techniques. In a later stage, the different tools and methods can be tested simultaneously in the field to explore the results of an integrated approach, provide insights to improve them individually and investigate the advantages that each method may have under different circumstances.

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 acquired in the field.

The use of heat as a tracer to estimate groundwater fluxes follows two different approaches. 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. We also 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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Introduction and literature review

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 hydrogeological 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 unsaturated near surface. The behavior of pressure (P) and shear (S) 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 spatial, temporal and seasonal changes in aquifers and earthworks (Pasquet et al., 2015; Bergamo et al., 2016a; Bergamo et al., 2016b; Dangeard et al., 2016; Pasquet et al., 2016). In this section, we briefly review these studies and comment on the current challenges of using seismic methods to monitor saturation changes.

1.2. Seismic methods in near-surface applications

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 to characterize the near surface and monitor 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 (Figure 1).

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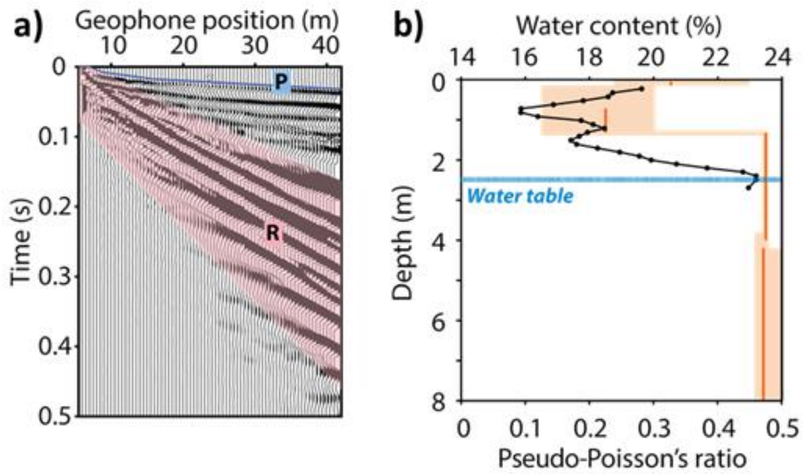

Figure 1: a) Seismogram of a direct shot recorded during a low water campaign highlighting the observed direct P-wave and Rayleigh waves, b) In orange: Pseudo-Poisson's ratio computed from V_P from P-wave refraction interpretation and V_S from surface wave dispersion analysis within error bars; the black dots correspond to water content measurements performed on auger sounding samples collected during the low water campaign. (Modified from Pasquet et al., 2015).

Bergamo et al. (2016a, 2016b) analyzed V_P and V_S 2D sections (Figures 2 and 3) 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.

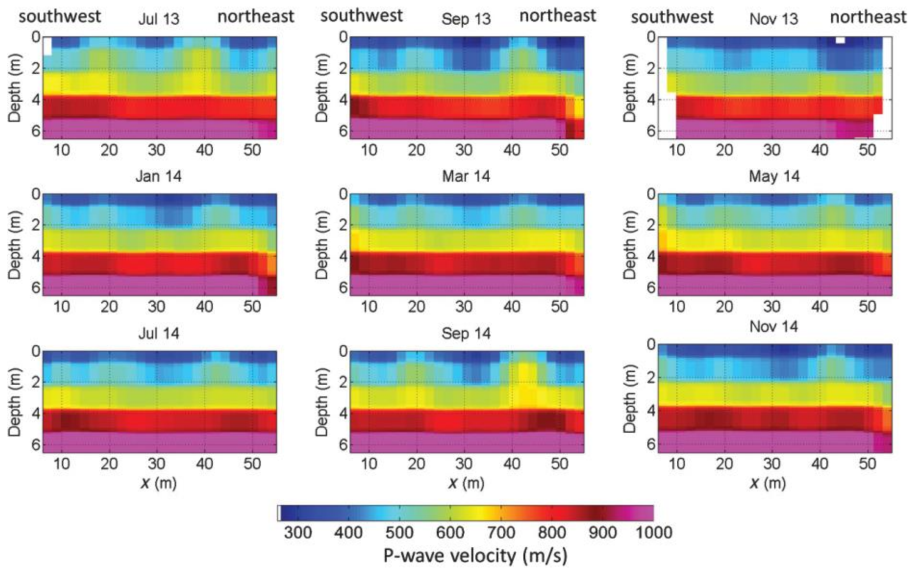

Figure 2: V_P sections obtained from P-wave refraction tomography from the periodical acquisition of seismic data (for a total period of 16 months). To focus on seismic velocities variations within the embankment the depth range is limited to 0–6.5 m. (From Bergamo et al., 2016b).

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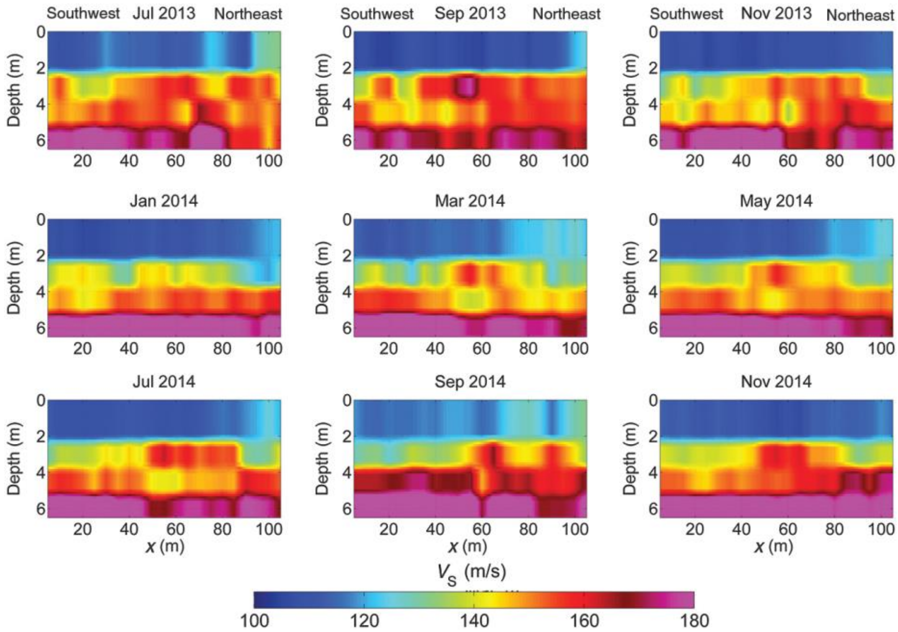

Figure 3: V_S sections obtained from inversion of Rayleigh-wave dispersion curves for all datasets. The depth is limited to 0–6.5 m to focus on seismic velocities variations within the embankment. (From Bergamo et al., 2016a).

Similarly, Dangeard et al. (2016) studied seismic data from two different time periods (October 2011 and May 2012) in the Hydrogeological Observatory of Ploemeur (France); they analyzed the differences in P-wave traveltime and Rayleigh wave phase velocity to image temporal variations of mechanical properties associated with water content (Figure 4).

