Hydrogeophysical studies in unrestored and restored river corridors of the Thur River, Switzerland

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Abstract

Dynamic hydrological systems are challenging targets for geophysical investigations, but they have the advantage that natural stimuli (e.g. fluctuations in river and groundwater height, salinity and temperature) may be used to infer system responses (e.g. infiltration rates and flow patterns). Three dimensional (3-D) high resolution crosshole and surface based ground penetrating radar (GPR) and electrical resistance tomography (ERT) studies have been carried out at unrestored and restored sections of the Thur River in Switzerland to improve our understanding of how lithological heterogeneities affect river - groundwater interactions. Hydrological and apparent resistivity time series acquired between 18 boreholes located close to the river at the unrestored section are found to be very sensitive to infiltration processes. Information that can be retrieved from geophysics at the two sites are different primarily because (i) a surficial 3 m thick low resistivity loam layer at the unrestored site precludes the application of surface based GPR and ERT methods and (ii) because the frequently flooded gravel bars at the restored section make long term monitoring very challenging. Since it is extremely difficult and costly to retrieve undisturbed cores in coarse gravel deposits, we argue that geophysics should form an integral part in investigations of the internal structures and porosity variations of gravel bars in restored river corridors. We recommend that geophysical surveys and geophysical monitoring be included in larger scale river restoration projects both before and after restoration to determine how river restorations affect aquifer morphology and infiltration patterns.

Introduction

Most major European rivers were channelised over the past two centuries, primarily to facilitate transport of goods and people, gain arable land and decrease the risk of flooding. Unfortunately, these measures have had adverse effects on ecological diversity, the self-cleaning capacity of river systems, fish stocks and recreation possibilities. Channelisation may even be an ineffective approach to flood protection at some locations, since it creates very fast response times that may lead to catastrophic events in the case of levee failure. Alternative engineering measures, such as re-creating floodplain wetlands, might moderate flow variability while cleaning pollutants (Palmer et al., 2005).

Many rivers worldwide are being restored to enhance water quality, improve in-stream habitat, facilitate fish passage, increase bank stabilization, reconnect floodplains, modify flows, improve aesthetics or recreation possibilities, and reconfigure river channels (Bernhardt et al., 2005). In the USA alone, river restoration is a billion dollar industry with huge growth during the past decade (Bernhardt et al., 2005). A similar situation exists in Europe where river restoration offers one strategy for obtaining good ecological states of the freshwater bodies as required by the EU Water Framework Directive (European Commission, 2000).

It is often tricky when designing a river restoration programme to strike a balance between the objectives stated above while accounting for existing infrastructure (e.g. houses, roads and water extraction wells) and the associated remediation costs. Past restoration programmes have been poorly monitored. For example, only 10% of river restoration projects in the USA have included some form of assessment or monitoring, implying that opportunities to learn from past successes and failures have been lost (Bernhardt et al., 2005). As a consequence, the performance of different river restoration designs remains largely speculative and there is little agreement on what constitutes successful river restoration (Palmer et al., 2005).

We present here some preliminary results from ongoing geophysical characterization and monitoring at both an unrestored channelised section (Widen) and a restored section (Neunforn) of the Thur River in Switzerland (see Figure 1), in which subsurface fluid flow takes place in a 6 - 7 m thick highly permeable gravel aquifer. This work is performed within the framework of the RECORD project (see http://www.cces.ethz.ch/projects/nature/Record for more detail), a multidisciplinary research programme aimed at developing a mechanistic understanding of ecological - hydrological - geochemical processes in river corridors. The Thur River is the largest Swiss river without natural or artificial reservoirs. It exhibits discharge and river stage fluctuations similar to unregulated alpine rivers.

We have been determining the background structural, lithological and hydrological framework at the two sites and monitoring changes to these properties. A dense array of boreholes with permanent geophysical and hydrological monitoring equipment has been installed at the first study site across rarely flooded overbank deposits in an unrestored channelised section of the river. The dynamic nature of the restored river section and associated sediment transport at the second study site makes it very challenging to install permanent monitoring stations in the river or on the surrounding gravel bars (Schneider et al., 2010). Consequently, geophysical work at this second site has been largely limited to periods of low flow stable hydrological conditions.

