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Innovative strategies for high resolution site characterization: application to a flood plain

Strategie innovative per la caratterizzazione ad alta risoluzione: applicazione al caso di una pianura alluvionale

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Riassunto: La risoluzione di complessi problemi idrogeologici spesso richiede una attenta comprensione delle condizioni (idro-) geologiche di sottosuolo. Ciò è particolarmente vero nel caso di depositi sedimentari con architettura complessa, dove la litologia e/o le proprietà idrodinamiche possono variare significativamente su distanze orizzontali e verticali piccole. In questi siti, un approccio di tipo tradizionale, basato su indagini a campione non è applicabile a causa delle limitazioni nell'accuratezza, risoluzione ed efficienza. Invece, e` richiesto un approccio di indagine di tipo adattativo che vada a combinare tecnologie di esplorazione differente risoluzione e scala di indagine. Questo contributo ha lo scopo di dimostrare la fattibilità di un tale approccio multiscala per la caratterizzazione di un sito nei pressi della città di Löbnitz, Germania, costituito da depositi alluvionali eterogenei. La nostra attenzione è posta sulla caratterizzazione della litologia e proprietà idrodinamiche, con un focus sulla definizione e caratterizzazione di un meandro abbandonato come esempio di una struttura geologica a piccola scala.

Parole chiave: caratterizzazione, conducibilità idraulica, Direct push, geofisica.

Keywords: *site characterization, hydraulic conductivity, Direct Push, surface geophysics.*

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Abstract: *Solving complex hydrogeological problems often requires a thorough understanding of (hydro-) geological subsurface conditions. This is especially true for sedimentary deposits with complex architecture, where lithology and/or hydraulic properties can significantly vary over short horizontal and vertical distances. At these sites, a traditional, solely sample-based investigation approach is often not applicable due to limited data accuracy, resolution, and efficiency. Instead, an adapted investigation approach is required that combines exploration technologies of different resolution and investigation scales. This paper aims to demonstrate the feasibility of such a multi-scale approach for the characterization of a test site near the city of Löbnitz, Germany, that is comprised of heterogeneous alluvial deposits. Our focus is on site characterization in terms of lithology and hydraulic properties, as well as on the delineation and characterization of an aggradated oxbow as a typical example of a small scale geological structure.*

Introduction

Many hydrogeological tasks require a detailed and profound understanding of ground water flow within the subsurface. Among these tasks, the sustainable management of ground water resources is an emerging challenge throughout the world. However, a reliable understanding of ground water flow preconditions a thorough understanding of the geological structures of the subsurface. This has been a challenging task for hydrogeologists for several decades especially at sites with complex geological settings or intricately constructed sedimentary deposits, e.g. fluviatile regimes where hydraulic conductivity can change over short horizontal and vertical distances in several orders of magnitude. Here, knowledge about hydraulic conductivity and its distribution in space is needed on a high resolution scale (see among others: Wolf et al. 1991, Boggs et al. 1992, Rehfeldt et al. 1992). However, traditional site investigation techniques, such as grain size analysis or pumping tests, often fail to provide data with the required resolution or accuracy to reliably parameterize increasingly complex flow and transport models (see Schulmeister et al. 2003, Köber et al. 2009, Lessoff et al. 2010, Vienken & Dietrich 2011) . With this background, exploration and monitoring technologies must be developed in order to meet the challenges which arise from the differences between process scale and exploration scale, the heterogeneity of geological systems, and the dimensions of the investigated system.

With the aim of combining different exploration and monitoring techniques to enable a problem-oriented, rapid site characterization, the Helmholtz Centre for Environmental Research - UFZ uses the MOSAIC research platform (Model-Driven Site Assessment, Information and Control), which is comprised of mobile modular data acquisition units for adaptive and modelling-based field investigations. This platform is made up of vehicles equipped with geophysical measuring techniques in combination with Direct Push probing devices, borehole logging, hydrogeological and geotechnical equipment. These innovative mapping and monitoring technologies enable high-resolution surveys of complex subsurface structures and processes. In this way, MOSAIC is a broad research platform for model-supported near-surface assessment, which can be used by scientists from different fields of interest and various study areas to connect and work together towards common aims (Helmholtz Association, 2013). A generalized scheme of an adaptive working plan with on-site decision making is presented in figure 1.