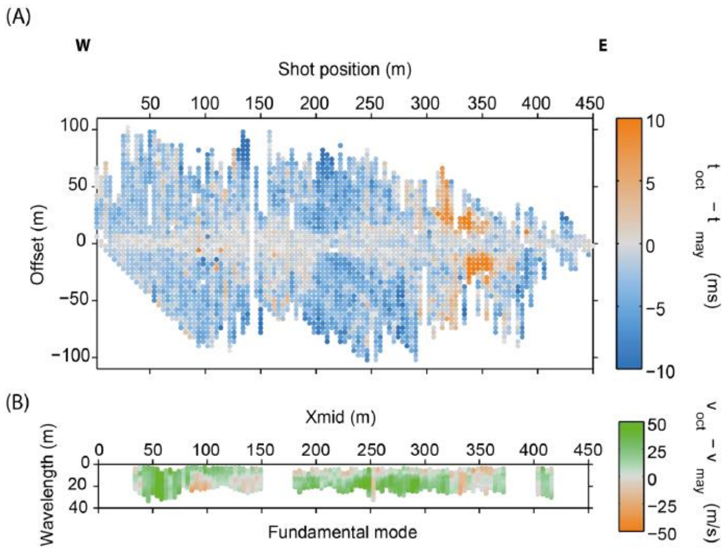

Figure 4: a) P-wave picked first arrival time absolute differences, represented as a function of the offset and source positions, b) Absolute differences of picked Rayleigh-wave phase velocity dispersion curves. Only the fundamental propagation mode is presented as a function of the wavelength and the spread mid-point (Xmid). In both cases, the differences are calculated between October 2011 and May 2012. (From Dangeard et al., 2016).

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The observed variations in these studies validate the interest in using seismic data to monitor spatio-temporal saturation changes. Nevertheless, these variations are only qualitative. In more quantitative applications of seismic methods in near surface contexts, 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 5a and 5b). 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 (Figure 5c and 5d). Finally, they discuss the consistency between the changes observed in the seismic data and the estimated parameters.

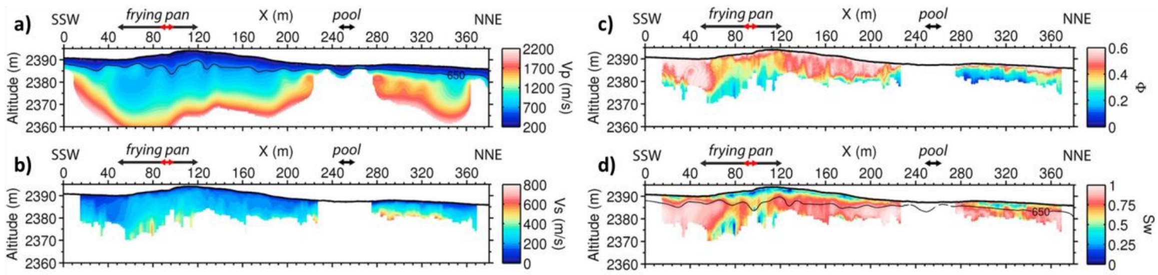

Figure 5: a) VP model from P-wave refraction tomography, b) VS model obtained from surface-wave dispersion analysis, c) porosity (ϕ) and d) water saturation (Sw) models calculated from the seismic data using a rock physics model. (Modified from Pasquet et al., 2016).

2. Thermal characterization for groundwater flux estimation

2.1. Introduction

Temperature has been widely used in hydrology for the past decades both to assess water quality issues and process understanding problems. 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 solar 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.

2.2. Groundwater temperature-depth data

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 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.

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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 (Figure 6). In this case, probes with several temperature sensors are installed into the streambed/lakebed, providing time series temperature data at different depths. The depth these systems reach is in the order of a few tens of centimeters, providing temporal evolution of the near surface temperature beneath the surface water body.

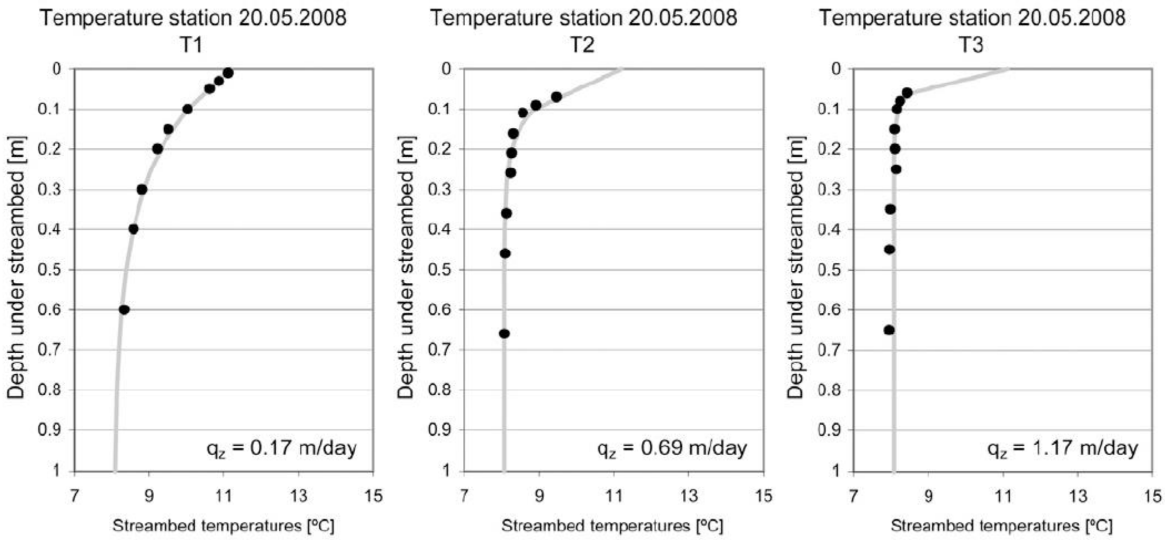

Figure 6: Measured and modeled temperature distributions beneath a streambed in Denmark. The fitted exchange fluxes (q_z) are shown. The exchange fluxes are all positive, indicating upward flow (groundwater discharge) (Jensen and Engesgaard, 2011).

2.3. Groundwater velocity measurement

Greswell et al. (2009) applied temperature measurements for groundwater velocity. They used thermistors for temperature measurement in a designed configuration in which a heater is surrounded by four thermistors. Their apparatus is capable of measuring the low ground water velocity in a good range of accuracy as well as understanding the direction of the flow. Later, Lewandowski et al. (2011) suggested a heat plus tracer technique to measure small-scale flow direction and velocity in streambeds. They used one rod with a heater as point source located in the middle and four rods with four temperature sensors, arranged concentrically diameter around the heating rod. They employed the apparatus in the laboratory as well as in the field. They found out the method is easy for field applications and good in estimating velocity values and direction. The most recent work is proposed by Banks et al. (2018) with a setup to measure the flow direction as well as the flow magnitude (Figure 7). 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 found out that the use of short-duration heat pulses can provide a rapid, accurate assessment of multi-directional flow fields.