Our framework studies have included detailed crosshole geophysical characterization at the unrestored channelised site through 3-D individual and joint inversions of electrical resistances and seismic and radar traveltimes (Doetsch et al., 2010b), whereas our larger scale surface-based framework investigations at the restored site have involved 3-D GPR and ERT surveys (Doetsch et al., 2010c). A 3-D framework is needed, because 3-D geological heterogeneity controls river groundwater interactions (e.g. distribution of seepage, groundwater table configurations and the connections between the river and the aquifer; Fleckenstein et al., 2006), which in turn is important for modelling biochemical reactions in catchments (Wriedt and Rode, 2006).

For surveillance of the unrestored section, we monitor the response of multi-borehole ERT data to natural forcing that is mainly caused by variations in river height and electrical resistivity of the river water and a relatively minor contribution due to temperature fluctuations. We intend to obtain information about preferential infiltration patterns from the monitoring data. Time series of groundwater electrical resistivity in these settings can be used to calculate traveltime distributions at both unrestored and restored sites (Cirpka et al., 2007; Vogt et al., 2010), but the application of these concepts remains to be tested for ERT data that have large support volumes (e.g., at our study sites). Geophysical surveillance on the gravel bar consists of self-potential (SP) monitoring under natural flow conditions and ERT monitoring following saline tracer injections.

Preliminary results from a small subset of these investigations are presented here to demonstrate that it is possible using a combination of geophysical and borehole techniques to (1) obtain 3-D models of the gravel aquifer structure and properties and (2) monitor groundwater flow and infiltration processes through the effects of natural forcing.

Site descriptions and instrumentation

The lower Thur River was originally a braided river that was channelised in the 1890s. It was converted into a double channel (trapezoidal cross sections) with a 45 m wide low water channel (flow capacity 230 m^3s^{-1}) that had stabilised banks and overbanks on both sides (total flow capacity 1100 m^3s^{-1}) bounded by levees with a 160 m spacing between the levee crowns. The vertical distance between the river bed and levee crown averaged 6 m.

One research facility was established at an unrestored section of the river (Widen, see Figure 1) that was known to display significant temporal fluctuations in the groundwater electrical resistivity (Cirpka et al., 2007) and that allowed equipment to be permanently installed. Following initial investigations based on several parallel 2-D surface ERT profiles, the dense borehole array was installed on an agricultural site close to the river. The 10 × 15 m array comprises eighteen 12 m deep monitoring boreholes spaced 3.5 m apart that completely penetrate the 7 m thick gravel unit (Figure 2). The underlying thick lacustrine clay layer can be considered to be impervious to flow. The borehole array pattern is sketched in Figure 2a and photographs of the installation process are displayed in Figure 3. Our borehole layout has the advantage that in addition to full 3-D studies, it is also possible to perform dedicated high resolution geophysical and hydrological 2-D studies in four different directions (i.e., parallel and perpendicular to (1) the river and (2) the expected flow direction).

Each borehole has been instrumented with ten 0.7 m spaced electrodes that span the thickness of the aquifer. A multichannel geoelectrical system programmed to cycle through various 4 point electrode configurations of the 180 electrodes in a rolling sequence allows ~15 000 measurements to be made every ~7 hours. In addition to the electrodes, 6 of the boreholes are equipped with sensors at different depths that provide time series (every 15 minutes) of groundwater table height and groundwater resistivity and temperature.

In 2002, a 2 km long section of the Thur River near Neunforn (see Figure 1) was restored by completely removing the northern overbank, so that a nearby forest (Figure 4) became part of the active floodplain again. This widening increased sediment deposition and re-established dynamic fluvio-morphological processes with frequently forming and alternating gravel bars that provide habitats for fauna and flora. This river section was chosen as the research site representing a restored river (Schneider et al., 2010). Figure 4 displays the gravel bar that is of primary interest together with some photos taken during GPR data acquisition campaigns.