The aim of this paper is to describe the MOSAIC site investigation approach and to use results obtained during UFZ field work at the Löbnitz site to demonstrate its feasibility. The test site is located on the banks of the River Mulde, near the city of Löbnitz, Germany. This site represents a typical heterogeneous fluviatile sedimentary system. The main task of the investigation is to characterize the adjacent river deposits and, in particular, to map the extent and hydraulic properties of small scale geological features using a three phase investigation approach. The example provided here is based on the work of Kreck (2011) and Hausmann et al. (2013).

Site investigation – Löbnitz case study

In the following, we will apply a three phase investigation approach which consists of Phase 1: Site Reconnaissance, Phase 2: Site Exploration, and Phase 3: Investigation and Parameterization (as described in figure 2 for the Löbnitz test site). Hence, the following section is subdivided according to the different phases. For each phase, the applied exploration techniques are presented followed by the respective results.

Site Reconnaissance

The test site is located in northern Saxony, close to the river Mulde, near the city of Löbnitz. The subsurface is mainly comprised of surface-near clayey and silty overbank deposits, followed by underlying terrace gravels, as well as sandy and gravelly channel fills. These alluvial sand and gravel deposits represent the uppermost aquifer, which is the main focus of this study. The aquifer is underlain by the silty and clayey sediments of the Vetschauer series at an approximate depth of 12-14 m below ground surface. Due to the proximity of the River Mulde, the ground water level at the tests site can vary by several decimeters within short time periods. In times of high ground water levels, the overlying alluvial clay/silt cover can lead to a locally confined head. Further information on the tests site is given by Kreck (2011) and Hausmann et al. (2013). Information on the regional geology is provided by Eissmann (1994). A schematic overview of the test site including a description of the location of the geophysical profiling and Direct Push probing points, is given in figure 3. Site reconnaissance started as stated and in accordance with the flow chart, with the analysis of aerial pictures and existing geological and hydrogeological information that was available from maps and existing drillings/wells. Based on this analy-

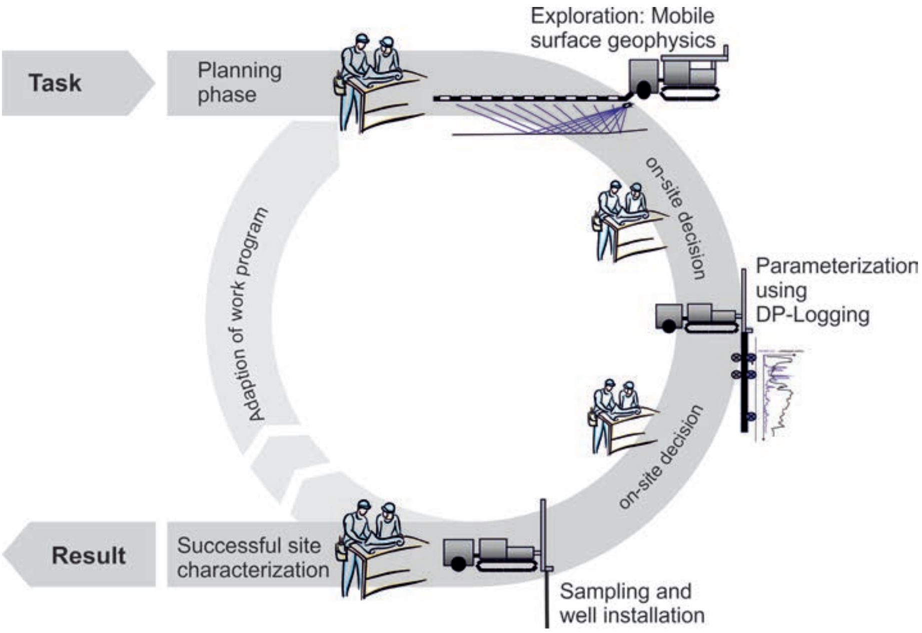

Fig. 1 - MOSAIC adaptive work approach based on the combination of exploration and monitoring techniques for on-site decision making. Modified after Leven et al. (2010).

Fig. 1 - Il metodo di lavoro adattativo MOSAIC basato sulla combinazione di tecniche di indagine e monitoraggio per il supporto alle decisioni *on-site*. Modificato da Leven et al. (2010).