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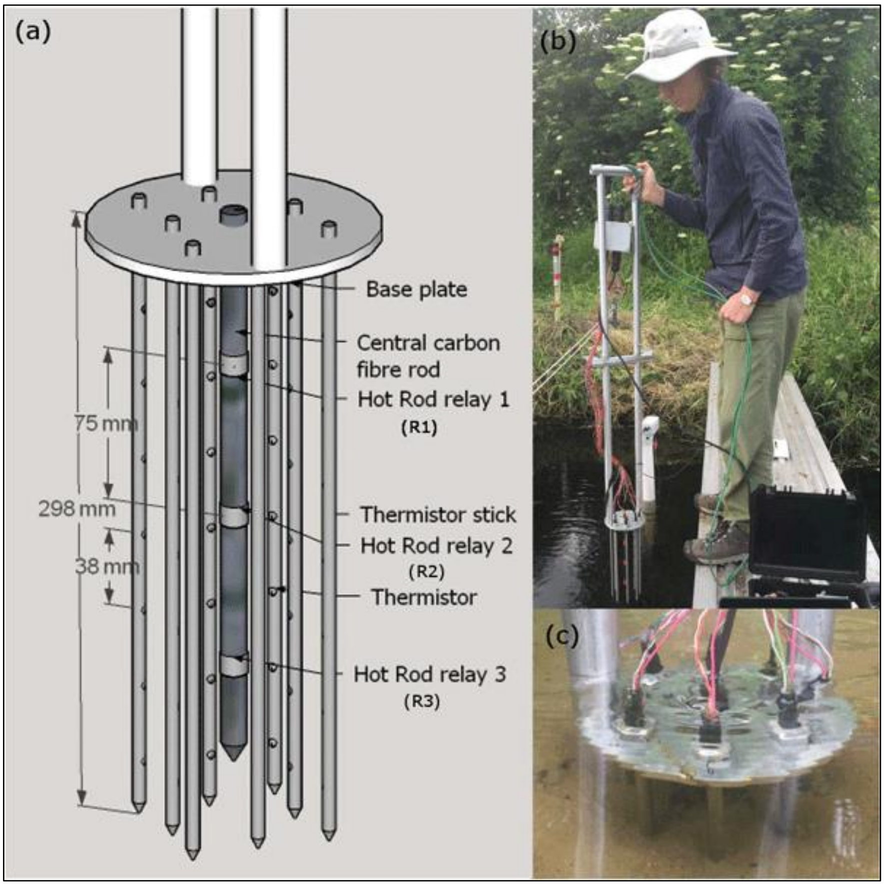

Figure 7: a) Schematic of the designed instrument, b) and c) Installation of the instrument in a shallow medium (Banks et al., 2011).

2.4. Distributed temperature sensing (DTS)

Distributed temperature sensors are optoelectronic devices being able to measure the temperature all along the fiber and provide a continuous temperature profile both in time and space. The working principle is based on sending light pulse inside the fiber, recording and analyzing the backscattered temperature-dependent light which contains information on both location and temperature value. DTS has found many applications in different industries ranging from oil and gas to environment and hydrology. There are three common types of DTS that have been proposed for hydrological applications: (i) Passive-DTS that simply records the temperature all along the fiber optic, (ii) Active-DTS: in which heat is also added to the system. Monitoring the thermal response of the media during heating and cooling allow us to know about the media, (iii) Combined active and passive DTS. DTS has been used for different hydrological applications such as ground and surface water flux exchange (Vogt et al., 2006; Briggs et al., 2012; Lewry et al., 2007; Westhoff et al., 2007, 2011), and groundwater velocity measurement (Bakker et al., 2015; Coleman et al., 2015).

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2.5. Groundwater velocity measurement using DTS

Coleman et al. (2015) suggested a technique in which they used FO-DTS with active heating in sealed boreholes to identify the short interval depth of active water flow in fractured media. The principle is quite easy as the active water flow intervals lead to more heat dissipation which can be understood by high resolution recorded temperature data. In another work by Bakker et al. (2015), the authors used an active heat tracer experiment to estimate horizontal groundwater velocity. They employed 6 FO-DTS and one heating cable with spacing of one meter and monitored the temperature change in 4 days while heating and cooling the aquifer. An analytical solution along with measured temperature at 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 other FO-cables. In one of the most recent works, Tombe et al. (2018) presented an approach to estimate specific discharge underground water using a heating cable and FO-DTS simulating heat pulse experiment. They used direct push method to insert the heating cable and DTS in the unconsolidated aquifer to minimize the installation disturbance. They monitored the change in temperature for few days and fitted two-dimensional analytical solutions to estimate the specific discharge profile along depth.

2.6. Thermal infrared imaging

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.

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.

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 (Figure 8).

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.

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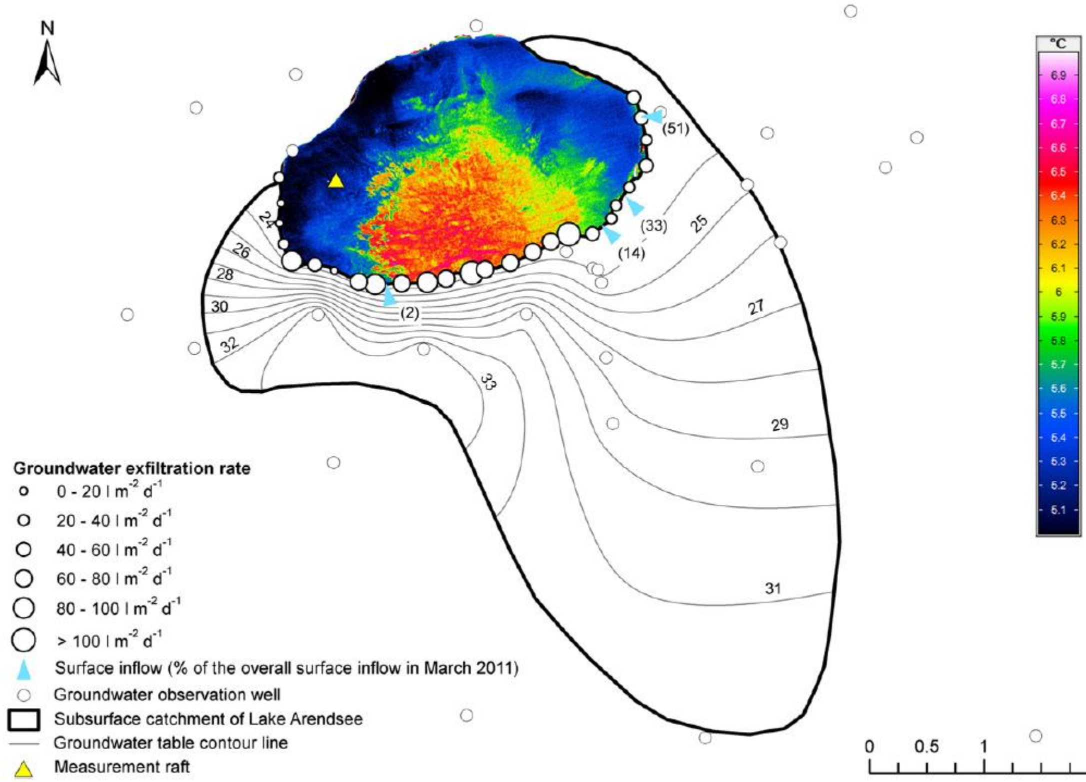

Figure 8: Thermal infrared image of Lake Arendsee. Water temperature is compared with groundwater exfiltration rates based on sediment-temperature depth profiles (Lewandowski et al., 2013).