Investigations at the unrestored channelised site

At the unrestored channelised river site, joint inversion of 3-D crosshole electrical resistances and seismic and radar traveltimes have revealed that the typically 6 m thick saturated part of the gravel unit is composed of a middle lower porosity layer (relatively high resistivity and high seismic and radar wavespeeds) embedded in higher porosity formations (Doetsch et al., 2010b; Linde and Doetsch, 2010). The conductive borehole fluid was found to create significant artefacts. Doetsch et al. (2010a) showed that including the boreholes and their fluids explicitly in the inversion process using an unstructured finite element mesh (Günther et al., 2006) largely removes these artefacts. Neutron - neutron and gamma - gamma logs provided information about total porosity and natural gamma logs that are related to the clay content were acquired in all boreholes.

Initial 3-D ERT inversions were performed on data acquired during low flow stable conditions. The inversions accounted for topography and the boreholes (including their lateral deviations) and the regularization was disconnected across the known groundwater table level and gravel - clay boundary. It was important to disconnect the smoothness constraints at these interfaces, since failure to do so generated false structures. For example, the low resistivity of the clay "created" artificial low resistive anomalies that spread into the more resistive gravel.

Figure 5 shows a resistivity section extracted from a 3-D ERT model along the line of boreholes closest to the river (for location see Figure 2a). The lower (blue) layer corresponds to the clayey aquitard. The saturated part of the aquifer displays an upper central zone two to three times more resistive than the overlying and underlying parts (i.e. the red - orange zone bounded above and below by the yellow regions; Doetsch et al., 2010a). We also observe a less resistive block (green) with resistivities of ~100 Ωm that corresponds to a lens of clayey silt and sand sediments seen in neutron - neutron well logs and encountered in drill core from neighbouring boreholes.

The neutron - neutron data were converted to approximate porosity estimates using the approach of Barrash and Clemo (2002), in which the highest number of counts in all 18 boreholes corresponds to a porosity of 50% and the lowest to 12%. The deduced porosities over the saturated section (Figure 5) match values obtained for the three-layer aquifer (26%, 19%, 23%) by means of traveltime (Doetsch et al., 2010b) and full waveform (Klotzche et al., 2010) inversion of crosshole GPR data. Both the GPR and neutron - neutron determined porosity estimates correlate closely with the aquifer's electrical variability defined by our ERT model.

The temporal variations in apparent resistivities at this site are mainly affected by groundwater table variations and changing pore water resistivity and less so by temperature. Figure 6 displays time series of apparent resistivity and groundwater resistivity measured in the boreholes during a period of strong variation in river stage following heavy precipitation in the catchment (Coscia et al., 2009). Clearly, there is a strong correlation between these parameters. Our initial results suggest that apparent resistivities based on certain electrode configurations are highly sensitive to variations in groundwater resistivity (e.g. Figure 6), whereas others are dominated by the effects of groundwater table height. We are currently investigating how to correct the apparent resistivity data for the effects of groundwater table fluctuations and temperature before inverting the corrected apparent resistivity time series to image the flow patterns of the infiltrating river water.

Investigations at the restored site

The main experiments conducted on the gravel bar (for location see Figure 4a) involved 3-D surface GPR and ERT surveys covering a total area of approximately 240 × 40 m (Doetsch et al., 2010c). We used a commercial GPR system with 100 MHz antennae mounted on a sledge together with a GPS tracking unit (Figure 4) to acquire data continuously along lines spaced 0.5 m apart. Figure 7 displays a chair type plot of a sub-section of the processed 3-D GPR data on one of the gravel bars. The processing included time zero shifts, gridding and applications of gain functions, frequency filters, topography corrections and f-xy deconvolution. The time-to-depth conversion was achieved using a constant velocity based on averaged common midpoint profiles. The lowermost prominent reflection in Figure 7 originates from the interface between the gravel aquifer and underlying clay layer. Other laterally continuous structures that can be traced throughout the gravel bar are probably reflections from interfaces between gravel sheets. Smaller scale dipping features represent foreset bedding (Beres et al., 1999).