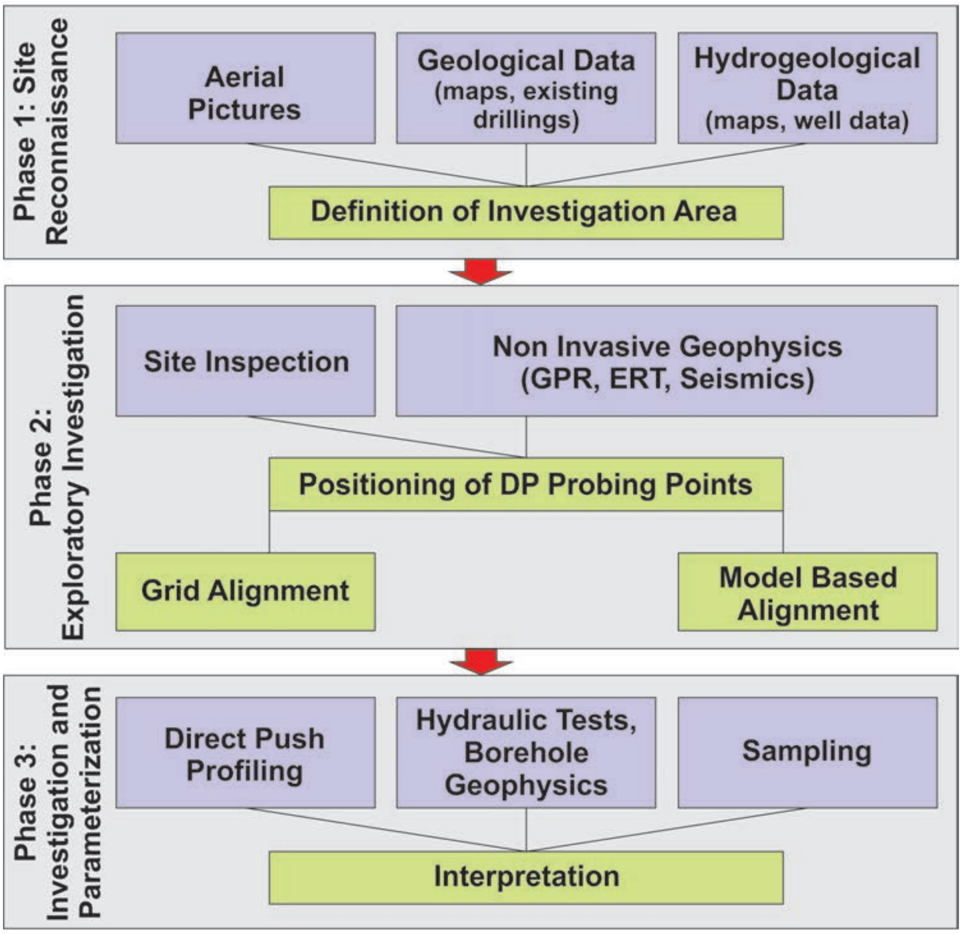

Fig. 2 - Three phase workflow for innovative site characterization.

Fig. 2 -Diagramma di flusso a tre fasi per la caratterizzazione innovativa.

sis, the area of interest, especially the area of an embankment cross-cutting oxbow, was identified and geophysical profile measurements were conducted parallel to the embankment (see Fig. 3).

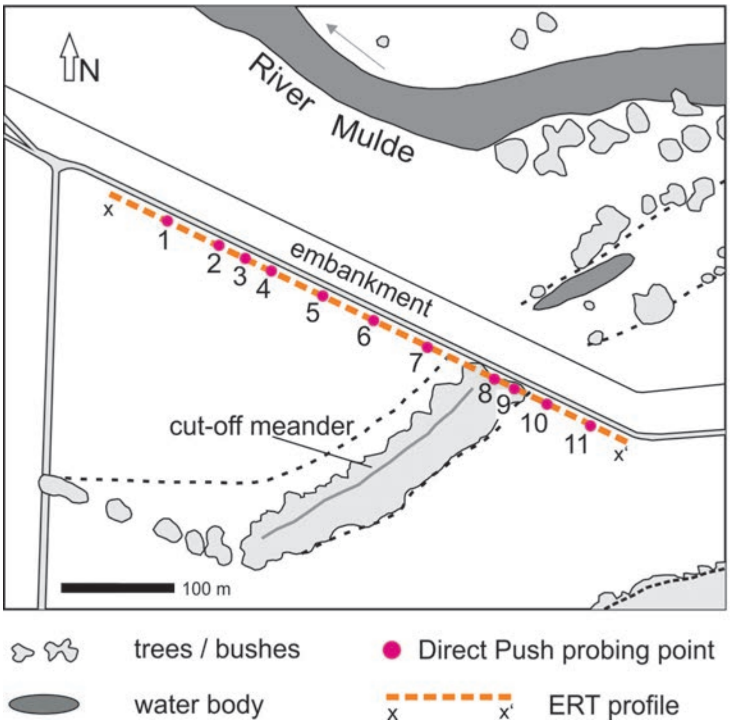

Fig. 3 - Schematic overview of the test site Löbnitz with indicated location of the geophysical profiling and location of the Direct Push probing points, modified after Hausmann et al. (2013).