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Achieved and on-going activities, results and challenges

In September 2018, a time-lapse infiltration test was carried out at the Ploemeur Hydrological Observatory (part of the H+ Network) with the main objective of assessing the seismic method as a useful tool to quantify changes in the subsurface water content. We performed the infiltration during two consecutive days and acquired both seismic and electrical resistivity data along two orthogonal lines crossing on the infiltration area. Figure 9 shows a sketch of the acquisition set-up and Figure 10 shows a picture in the field site.

We did 11 acquisitions for each line, both of seismic and electrical resistivity, where the first and the last acquisitions were performed before the first infiltration and after the last infiltration, respectively. For the seismic acquisition, the shot positions were between geophones. The CRITEX project supported us with the seismic equipment and methodology, whereas the electrical resistivity equipment was rented from the METIS laboratory (Sorbonne University).

In total, 3.3 liters of water were infiltrated. Adjacent to the infiltration area, there was a pit equipped with TDR probes and the water content was monitored in real time thanks to the H+ Network (Figure 11). With this experiment, we had full control on the amount of water being infiltrated (and the corresponding change in water content in the subsurface) before each acquisition, and we rely on this control to assess the seismic method as a valid tool to quantify spatial and temporal changes in the unsaturated zone.

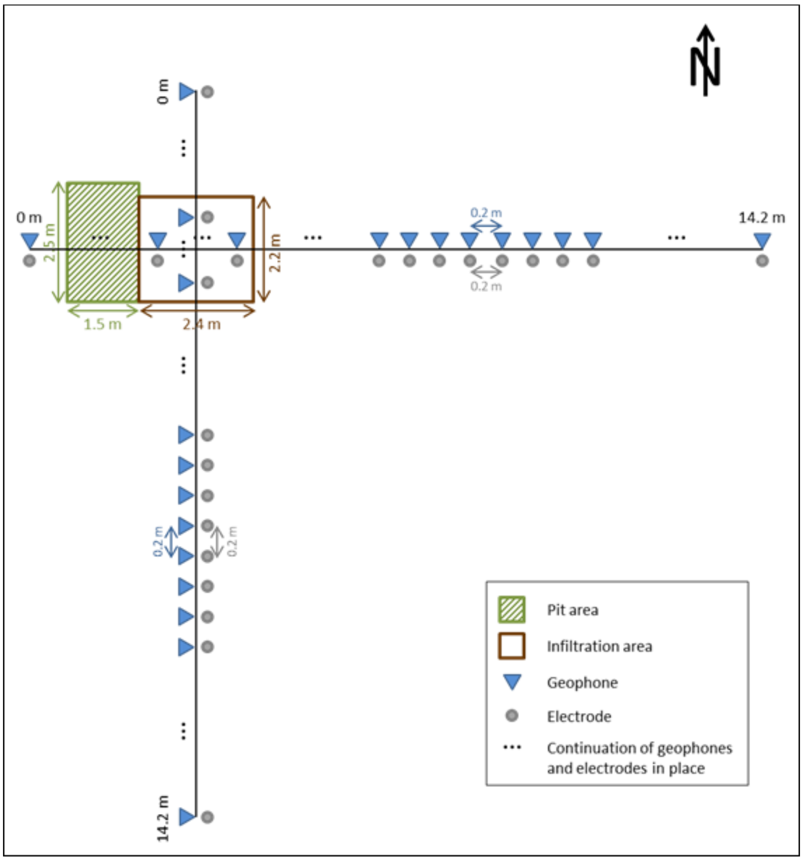

Figure 9: Acquisition set-up sketch for the Ploemeur experiment.

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Figure 10: Acquisition set-up for the infiltration test at the Ploemeur Hydrological Observatory. The wood planks delimit the infiltration area.

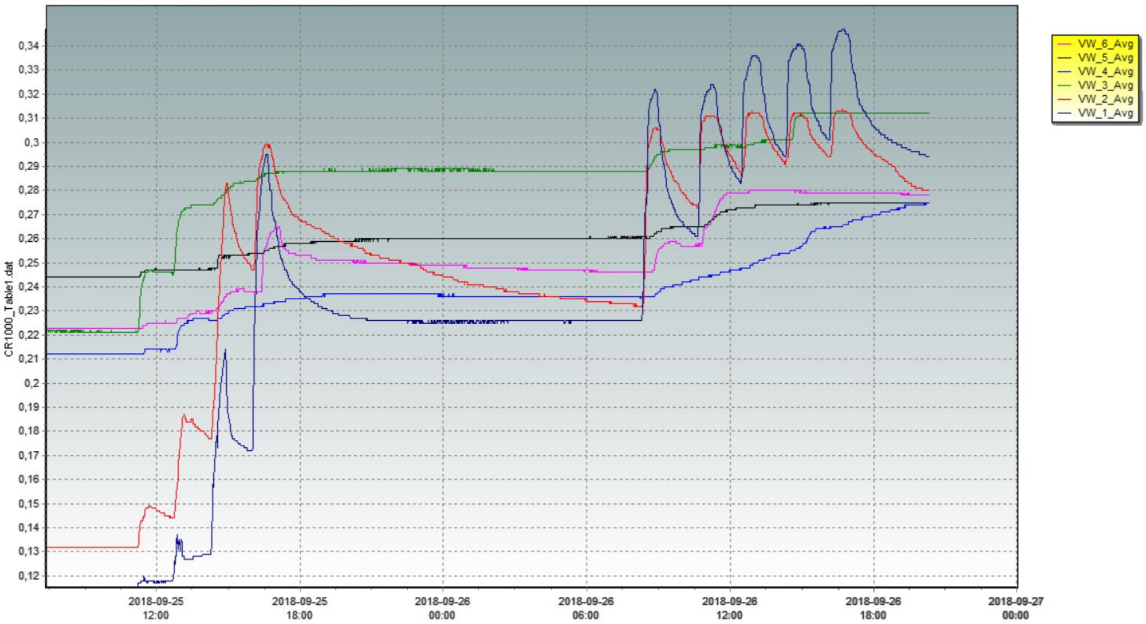

Figure 11: Changes in water content with time as measured by the TDR probes in the pit. VW_1_Avg corresponds to the shallowest TDR probe while VW_6_Avg corresponds to the deepest one.

The further steps are to process the data; we have started with the electrical resistivity, checking the pseudo-sections for each acquisition and performing a statistical study on the data. We will continue by producing time-lapse ERT images, and then we will work with the seismic data sets to obtain V_P sections from P-wave refraction tomography and V_S sections from surface wave dispersion analysis. Additionally, we plan on performing clustering and joint inversion of these data.