Our surface ERT data were acquired using 522 electrode positions along 22 lines, with each suite of 3-D measurements taking advantage of 6 lines. The total ERT data set includes > 100 000 measurements made over two days. We are currently exploring how to use the GPR sections to guide the 3-D inversion of the ERT data (Doetsch et al., 2010c). An initial 3-D ERT inversion constrained by the boundaries defined by the 3-D GPR image indicates a 100 - 400 Ωm range of resistivities for the gravels and ~40 Ωm for the underlying clay at the restored site. We also plan to investigate (1) how the different depositional features displayed in Figure 7 affect groundwater flow and transport and (2) how this information can be used to build hydrogeological models.

The groundwater level, electrical resistivity and temperature display both small (daily) and large scale fluctuations due to precipitation or snowmelt (Vogt et al., 2010). These fluctuations make it challenging to monitor saline tracer experiments with time lapse ERT, since it is difficult to assess to what degree observed changes are due to the tracer mass vis-à-vis natural river fluctuations. One could consider time lapse ERT monitoring using natural fluctuations in a similar manner to the investigations at the unrestored channelised section. In all cases, it appears necessary to acquire ERT time lapse data prior to tracer injection to better differentiate between induced and natural variability.

We have also explored the use of self-potential (SP) monitoring data in these settings. The SP data are of high quality, displaying a strong correspondence with the hydrological data. Unfortunately, interpretation of the SP data is complicated because they are sensitive to several variables (e.g. variations in the groundwater table height, flow in the vadose zone, the hydrological flow regime and the pore water electrical resistivity). A dedicated modelling analysis should help us assess the influence of these possible effects on the data. For a quantitative hydrogeological understanding in this type of dynamic environment, we suggest that it is necessary to develop 3-D groundwater flow and transport models in which the geophysical data, images and models are used for calibration purposes.

Discussion

Comparisons between the results obtained at the unrestored and restored sections of the Thur River are difficult because the geophysical methods employed at the two sites are different. Surface based GPR and ERT methods are of only limited value along the unrestored section as a result of the low resistivity surface loam layer. At this site, we rely on crosshole geophysical investigations and long term autonomous ERT monitoring. Our geophysical models (electrical resistivity and radar and seismic wavespeeds) demonstrate that the gravel aquifer is made up of three layers. The middle layer having a lower porosity and a lower content of fines, which is in qualitative agreement with the higher permeabilities found by Diem et al. (2010). The amplitudes of the apparent resistivity time series agree with those of the pore water resistivities. We intend to investigate how such time series can be used to investigate infiltration processes and the permeability structure of the site. Because of the different resolution characteristics, it is going to be challenging to compare the results of the lower resolution static and time lapse geophysical experiments with those of the borehole logging and hydrological testing (Day-Lewis et al., 2005).

The situation at the restored river section is quite different from that at the unrestored section, since surface-based geophysical measurements can be performed in close proximity to the gravel aquifer of interest. Geophysical characterization can be achieved non-invasively at high spatial resolution over much larger volumes than is possible with crosshole data alone. In particular, the surface GPR data provide detailed images of the sedimentary structure that can hardly be obtained from the crosshole data. Since frequent flooding precludes permanent installations along the restored section, time lapse studies are more challenging in this environment.

Conclusions

Geophysical methods provide detailed 3-D information on the lithological sub-units of the gravel aquifers at both the unrestored and restored sections of the Thur River. A combination of crosshole GPR and ERT techniques at the unrestored section makes it possible to obtain high resolution images and models of the gravel aquifer underlying a low resistivity 3 m thick surface loam layer. At the restored section, where there is only very limited conductive overburden or none at all, surface-based measurements can be made literally on the groundwater table. At this location, surface-based 3-D GPR and ERT techniques provide very high resolution images and models throughout the full thickness of the gravel aquifer. These images and models will now be correlated with results from detailed biogeochemical, water chemistry and ecological sampling to improve our understanding of how variations in geophysical properties might facilitate the interpretation of such results. We expect that time lapse monitoring of natural variations in the apparent resistivity data can be used to better understand river - groundwater interactions and to determine preferential flow paths. We have also performed targeted saline tracer experiments (not shown here) to image specific flow paths and to understand the origin of SP signals. A future goal is to develop hydrogeological models that are consistent with the diverse geophysical and hydrological data at the two sites.