Fig. 3 -Schema del test site di Löbnitz con indicata a posizione dei profili geofisici e deille indagini Direct Push, modificata da Hausmann et al. (2013).

Exploratory Investigation

The work of Kreck (2011) and Hausmann et al. (2013) includes Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT) and seismic measurements. Hausmann et al. (2013) compare different geophysical methods for subsurface characterization at the Löbnitz test site. In this study, the focus is placed on ERT measurements. ERT is used to measure the apparent electrical resistivity distribution of the subsurface by injecting a current into the subsurface and measuring the resulting potential difference at the surface (Ernston & Kirsch, 2006). In this study, ERT was used in a dipole-dipole array, i.e. the current injecting electrodes and the potential electrodes are in each case closely spaced to form a current dipole and a potential dipole (Ernston & Kirsch, 2006). The results of the ERT dipole-dipole array measurements are shown in figure 4A. Measurement quality was influenced by man-made gravel banquettes, which limited coupling of the electrodes to the subsurface. However, ERT dipole-dipole results yield a sufficient basis to assess the near-surface sedimentary structures. The shallow subsurface is made up of two layers. The underlying layer is characterized by high resistivity values, indicating sand and gravelly deposits (corresponding to the alluvial sand and gravels); the overlaying layer is of varying thickness and characterized by low resistivity values, indicating organic and/or clayey (overbank) deposits. The extent of the oxbow structure can be clearly identified on the south-eastern section of the profile (profile length 330-430 m). Results were used to define Direct Push probing positions, see figure 3.

Investigation and Parameterization

For reliable subsurface parameterization, Direct Push in-situ sensor probe measurements were utilized. Direct Push describes a technology that uses hollow steel rods that are hammered and/or pushed into the subsurface (EPA 1997). Attaching sensor probes to the end of the rod string enables continuous in-situ vertical high resolution profiles of hydrogeological, geotechnical, geophysical or geochemical properties to be collected (Dietrich & Leven, 2006). Alternatively, Direct Push can be used to rapidly install permanent or temporary ground water or soil gas monitoring wells or to re-

