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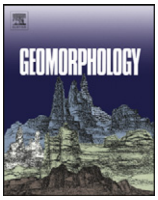

Two-dimensional geomorphological characterization of a filled abandoned meander using geophysical methods and soil sampling

Jörg Hausmann [a,*], Hannes Steinel [a], Manuel Kreck [a], Ulrike Werban [a], Thomas Vienken [a], Peter Dietrich [a,b]

[a] *UFZ Helmholtz Centre for Environmental Research, Department Monitoring and Exploration Technologies, Permoserstrasse 15, 04318 Leipzig, Germany*
[b] *Eberhard Karls University of Tübingen, Institute of Geosciences, Hölderlinstrasse 12, 72076 Tübingen, Germany*

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ABSTRACT

Using geophysical methods for the geomorphological characterization of subsurface features has numerous advantages over traditional exploration methods, because of their noninvasive and rapid nature. In this study, we compared the results of four geophysical methods with each other. We also discuss their possibilities and limitations in a geomorphological investigation. Electrical resistivity tomography (ERT), refraction seismic (RS), ground penetrating radar (GPR), and multichannel analysis of surface waves (MASW) methods were applied at an abandoned meander in northern Saxony to map a predefined structure. By combining these methods, we were able to characterize and delineate subsurface features of the abandoned meander, including a point bar, a channel, and a cutbank. Core samples obtained from sonic drilling were used to validate the findings of both seismic methods. However, we found that electrical resistivity tomography and ground penetrating radar lacked penetration depth and could only be used to resolve shallower subsurface layers. The ERT, GPR, RS, and MASW can be used to gather images of subsurface structures. The MASW in particular provides supplementary information about the channel's internal structure (with respect to lateral and vertical resolution). Besides fluvial–morphological features, we also detected inverse velocity structures within the channel. This allowed us to characterize the abandoned meander using information about its layer distribution and material composition. However, we were only able to characterize and delineate the subsurface features of the abandoned meander by combining all of the aforementioned methods.

1. Introduction

The use of shallow geophysical methods for the geomorphological characterization of subsurface features has become very popular in recent years. Schrott and Sass (2008) and Van Dam (2012) provided examples of how geophysical methods can be utilized for multidimensional identification, distinction, and characterization of glacial, fluvial, aeolian, volcanic, and tectonic landforms in relation to different survey aims. Noninvasive geophysical investigation techniques map the contrasts between certain physical properties of the subsurface, which can limit the application range of a particular method. Over the last decade, *ground penetrating radar* (GPR), *electrical resistivity tomography* (ERT), and *refraction seismic* (RS) methods have been proven to deliver valuable information on the dielectric, resistivity, and density properties of subsurface sedimentary structures and compositions for their characterization (Schrott and Sass, 2008; Van Dam, 2012). In addition, seismic surface wave techniques, e.g., *multichannel analysis of surface waves* (MASW), have been recently applied in geomorphological studies, showing that it is possible for this method to complement these techniques, precisely because the same seismic data set can be analyzed with regard to surface and refraction waves (Socco et al., 2010; Yamakawa et al., 2012). Even though the applied surface wave method delivers more detailed results in comparison with RS, it however failed to accurately estimate soil thickness (Yamakawa et al., 2012). Although increased computational power and light-weight equipment help to improve user-friendliness and time/cost-efficient gathering and processing of high resolution two- and three-dimensional subsurface data, every method has its drawbacks and limitations. These are mainly caused by a lack of contrast between the physical properties of the subsurface to which each technique is sensitive (Schrott and Sass, 2008). Furthermore, the measurement parameters are proxies for several mechanical and physical subsurface characteristics (Yamakawa et al., 2012). Multiple GPR reflections can occur in gravelly sediments without achieving the main aim of a particular survey (e.g., measuring thickness distribution). The electrical resistivity is mainly dependent on the water content, the fluid composition of the subsurface, and the grain size, thereby leading to the problem of equivalence in two-dimensional resistivity interpretation (Hoffmann and Dietrich, 2004). Methodical difficulties of refraction seismic surveys become apparent with increasing density and therefore increasing velocity with depth. Therefore, measurements for low velocity and *hidden layers* cannot be registered by the seismogram. Schrott and Sass (2008) discussed advantages and disadvantages of various geophysical methods for the characterization of geomorphological subsurface

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* Corresponding author. Tel.: +49 341 235 1039; fax: +49 341 235 1939.
E-mail address: joerg.hausmann@ufz.de (J. Hausmann).

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features. As a result, combining different geophysical methods has become *state-of-the-art* for geomorphological studies, making it possible to overcome the limitations of each technique and to cross-check the results as well as to determine which method is most suitable for a particular environment (Otto and Sass, 2006; Schrott and Sass, 2008; Socco et al., 2010).

Although applied for many geomorphological investigations with various geological settings, studies have shown that GPR, ERT, and RS often yield uncertain results (Otto and Sass, 2006; Socco et al., 2010; Yamakawa et al., 2012). The MASW, as a surface-wave method, is a very powerful tool for the near-surface characterization of shallow layers that is able to accurately reflect, e.g., the soil–bedrock interface more appropriately than the refraction seismic method, even though larger variations in lateral directions of the one-dimensional profiles also occur (Socco et al., 2010; Yamakawa et al., 2012). We considered data acquisition with two different source-offsets to recognize the near-field effects (Dikmen et al., 2010). Furthermore, we combined the resulting dispersion curves of both offsets to increase the bandwidth frequency and to resolve shallower and deeper subsurface layers (Park and Shawver, 2009). This allows increased resolution to be achieved for near-subsurface characterization.