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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 acquisition of temperature profiles is carried on by the introduction of a temperature and pressure sensor in boreholes drilled around the stream, obtaining a map of the groundwater temperature (Figure 12). By locating areas with thermal anomalies, it is possible to identify sites of potential groundwater discharge. This data can also be used to obtain groundwater upwelling fluxes by fitting an analytical solution to the measured vertical temperature profiles.

A FO-DTS system was 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 a 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.

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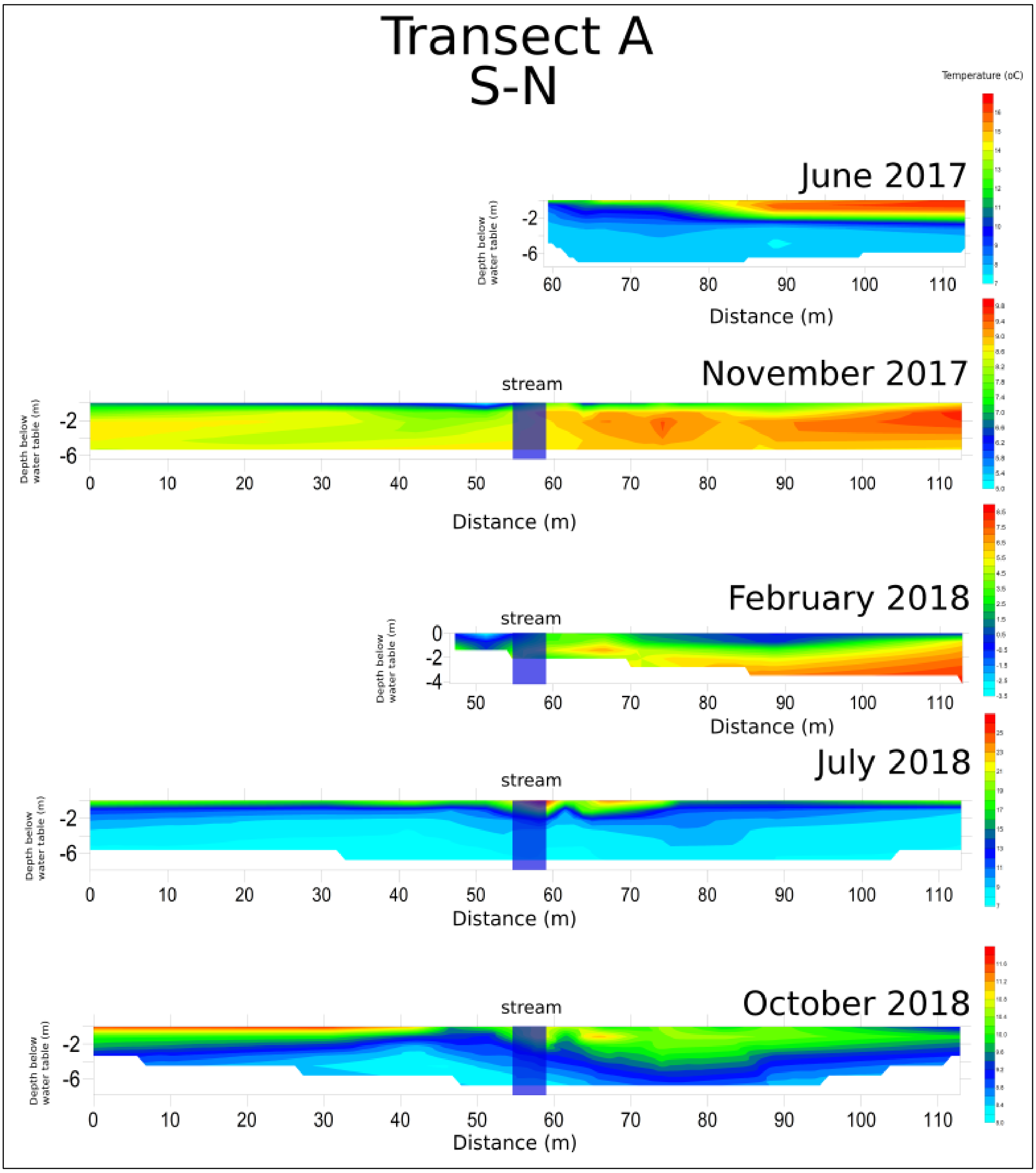

Figure 12: Groundwater temperature cross-section from interpolated temperature profile data. The data was collected at the Holtum stream ca, Denmark (by Joel Tirado-Conde).

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.

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

In order to use temperature data for the description of subsurface flow in fractured media, a temperature model and inversion approach has been developed which uses distributed temperature data to calculate the flow rate inside the wellbore. This sheds a 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 sections 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. In October 2018 a series of distributed temperature measurement using DTS inside a wellbore were 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 also been done for a continuous period of 36 hours to cover a complete and a half tide cycle. The tidal temperature data will be analyzed to discern the effect of tide on production from each fracture and possible understanding of fracture properties. Figures 13 and 14 show the experiment set-up, site and recorded temperature data inside the wellbore, respectively.

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

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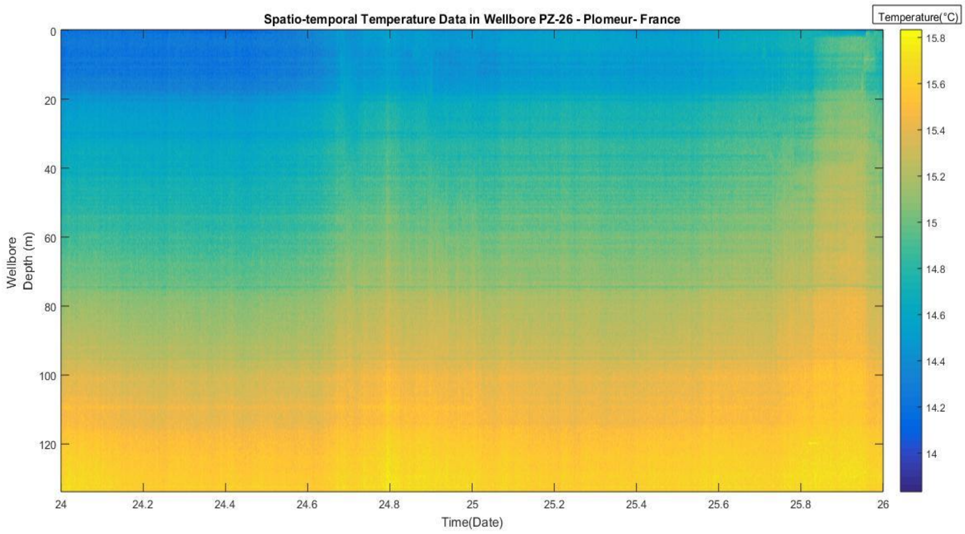

Figure 14: Spatio-temporal temperature data recorded in wellbore PZ-26 during ambient and pumping conditions (Ploemeur, France).