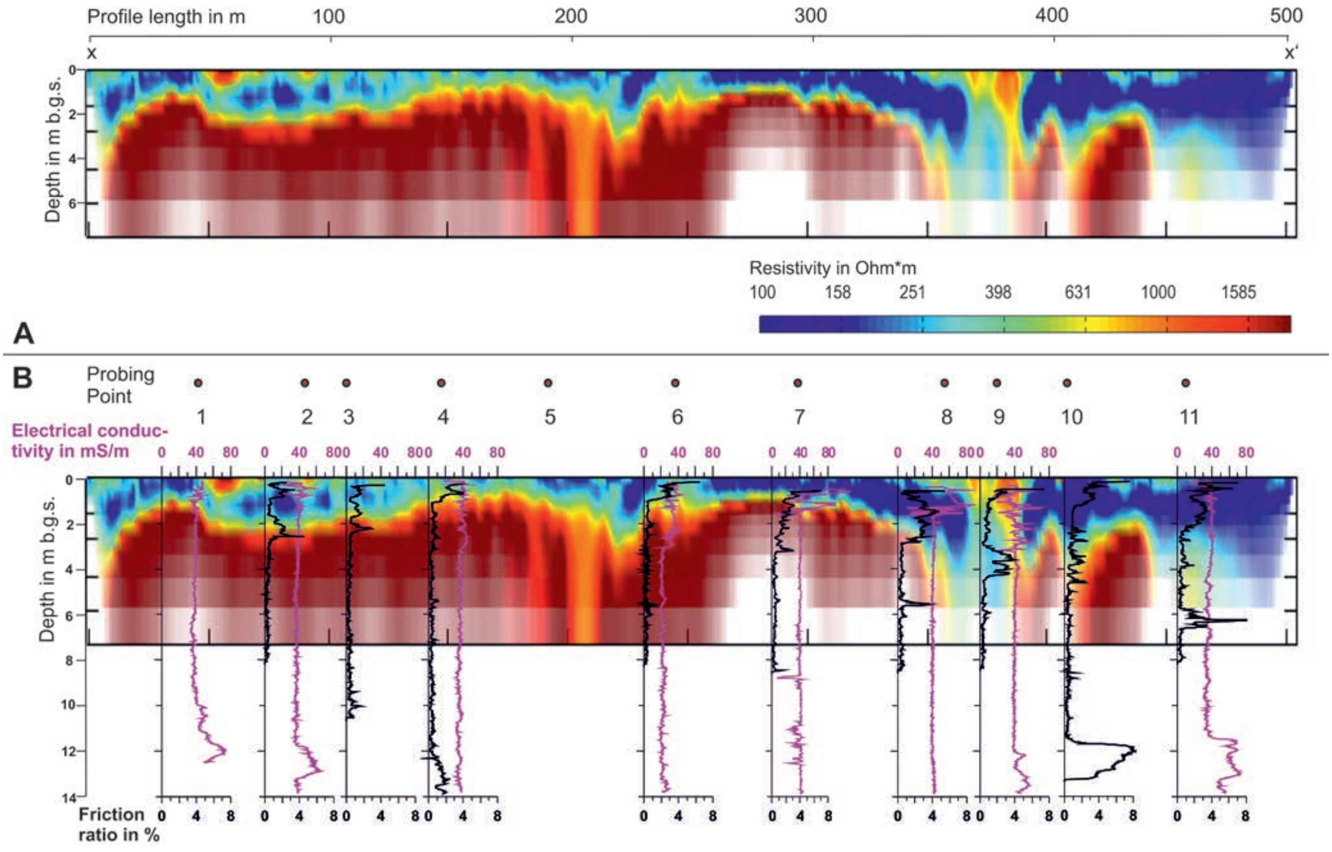

Fig. 4 A, B - A) Results of the ERT measurements using a dipole-dipole array; white indicates areas with no available data; B) ERT results in comparison to Direct Push probing results showing CPT based friction ratio and DPIL relative hydraulic conductivity measurements.

Fig. 4 A, B - A) Risultati dell-indagine ERT svolta utilizzando una configurazione dipolo-dipolo. Le aree in bianco indicano l'assenza di dati. B) Confronto tra ERT e indagini Direct Push per CPT basate su prove *friction ratio* e DPIL per la detrminzaione della conducibilita` idraulica relativa.

trieve soil samples. As Direct Push technology allows on-site decision making, it is often advantageous over conventional, solely sample-based site characterization approaches in terms of data reliability, adaptability, and efficiency (see also EPA, 1997; McCall et al., 2006). In the following section, the applied Direct Push methods are briefly introduced. This short introduction is based on the description provided in Vienken et al. (2012). Further information on Direct Push technology is provided by Butler et al. (2002), Dietrich & Leven (2006), McCall et al. (2006), Leven et al. (2011), and Liu et al. (2012). Additional tool specific references are listed in the individual descriptions.

Cone penetration testing with pore pressure measurement (CPTU)

Cone penetration testing with pore pressure measurement (CPTU) is one of the most commonly used and most versatile applications among the Direct Push tools. A detailed introduction of cone penetration testing (CPT) is given by Meigh (1987), Lunne et al. (1997), and Brouwer (2007). During CPT, a cone penetrometer is statically pushed into the subsurface at a constant rate of 20 mm/s, while measuring the resistance (q_c) at the cone tip and friction (f_s) along the cone sleeve. Cone resistance (q_c) is defined as the total force acting on the cone divided by the projected area of the cone and sleeve friction (f_s) as the total force acting on the sleeve divided by the total area of the sleeve (Lunne et al., 1997). The primary application of CPT is the geotechnical characterization of the subsurface, e.g. for (pile) foundations, soil liquefaction assessment, as well as settlement and density analysis. However, CPT may also be very efficiently used to infer soil classification data, for stratigraphy and for the deduction of hydraulic conductivity values at high resolution scales (see Vienken et al. 2014). In this study, CPT is used for distinguishing between layers of different soil behavior. A simple indicator for soil behavior that is linked to lithology is the friction ratio (R_f) which is defined as:

$$R_f = \frac{f_s}{q_t} \times 100 \qquad (1)$$

where q_t is the corrected cone resistance defined as

$$q_t = q_c + (1 - a)u_2 \qquad (2)$$

where a is the area ratio of the cone (cone specific) and u_2 is the dynamic pore water pressure measured behind the tip. High R_f values, i.e. low q_t and high f_s values, indicate cohesive sediment behavior (mainly silts and clays); low R_f values are typical for non-cohesive sediments (sands and gravels). Several other approaches for the stratigraphic characterization of sedimentary deposits based on CPT measurements are available, e.g. calculation of the Soil Behavior Type Index. For an overview see Lunne et al., 1997. In this case study, the friction ratio was used as a qualitative indicator to detect changes in soil behavior type, which are interpreted as changes in lithology.

A standard piezocone with a projected tip area of 1,000 mm^2 was used for CPTU profiling. Pore pressure was measured at the u_2 position behind the tip.

Electrical conductivity logging

Electrical conductivity logging is an efficient tool for rapidly gaining high resolution vertical profiles of the distribution of soil electrical conductivity. Therefore, as the probe is advanced into the ground, an electrical current is applied. The current and resulting voltage are measured, e.g. using a Wenner configuration with equally-spaced electrode points. Based on this information, soil stratification or layer boundaries within the subsurface can be inferred, as an increase in the electrical conductivity can indicate an increased abundance of fine material in the soil under non-saline conditions. Specific details on electrical conductivity logging are provided by Schulmeister et al. (2003) and Sellwood et al. (2005).

Direct Push Injection Logger (DPIL)

The Direct Push Injection Logger working principle, application and interpretation routine is described in detail by Dietrich et al. (2008). In principle, this tool consists of a probe with an injection screen for water injection into the subsurface and a flowmeter and a pressure transducer at the surface. DPIL is used for describing the vertical distribution values of relative hydraulic conductivity, a value that is often closely correlated with absolute hydraulic conductivity. To obtain measurements, tool advancement is stopped at desired depth intervals (in this study 0.2 m) to conduct the testing. Therefore, flow rate and water pressure in the injection tubing is measured at different injection rates. For quality assurance, three measurements with different injection rates (max. 400 l/h) are taken at each depth interval. Relative hydraulic conductivity (K_{DPIL}) is calculated as the reciprocal value of the difference of total flow resistance R_{total} and the resistance of the tube (R_{tube}), as described in Dietrich et al. (2008):

$$K_{DPIL} = \frac{1}{R_{total} - R_{tube}} \qquad (3)$$

R_{total} can be derived from the relation between the injection pressure (p_{inj}) and the flow rate (Q) that is measured with the flow meter:

$$R_{total} = p_{inj} / Q \qquad (4)$$

For laminar flow, the tube resistance is mainly governed by the length of the tube and the tube diameter. This can be calculated based on the Hagen-Poiseuille equation (see Dietrich et al., 2008).

For turbulent flows, the tube resistance is a function of the flow rate. The tube resistance can be determined using a linear regression by measuring different flow rates and respective pressure measurements with the probe above ground surface level.

Direct Push Slug Test (DPST)

The slug test is a well-established method in the field of hydrogeology which is used to determine hydraulic conductivity in ground water monitoring wells (Butler, 1997; Butler et al., 2002; Hinsby et al., 1992). Therefore, a near-instantaneous change of head is induced in the well and the recovery of the head is logged. This instantaneous change of head can typically be realized by introducing or removing a known volume of water or displacer (see among others: Papadopulos et al., 1973). Slug tests were performed in temporary Direct Push-installed monitoring wells with a screened interval of approximately 0.5 m. To install a temporary monitoring well, the Direct Push probing rods are driven into the soil while the well screen is protected inside the rods. Upon reaching the desired depth, an expandable tip at the end of the rod string is pushed out and the rod string is pulled back. While holding the screen in place, it is exposed to the formation (see Sellwood et al., 2005 and McCall et al., 2006 for a description of installation procedures). For vertical multilevel slug testing, the screen was subsequently pulled back until the desired depths were reached, in this case 0.5 m after each test. For the Direct Push adapted version, a pneumatic slug test assembly was employed based on the methods described by Hinsby et al. (1992); initiating a change in head by pressurized air. Slug tests were analyzed after Zlotnik and McGuire (1998) and Butler (2002) that specifically consider the effects induced by the small diameter wells. Guidelines to ensure quality control of results, provided by Butler (1997), were followed.