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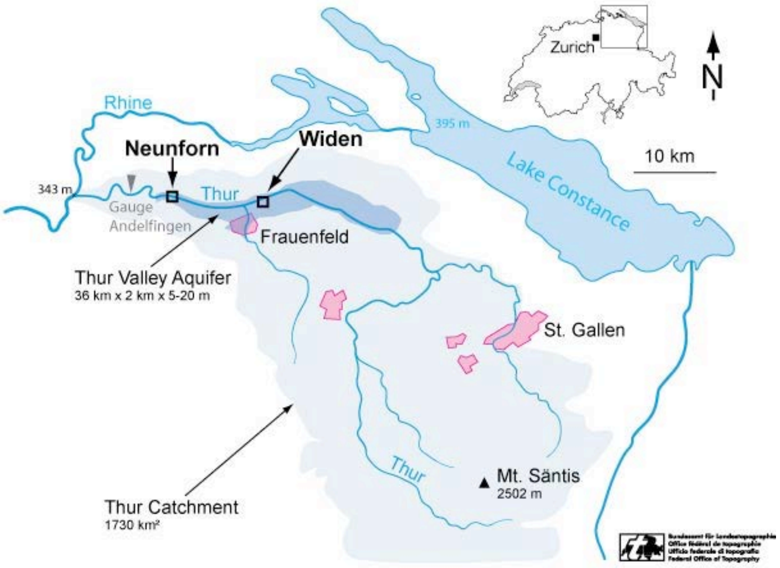

Figure 1 *Location of the Thur catchment, Thur valley aquifer and unrestored channelised (Widen) and restored (Neunforn) test sites in NE Switzerland.*