The interpretation of data is the next step. The acquired DTS data will be quality checked and possible noise will be removed from the data. Flow rate in two ambient and pumping condition will be calculated along the borehole with the developed temperature model using the DTS data and will be cross-checked with flow rates measured by heat pulse flowmeter (Figure 15). Next, the ambient temperature data which are affected by tidal signal will be analyzed to find out how the flow in fracture changes with tidal signals.

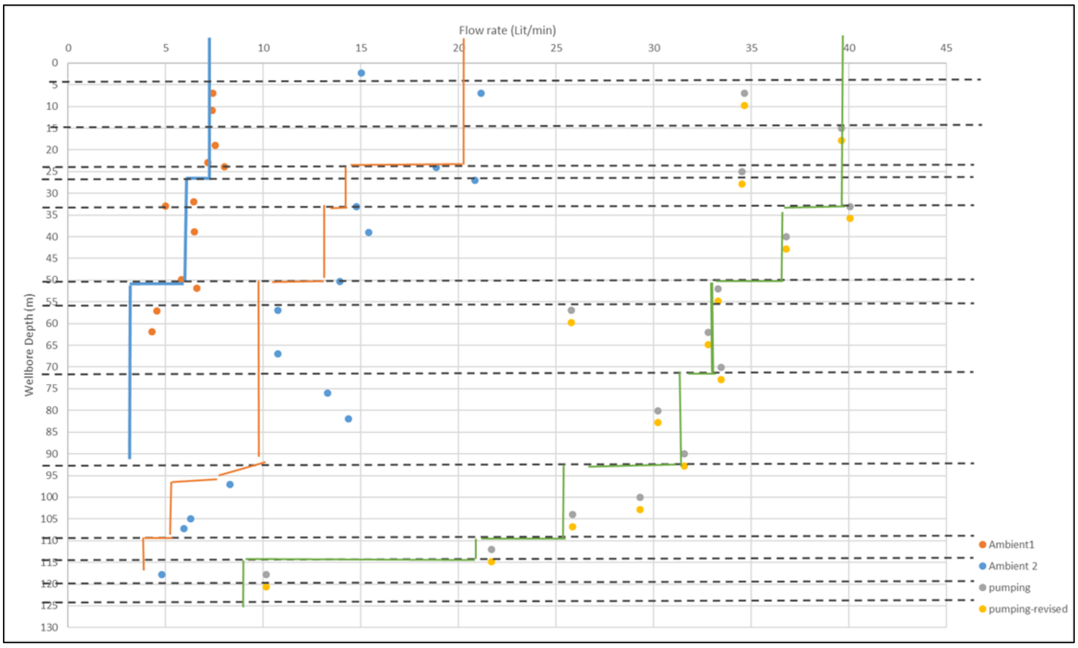

Figure 15: Provisional heat pulse flow measurement interpretation in wellbore PZ-26 during two ambient and pumping conditions (Ploemeur, France).

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Link between data and models

Field data and petrophysical models

The seismic signal is certainly related to mechanical properties that partly depend on porosity and saturation. However, the interpretation of these properties remains complex in unconsolidated near surface materials, limiting the quantitative description of linked hydrodynamic properties.

There exist several models that allow us to estimate the effective elastic moduli and velocities of a medium, ranging from Effective Medium Theory (EMT) models to empirical relationships proposed by the geotechnical community. Nevertheless, each of them has its limitations and some of them might only be constrained to laboratory experiments.

Using petrophysical relationships in geophysical field data with the aim of quantifying spatiotemporal changes can be challenging if there is not enough control over the conditions producing these changes. To validate the relationships and models, it is necessary to first perform a controlled experiment and then test them.

With the infiltration experiment at the Ploemeur Hydrological Observatory, we have a controlled field experiment where we know how much water we infiltrated and how it changed the water content in the subsurface. We will be able to use this information to constrain the data and validate the petrophysical models.

Integrated surface and subsurface hydrological models

Integrated surface and subsurface hydrological models handle both the overland flow on the surface domain and the variably saturated groundwater flow in the subsurface. This is done in a way that does not rely on the conductance concept as other coupled models do. Instead, the surface water equations are used to close the initial value problem of the groundwater flow, resulting in an overland flow boundary condition (Kollet and Maxwell, 2006), thus removing the inconsistency of both the conductance concept and the linkage of separate surface and subsurface modeling codes (Therrien et al., 2010). These models can also simulate thermal energy transport, and the user can decide whether these changes in heat concentrations affect fluid properties such as density or viscosity (Brunner and Simmons, 2012).

The use of these models allows us to model both the hydrological processes occurring in the stream and the groundwater flow and heat transport. Incorporating the thermal and hydrological data obtained in the field 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 the effect of temperature in the 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, tool still in an early stage of development as stated before.

Furthermore, integrated models have already been a useful tool to assess the limitations of the field techniques, providing information regarding the quality of the data obtained in the field (in this case how strong the thermal signal can be expected to be) and about the most suitable locations for data acquisition as well.

Another benefit we obtain by using these models is the possibility to build synthetic representations of the reality. That is, creating different parameter configurations (e.g. hydraulic conductivity of the media, porosity, etc.), it is possible to test the thermal and hydrological response of the system, obtaining with it insights about the geological setting under the ground.

For a comprehensive review of all the processes involved in the surface water – groundwater exchange, as well as the possibilities available in terms of modelling to correctly simulate these processes, refer to Brunner et al. (2017).

Distributed temperature data inside borehole, flow rate and geomechanical behavior of fractures

In a flowing well, the temperature change trend alongside the wellbore is dependent on the heat transfer parameters between the fluid and surrounding earth. The heat transfer parameters include fluid entry temperature into the wellbore, surrounding earth temperature and thermal properties as well as fluid velocity inside the wellbore. The more the fluid velocity, the less change in temperature alongside the wellbore as fluid has less time to do heat exchange with the surrounding earth. This trend of change in the temperature with respect to the depth which may be provided by DTS, can be used to find velocity and flow rate of the fluid inside the wellbore by performing an inversion on distributed temperature data. This sheds light on using DTS as a permanent downhole monitoring tool.

In coastal aquifers, tidal fluctuation will result in water level response and consequently change in the flow rate inside the wellbore and real time monitoring of the fluid rate is possible through the analysis described previously using distributed temperature data. So this can be a cost effective approach to characterize the hydrological parameters in coastal aquifers with tidal signals. Recording distributed temperature data during the tidal signals will allow us to have a real time monitoring of the flow rate (using the previously discussed approach) change caused by tide changes.

In the fractured site wellbore in Ploemeur, tidal signals affect production of the fractures crossing the wellbore. In the recent experiment performed in Ploemeur, temperature data has been recorded for one and half tidal cycle and it will be used to track the change of production from each fracture during tidal fluctuation. This can provide us with some understanding about geomechanical properties of the fractures crossing the wellbore.

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Added-value of the network

The network provides us with collaboration opportunities that extend beyond the work package framework. For ESR 5 a secondment in UNIL (University of Lausanne) will take place in 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 infiltration experiment at the Ploemeur Hydrological Observatory (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 on the site.

For ESR 6, two different periods of three-month secondment are planned at the University of Lausanne. The first secondment period starts at the 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 in the University of Lausanne will take place after the acquisition of field data to use the developed inversion approach on real data.