Results of the Parameterization

Based on the results of the exploratory phase, 11 Direct Push probing points were chosen, with the aim of detailed investigation and parameterization of the identified near-surface structures - in terms of lithology and hydraulic properties. Therefore, EC profiling at 8 probing points and CPT measurements at 9 probing points were conducted to assess the lithological structures (see figure. 3). To support EC and CPT interpretation, EC and CPT R_f profiles are plotted in comparison to the ERT results (Fig. 4B). In this case, the EC profiles do not allow a detailed subsurface characterization. However, it can be seen that the ERT low resistivity surface layer is captured to its full extent by the CPT measurements, indicated by high R_f values. In comparison, ERT and CPT data yield coherent results. The high resistivity sandy-gravelly bottom layer is captured by low CPT R_f values. In addition, CPT measurements capture the base of the aquifer, i.e. the beginning of the Vetschauer series clays at probing point 10 and 4. In contrast to the ERT measurements, the CPT data reveal additional information about the composition and extent of the oxbow in more detailed depth resolution. CPT data infers a cohesive (clayey/organic) rich channel filling that was deposited during oxbow aggradation being underlain by non-cohesive (gravelly/sandy) channel deposits. Isolated peaks in the CPT R_f values indicate discontinuous clayey lenses.

The hydrogeological DPIL characterization was only performed in the saturated zone in depth greater 3 m below ground surface. As such, the CPT characterization of the uppermost layer cannot be resolved. However, the DPIL results (Fig. 5) clearly reveal several areas of reduced relative hydraulic conductivity at depths of 7 and 8 m respectively, as well as the confining clays in depths of 12 - 13 m. CPT data (Fig. 4) within depths of 7-8 m does not reflect a significant change in soil behavior type within this area of reduced relative hydraulic conductivity which is also captured by the DPST results (Fig. 6), leading to the conclusion that the reduction of hydraulic conductivity is not caused by differences in sedimentary composition but is most likely caused by a change in texture, e.g. reduction of porosity due to compaction or differences in packing. These findings clearly highlight the strength of vertical in-situ hydraulic profiling over traditional approaches, such as sampling and grain size analysis. During grain size analysis the soil texture is destroyed, hence, the influence of differences in compaction, packing or tortuosity on hydraulic conductivity cannot be captured. In this regard, but also in consideration of the uncertainty that is introduced by many of the empirical formulae, calculation of hydraulic conductivity based on grain size distribution is not a feasible approach for the high resolution hydraulic characterization of heterogeneous sediments (see also Vienken & Dietrich, 2011). This is especially true for heterogeneous fluviatile sedimentary deposits in this case study. However, the DPIL only provides information that allows layers with different hydraulic properties to be identified. To derive absolute values of hydraulic conductivity, Direct Push multilevel slug tests were performed at probing point 10 (see figure 3). Therefore slug tests were performed in 15 depths in a temporary Direct Push monitoring well, with a screen length of 0.5 m from 4.4-11.9 m below ground surface. Measured hydraulic conductivity values for these intervals ranged between 1.85 10^{-3} to 1.3 10^{-4} m/s (see Fig. 6). In the case of continuous slug test profiling, a correlation between DPIL-derived relative and DPST-derived absolute hydraulic conductivity values was not needed. Information linking relative DPIL hydraulic conductivity and absolute hydraulic conductivity is given by Lessoff et al. (2010) and Rogier et al. (2014). However, continuous DPST profiling following the high quality standards set out by Butler (1997), with two series of three repeat measurements of three different initial head displacements (18 slug test measurements in total per depth interval), is very time consuming compared to the rapid DPIL profiling.

Summary/Conclusion

The aim of this paper was to explain the MOSAIC approach and demonstrate its feasibility for reliable and efficient high resolution subsurface characterization based on the Löbnitz case study. The most important points can be summarized as follows:

- The three phase investigation approach consisting of site reconnaissance, exploratory investigation, and investigation and parametrization was successfully applied for the