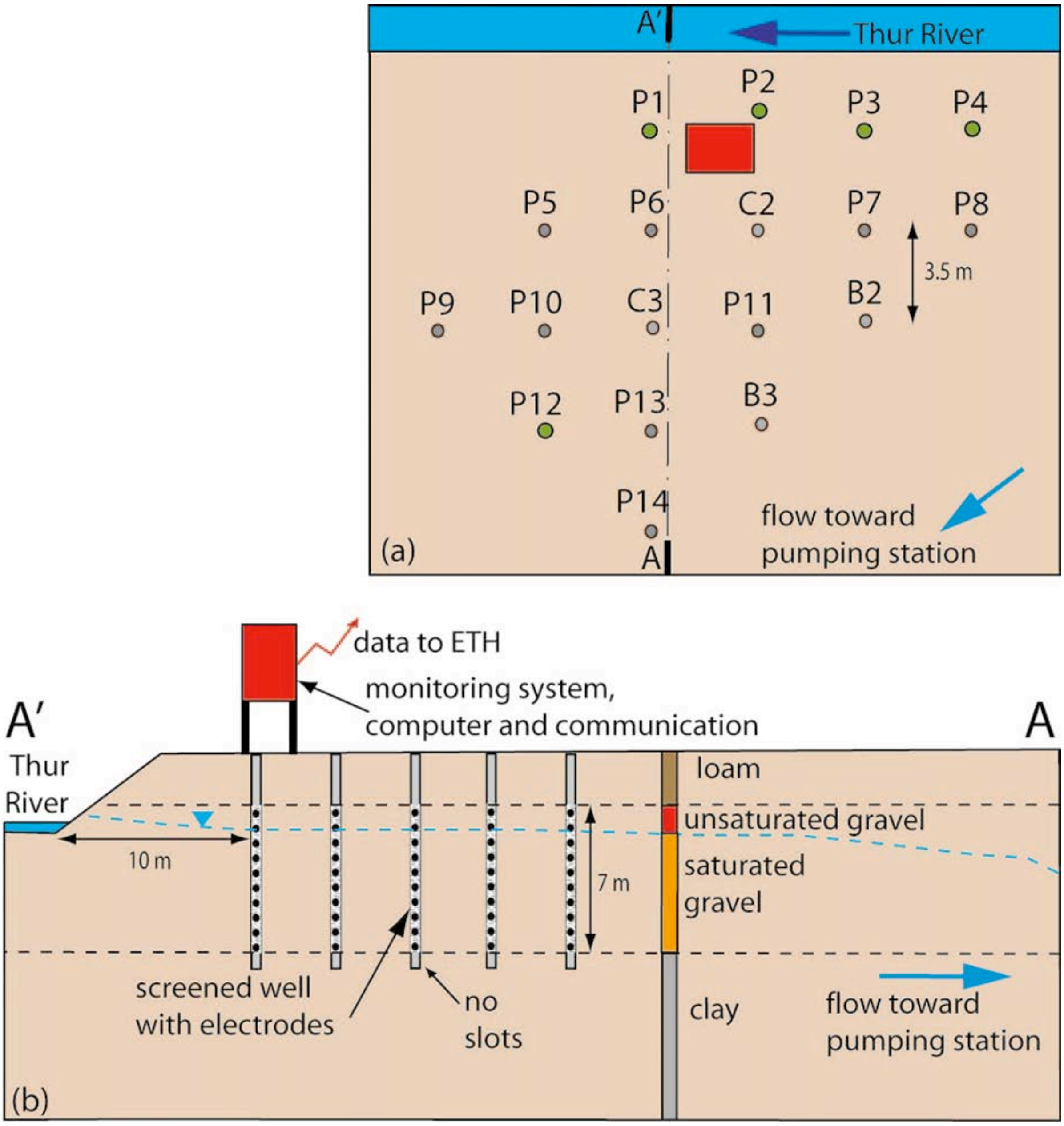

Figure 2 *Crosshole ERT monitoring system at the unrestored channelised (Widen) site with the flood protected housing of the ERT system. (a) Plan view and (b) profile view. The resistivity image shown in Figure 5 was extracted from the full 3-D inversion model along the line of boreholes P1 - P4 shown in (a).*