Thus, a validation and a comparison of these resolutions are necessary in order to understand the capabilities, advantages, and limitations of each method. In this study, we use GPR, ERT, RS, and MASW to delineate geomorphological features of a filled abandoned meander of the River Mulde in northern Saxony, Germany. We conducted a multimethodical investigation to cross-check and verify the results of each individual method. In addition, we compared the findings with data obtained from core samples to evaluate the aforementioned geophysical techniques to establish their capacity to provide imaging of fluvial–morphological features.

Structural information about the near-subsurface is not only of great interest in explaining geomorphological evolution but also for geotechnical site assessment. At the study site, we assume a subsurface hydraulic connection given by cutoff oxbows that cross a dike structure beneath ground level. This allows a base flow in the direction of the river and in the land along those channel structures, which is controlled by steam gauge fluctuations and groundwater level. Therefore, these subsurface streams along the abandoned channel structure have a severe impact on the protection capacity of the dike in the case of a flood event.

2. Study area

For our investigation, we selected an abandoned meander oxbow structure, preselected using aerial imaging and on-site reconnaissance. The abandoned meander is located in northern Saxony, Germany, close to the village of Löbnitz (Fig. 1A). The entire length of the River Mulde is characterized by a vast number of meanders and their typical point bar and cutbank dynamic (Fig. 1A, B). Because of embankment creation, many of these have now been abandoned.

The recent River Mulde valley was formed in the lower gravel terrace that originates from the end of the Weichselian glacial period and began to meander later on. The subsurface is therefore composed of Holocene haugh, composed of alluvial clayey and loamy material, which overlay fluvial gravelly sands, changing sands, and the gravel layers of the lower terrace. Owing to the active meander being cut off from the river's course, dead meanders were created and developed limnic conditions that led to the accumulation of organic matter and the generation of peaty sediments in the abandoned channels (Fig. 2; Eissmann, 1994). Finally, shifted masses of alluvial clay and fluvial sands filled the structure as an embankment was constructed.

In the foreland of the dike, we can follow the course of the meander up to the River Mulde. At the dike, a path crosses the meander. Owing to the route of the abandoned meander, we assume a point bar and a cutbank in the northeast and southwest, respectively (Figs. 1B, 2). We performed a multimethod geophysical investigation along the path (including GPR, ERT, RS, and MASW surveys) in order to establish the ability of the different methods to provide images of the structure.

3. Methods

3.1. Electrical resistivity tomography (ERT)

The ERT surveys measure the apparent electrical resistivity between a pair of potential electrodes and a second pair of electrodes, which injects a current into the subsurface. The electrical resistivity and its reciprocal, the electrical conductivity, are therefore as such dependent on several subsurface properties, e.g., sediment type, water content, grain size, or fluid composition (Hoffmann and Dietrich, 2004; Rein et al., 2004; Schrott and Sass, 2008).

Multielectrode resistivity systems allow two-dimensional images of the subsurface conductivity distribution to be rapidly obtained. A control unit changes the electrode separations and configurations to sample various depths along the profile. The configuration of the electrodes determines the spatial resolution of the measurement. Wenner, Schlumberger, and Dipole–Dipole are the most commonly used electrode geometries. Because of the large variety of electrode configurations, many applications exist for ERT measurements in geomorphological investigations.

One field of application is for characterization of alluvial deposits (e.g., Gourry et al., 2003; Crook et al., 2008; Clifford and Binley, 2010; Chambers et al., 2012). In this study, we acquired ERT data with the *Geoserve Resecs* multiple-electrode resistivity device. Owing to the shallow target depth of 10 m, we chose the Wenner-α configuration (Table 1) to gain a high resolution image of the electrical resistivity of the subsurface, especially to make distinctions between lateral subsurface features. The ERT distributions measured across the filled abandoned meander reflected the transition from alluvial clay/silt and gravelly sand to the saturated gravel of the lower terrace. In this respect, a delineation of the assumed point bar, the channel, and the cutbank should be possible (Fig. 2).

To obtain the two-dimensional spatial distribution of the electrical resistivity, we then subsequently inverted the measured apparent resistivity data using *DC2DInvRes* software (Günther et al., 2006; Rücker et al., 2006). Based on the gathered data, we generated a subsurface model by statistical estimation of the electrical resistivity distribution. We continued the inversion procedure until the root mean square value reached its minima.

3.2. Ground penetrating radar (GPR)

The GPR is based on changes in the dielectric properties of the subsurface. The GPR surveys are conducted by pulling an antenna along the earth's surface and measuring at various frequencies (10 Hz to 1 GHz). As such, any inhomogeneities or layer boundaries reflect the emitted electromagnetic signal. The receiver antenna subsequently registers the reflected signal. Dielectrical contrasts originate from changes of material texture, water content, and the electrical conductivity of the pore fluids. Variations of the water content especially affect the dielectrical properties of the subsurface and cause radar reflections.

Alluvial environments often provide good conditions for the application of GPR to detect the architecture of deposits as demonstrated by several case studies (e.g., Bridge et al., 1998; Vandenberghe and van Overmeeren, 1999; Bano et al., 2000; Anderson et al., 2003; Gourry et al., 2003; Froese et al., 2005).

The penetration depth of GPR investigations is (apart from structural setup) mostly dependent on the frequency of the emitting antenna. Whereas low frequencies sample deeper layers, high frequencies achieve a higher spatial resolution in shallower parts of the subsurface, but at the expense of penetration depth. In this study, we conducted GPR measurements along the indicated survey line using a 200-MHz