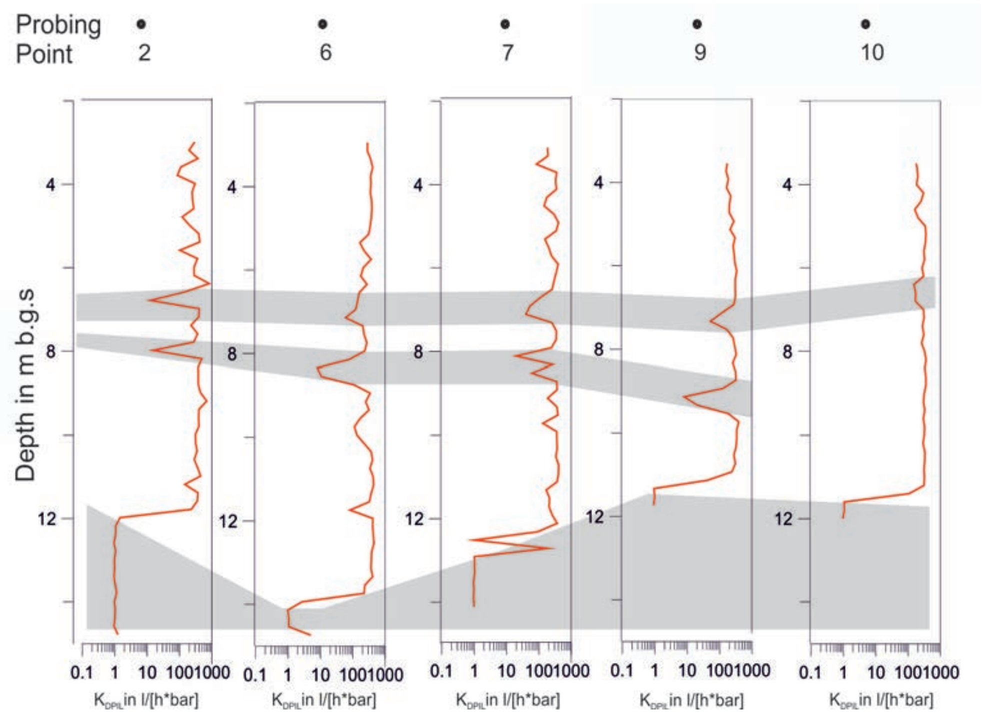

Fig. 5 - Results of the DPIL profiling with indicated layers of reduced hydraulic conductivity.

Fig. 5 - Risultati del profilo DPIL con indicati i *layer* a minore conducibilità idraulica.

characterization of the test site Löbnitz (with length = 500 m), as well as for the detailed delineation and characterization of a small scale oxbow.

- Thereby, the combination of surface geophysics, in this case ERT, and minimally-invasive Direct Push technology proved to be very suitable for the delineation and parameterization of the sedimentary structures in terms of lithology and hydraulic properties.
- CPT data provided information to detect changes in soil behavior, in this case interpreted as change in lithology, on a vertical high resolution scale. In addition, Direct Push based hydraulic characterization (DPIL and Direct Push slug testing) yielded reliable hydraulic data for vertical high resolution model parameterization. Therefore, not only changes in hydraulic properties due to changes in lithology but also changes in texture could be detected.
- In this regard, the MOSAIC approach with in-situ measurements is advantageous over traditional, solely sample-based site investigation approaches - in terms of data reliability, data resolution and efficiency.

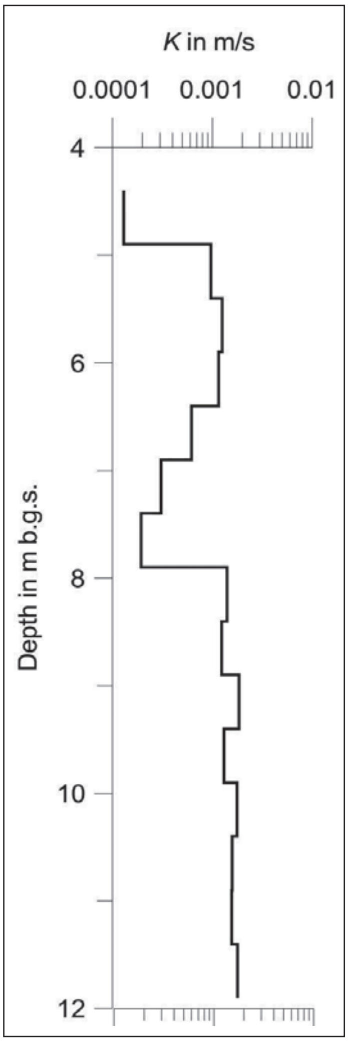

Fig. 6 - Results of Direct Push based multilevel slug tests at probing point 10.

Fig. 6 -Risultati della indagine Direct Push basata su uno *slug test* multilivello al punto 10 .

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