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 modeling 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.

Dissemination activities

ESR 05: Lara Blazevic, CNRS, Sorbonne University

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, Universite de Rennes 1

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"*.

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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"*.

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Activities/Experimental campaigns/Monitoring

1. Already done experimental campaigns or monitoring

ESR5 Experimental plan	Dates	Site	Scientific Objectives	Participants	Datasets expected from the experiment & format
Experiment 1	24/09/2018-28/09/2018	Ploemeur (France)	Monitor the changes of the seismic response (more specifically wave propagation velocities) with varying water saturation by acquiring seismic data during an infiltration test	Ludovic Bodet (Sorbonne Université), Laurent Longuevergne (Université de Rennes 1, CNRS), Sylvain Pasquet (IPGP), Lara Blazevic (Sorbonne Université, CNRS)	Waves travel distance and traveltimes (.dat) to be converted to P-wave velocity, V_P (using P-wave refraction tomography), and S-wave velocity, V_S (using surface wave dispersion analysis), profiles. ERT profiles TDR data

ESR6 Experimental plan	Dates	Site	Scientific Objectives	Participants	Datasets expected from the experiment & format
Experiment 1	24/10/2018-26/10/2018	Ploemeur (France)	Monitoring the temperature during ambient and pumping conditions Monitoring the change in the temperature due to tidal fluctuation Measuring the wellbore flow rate using heat pulse flow measurement	Behzad Pouladi (Université de Rennes 1, CNRS), Olivier Bour (Université de Rennes 1), Longuevergne (Université de Rennes 1, CNRS), Jérôme de La Bernardie (Université de Rennes 1)	Distributed Temperature Data (.dat) Flow profile of the wellbore (.xlsx)

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ESR7 Experimental plan	Dates	Site	Scientific Objectives	Participants	Datasets expected from the experiment & format
Monitoring	June 2017 November 2017 February 2018 March 2018 July 2018 October 2018	EVI1 (Ejstrupholm, Holtum catchment, Denmark)	Monitoring of temperature evolution in lowland/wetland stream valley system	Joel Tirado-Conde (University of Copenhagen)	Depth below GWT - Temperature profiles (.dat) Unsaturated zone temperature data along a transect from DTS (.dat) Thermal infrared images from drone (.tiff, .jpeg)
Experiment 1	October 2018	EVI1 (Ejstrupholm, Holtum catchment, Denmark)	ERT surveys following the boreholes and DTS transect	Joel Tirado-Conde (University of Copenhagen), Andrea Palacios (CSIC)	Apparent resistivity in depth along a transect (.dat) Soil moisture along a transect (.dat) Electroconductivity in boreholes along a transect (.dat)

2. Planned experimental campaigns or monitoring

ESR5 Experimental plan	Dates	Site	Scientific Objectives	Participants	Datasets expected from the experiment & format
Experiment 2	2019	Äspö HRL (Sweden)	Estimate the shear stiffness of the rock mass by means of the seismic data and correlate it to fracture density	Ludovic Bodet (Sorbonne Université), Lara Blazevic (Sorbonne Université, CNRS)	Travel distance, traveltime, VP, VS

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Expected scientific outputs

- A paper on the use of petrophysical models for the interpretation of the seismic and electrical resistivity data from the infiltration experiment at the Ploemeur Hydrological Observatory.
- A paper on clustering and joint inversion of seismic and electrical resistivity data from the infiltration experiment at the Ploemeur Hydrological Observatory.
- Article on thermal characterization of lowland stream valleys with focus on the groundwater upwelling impacts on subsurface temperature distributions.
- Article on integrated modeling for quantification of groundwater – surface water exchanges using both classic hydrological and thermal data.
- A paper on proposing a novel computationally cheap framework for flow profiling inside the borehole. The distributed temperature data and heat pulse flow measurement will be used in this paper.
- A possible paper on geomechanical characterization of fractures in coastal aquifers using passive distributed temperature data and tidal signals.

Expected joint scientific publications

Our goal is that the literature review and achieved activities presented in this report and in the D3.3 report serve as a base for a joint publication such as a reviewlet. The innovative value of our project lies in applying methods that have not, to our knowledge, been combined before for the purpose of water flux and storage estimation and we believe this would be of great interest for the scientific community.

Moreover, both the achieved and planned activities offer publication opportunities with other members of the network outside the Workpackage. For ESR5, working on clustering and joint inversion with the dataset from the infiltration experiment opens collaboration opportunities with the ESRs in Workpackage 5. Furthermore, the planned seismic experiment at the Äspö Hard Rock would contribute to a joint publication with ESR 9, who has acquired GPR data on the site.

University of Copenhagen is hosting ESR2, ESR8 and ESR14 for secondments. Different techniques these ESRs are developing will be tested in the HOBE sites. It is complicated to assess the output from these visits beforehand, but it is no difficult to imagine that the insights obtained from these experiments could lead to joint articles. For instance, ESR14 has already performed a series of electrical resistivity tomography (ERT) surveys in one of these field sites, and the inversion for temperature and its comparison and discussion with the thermal data collected by ESR7 is planned, potentially leading to a joint publication on these topics.

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Data archiving and dissemination

ESR	Sites	Data types	Database	Contact person for the database	Format
ESR5 **Lara Blazevic**	- Ploemeur - HRL SKB	- Seismic data - Electrical resistivity data - TDR data - Core data	- H+ database - Aspo HRL database	Annick Battais annick.battais@univ-rennes1.fr	H+ format
ESR6 **Behzad Pouladi**	- Ploemeur	DTS, DSS	H+ database	Annick Battais annick.battais@univ-rennes1.fr	H+ format
ESR7 **Joel Tirado Conde**	-HOBE sites (UCPH) -TERENO sites (UFZ)	- UAV data - Hydraulic data - DTS data - Temperature (profile) data	HOBE database		

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References

Bakker, M., Caljé, R., Schaars, F., van der Made, K. J., & de Haas, S. (2015). An active heat tracer experiment to determine groundwater velocities using fiber optic cables installed with direct push equipment. *Water Resources Research*, *51*(4), 2760-2772.

Banks, E. W., Shanafield, M., Noorduijn, S., McCallum, J., Lewandowski, J., & Batelaan, O. (2018). Active heat pulse sensing of 3-D-flow fields in streambeds. *Hydrol. Earth Syst. Sci., 22,* 1917-1929.

Bergamo, P., Dashwood, B., Uhlemann, S., Swift, R., Chambers, J. E., Gunn, D. A., & Donohue, S. (2016a). Time-lapse monitoring of climate effects on earthworks using surface waves. *Geophysics*, *81*(2), EN1-EN15.

Bergamo, P., Dashwood, B., Uhlemann, S., Swift, R., Chambers, J. E., Gunn, D. A., & Donohue, S. (2016b). Time-lapse monitoring of fluid-induced geophysical property variations within an unstable earthwork using P-wave refractionP-wave refraction time-lapse monitoring. *Geophysics*, *81*(4), EN17-EN27.