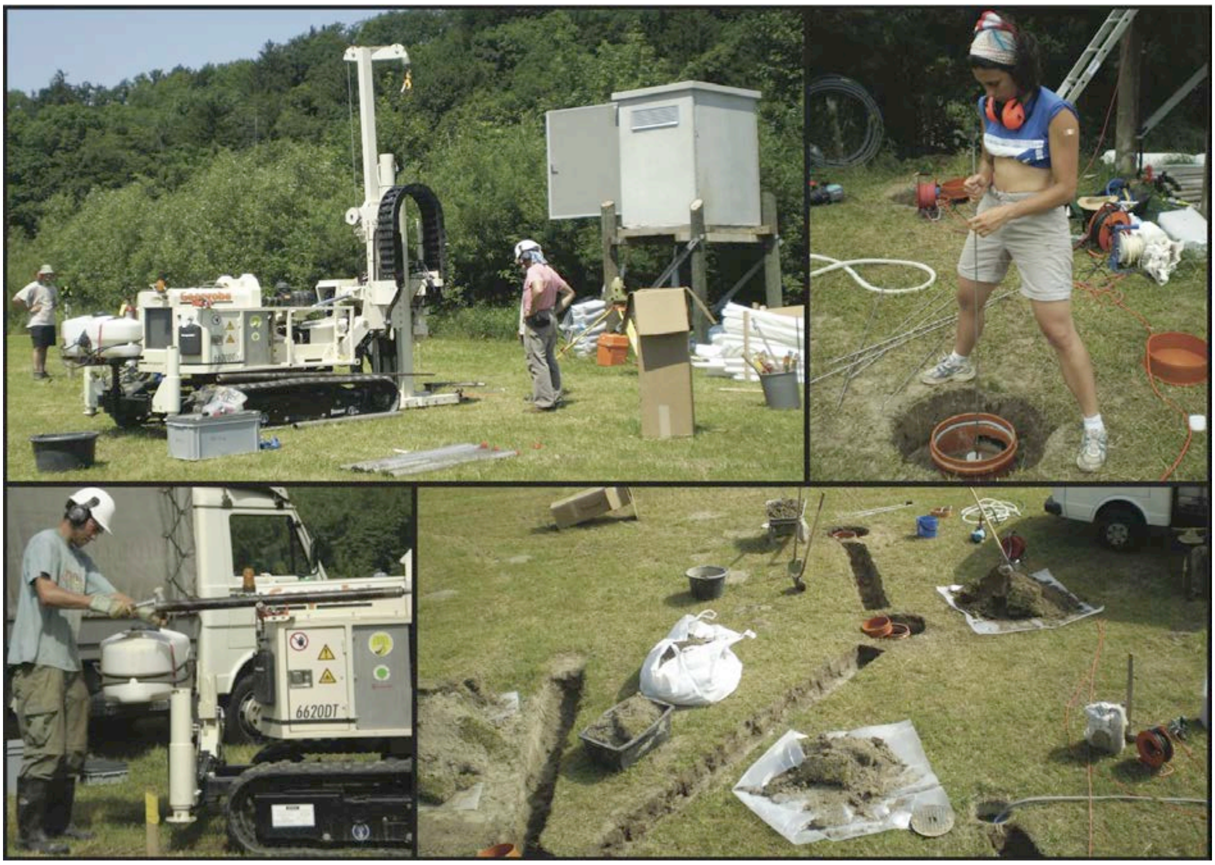

Figure 3 *Borehole and ERT monitoring installation at the unrestored channelised (Widen) site. Location of the site is shown in Figure 1.*

Figure 4 *(a) Areal photograph of the gravel bar (North of arrow) where most of the research on the restored part of the river section is focussed. Blue arrow identifies the water flow direction. (b) Acquisition of surface based GPR and (c) calibration for crosshole GPR data on the gravel bar. Location of the site is shown in Figure 1.*