Bingham, Q. G., Neilson, B. T., Neale, C. M. U. and Cardenas, M. B. (2012). Application of high-resolution, remotely sensed data for transient storage modeling parameter estimation. *Water Resources Research, 48(8)*.

Bredehoeft, J. D., & Papaopulos, I. S. (1965). Rates of vertical groundwater movement estimated from the Earth's thermal profile. *Water Resources Research*, *1*(2), 325-328.

Briggs, M. A., Lautz, L. K., McKenzie, J. M., Gordon, R. P., & Hare, D. K. (2012). Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux. *Water Resources Research*, *48*(2).

Brunner, P., & Simmons, C. T. (2012). HydroGeoSphere: a fully integrated, physically based hydrological model. *Groundwater*, *50*(2), 170-176.

Brunner, P., Therrien, R., Renard, P., Simmons, C. T., & Franssen, H. J. H. (2017). Advances in understanding river-groundwater interactions. *Reviews of Geophysics*, *55*(3), 818-854.

Cardenas, M. B., Harvey, J. W., Packman, A. I., & Scott, D. T. (2008). Ground-based thermography of fluvial systems at low and high discharge reveals potential complex thermal heterogeneity driven by flow variation and bioroughness. *Hydrological Processes: An International Journal*, *22*(7), 980-986.

Cardenas, M. B., Neale, C. M., Jaworowski, C., & Heasler, H. (2011). High-resolution mapping of river-hydrothermal water mixing: Yellowstone National Park. *International journal of remote sensing*, *32*(10), 2765-2777.

Coleman, T. I., Parker, B. L., Maldaner, C. H., & Mondanos, M. J. (2015). Groundwater flow characterization in a fractured bedrock aquifer using active DTS tests in sealed boreholes. *Journal of Hydrology*, *528*, 449-462.

Constantz, J. (2008). Heat as a tracer to determine streambed water exchanges. *Water Resources Research*, *44*(4).

ENIGMA ITN - This project has received funding from European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement N°722028.

Dangeard, M., Pasquet, S., Bodet, L., Guérin, R., Longuevergne, L., & Thiesson, J. (2016). Temporal variations of near-surface seismic data at the Ploemeur (France) hydrogeological observatory. In *Near Surface Geoscience 2016-22nd European Meeting of Environmental and Engineering Geophysics*.

des Tombe, B., Bakker, M., Smits, F., Schaars, F., & van der Made, K. J. (2018, April). Measurement of the specific discharge up to 50 m depth using heat pulses and DTS. In *EGU General Assembly Conference Abstracts* (Vol. 20, p. 8062).

Greswell, R. B., Riley, M. S., Alves, P. F., & Tellam, J. H. (2009). A heat perturbation flow meter for application in soft sediments. *Journal of hydrology*, *370*(1-4), 73-82.

Haeni, F. P. (1988). *Application of seismic-refraction techniques to hydrologic studies*. US Government Printing Office.

Hatch, C. E., Fisher, A. T., Revenaugh, J. S., Constantz, J., & Ruehl, C. (2006). Quantifying surface water–groundwater interactions using time series analysis of streambed thermal records: Method development. *Water Resources Research*, *42*(10).

Jensen, J. K., & Engesgaard, P. (2011). Nonuniform Groundwater Discharge across a Streambed: Heat as a Tracer. *Vadose Zone Journal*, *10*(1), 98-109.

Kelly, J. L., Glenn, C. R., & Lucey, P. G. (2013). High-resolution aerial infrared mapping of groundwater discharge to the coastal ocean. *Limnology and Oceanography: Methods*, *11*(5), 262-277.

Kollet, S. J., & Maxwell, R. M. (2006). Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Advances in Water Resources*, *29*(7), 945-958.

Lewandowski, J., Angermann, L., Nützmann, G., & Fleckenstein, J. H. (2011). A heat pulse technique for the determination of small-scale flow directions and flow velocities in the streambed of sand-bed streams. *Hydrological Processes*, *25*(20), 3244-3255.

Lewandowski, J., Meinikmann, K., Ruhtz, T., Pöschke, F., & Kirillin, G. (2013). Localization of lacustrine groundwater discharge (LGD) by airborne measurement of thermal infrared radiation. *Remote sensing of environment*, *138*, 119-125.

Lowry, C. S., Walker, J. F., Hunt, R. J., & Anderson, M. P. (2007). Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. *Water Resources Research*, *43*(10).

Pasquet, S., Bodet, L., Longuevergne, L., Dhemaied, A., Camerlynck, C., Rejiba, F., & Guérin, R. (2015). 2D characterization of near-surface VP/VS: surface-wave dispersion inversion versus refraction tomography. *Near Surface Geophysics, 13(4)*, 315-331.

Pasquet, S., Holbrook, W. S., Carr, B. J., & Sims, K. W. W. (2016). Geophysical imaging of shallow degassing in a Yellowstone hydrothermal system. *Geophysical Research Letters*, *43*(23).

Pride, S. R. (2005). Relationships between seismic and hydrological properties. In *Hydrogeophysics* (pp. 253-290). Springer, Dordrecht.

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Röper, T., Greskowiak, J., & Massmann, G. (2014). Detecting small groundwater discharge springs using handheld thermal infrared imagery. *Groundwater*, *52*(6), 936-942.

Stallman, R. W. (1965). Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature. *Journal of geophysical Research*, *70*(12), 2821-2827.

Suzuki, S. (1960). Percolation measurements based on heat flow through soil with special reference to paddy fields. *Journal of Geophysical Research*, *65*(9), 2883-2885.

Therrien, R., McLaren, R. G., Sudicky, E. A., & Panday, S. M. (2010). HydroGeoSphere: A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport. *Groundwater Simulations Group, University of Waterloo, Waterloo, ON*.

Vogt, T., Schirmer, M., & Cirpka, O. A. (2012). Investigating riparian groundwater flow close to a losing river using diurnal temperature oscillations at high vertical resolution. *Hydrology and Earth System Sciences*, *16*(2), 473-487.

Wawrzyniak, V., Piégay, H., Allemand, P., Vaudor, L., & Grandjean, P. (2013). Prediction of water temperature heterogeneity of braided rivers using very high resolution thermal infrared (TIR) images. *International journal of remote sensing*, *34*(13), 4812-4831.

West, M., & Menke, W. (2000). Fluid-induced changes in shear velocity from surface waves. In *Symposium on the Application of Geophysics to Engineering and Environmental Problems 2000* (pp. 21-28). Society of Exploration Geophysicists.

Westhoff, M. C., Savenije, H. H. G., Luxemburg, W. J., Stelling, G. S., Van de Giesen, N. C., Selker, J. S., ... & Uhlenbrook, S. (2007). A distributed stream temperature model using high resolution temperature observations. *Hydrology and Earth System Sciences Discussions*, *11*(4), 1469-1480.

Westhoff, M. C., Gooseff, M. N., Bogaard, T. A., & Savenije, H. H. G. (2011). Quantifying hyporheic exchange at high spatial resolution using natural temperature variations along a first-order stream. *Water Resources Research*, *47*(10).

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End of deliverable WP3 D3.2 D7

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