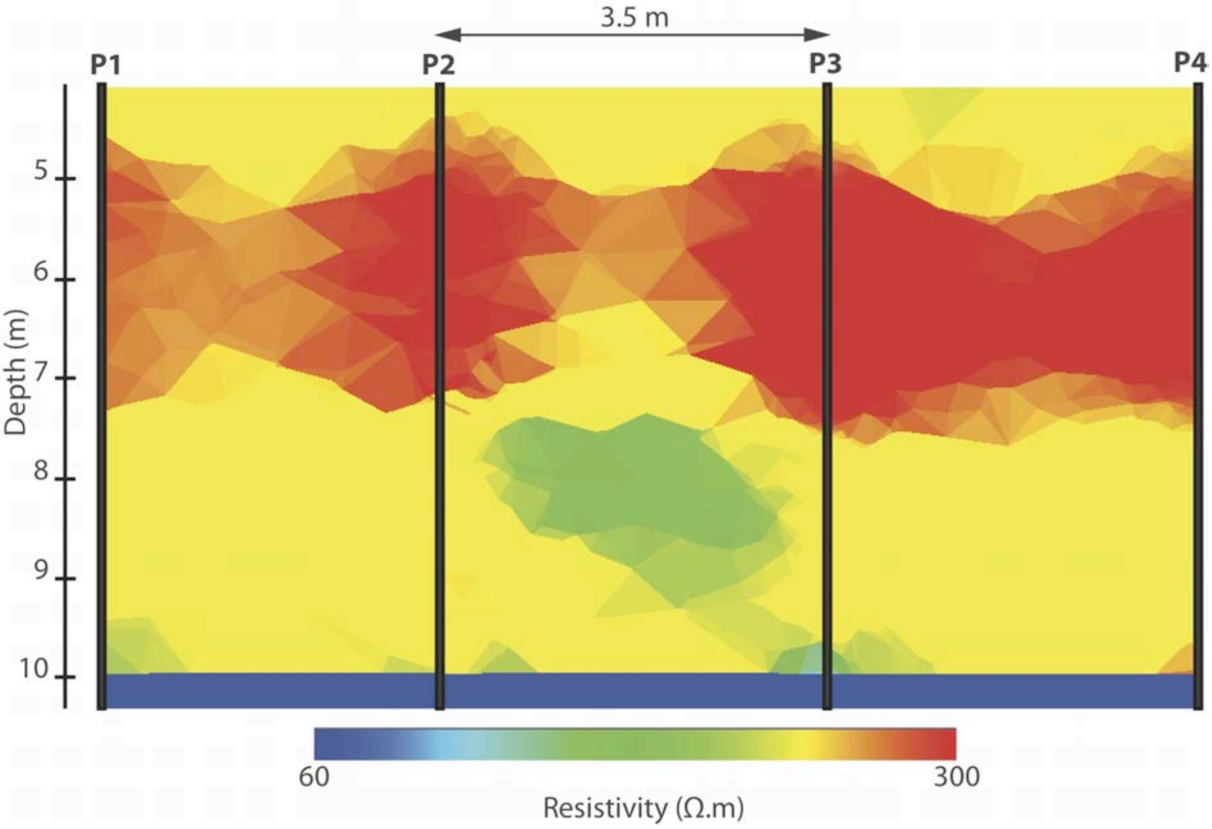

Figure 5 *Vertical section extracted from the 3-D ERT inversion model (logarithmic scale) along the boreholes located closest to the river (P1 - P4 in Figure 2). The high resistivity (low porosity) zone in the upper middle part of the section can be traced throughout the resistivity volume. Location of the site is shown in Figure 1.*

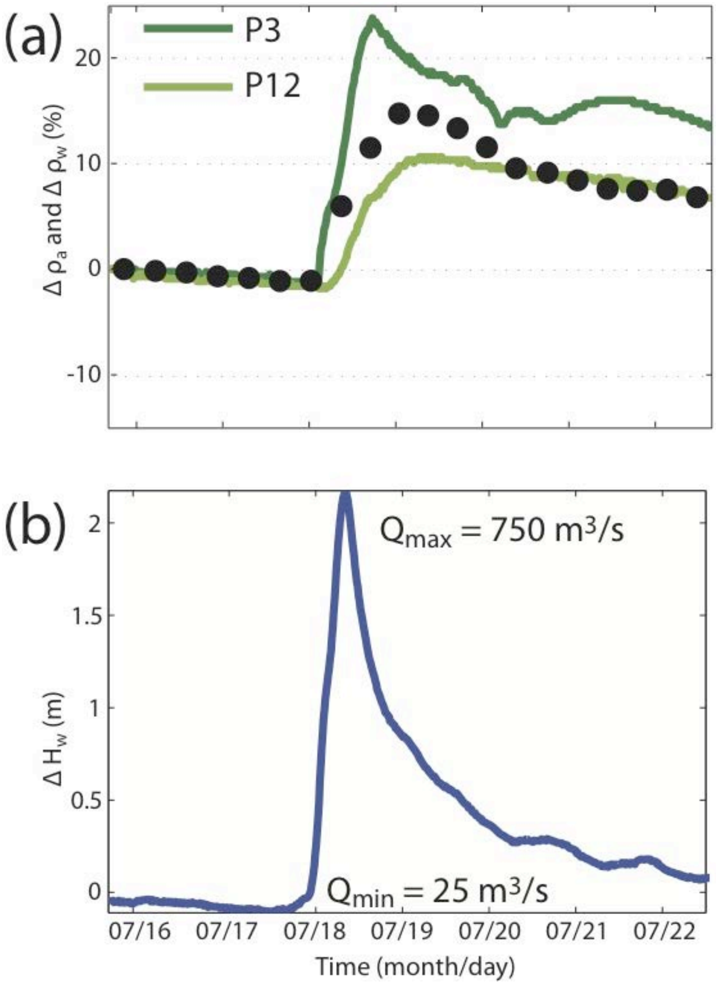

Figure 6 *For the unrestored channelised (Widen) site, comparison between time series acquired in July 2009 of (a) percent variation of apparent resistivity (Δρa - black dots), percent variation of groundwater electrical resistivity (Δρw - two green curves) and (b) variation of the groundwater table height (ΔHw - blue curve). Our studies demonstrate that for this particular electrode configuration the variations in apparent resistivity are mostly caused by changes in the electrical properties of the infiltrating river water. For other electrode configurations, the apparent resistivity variations are dominated by changes in groundwater table height. Location of the site is shown in Figure 1 and the geometry of the boreholes is presented in Figure 2.*

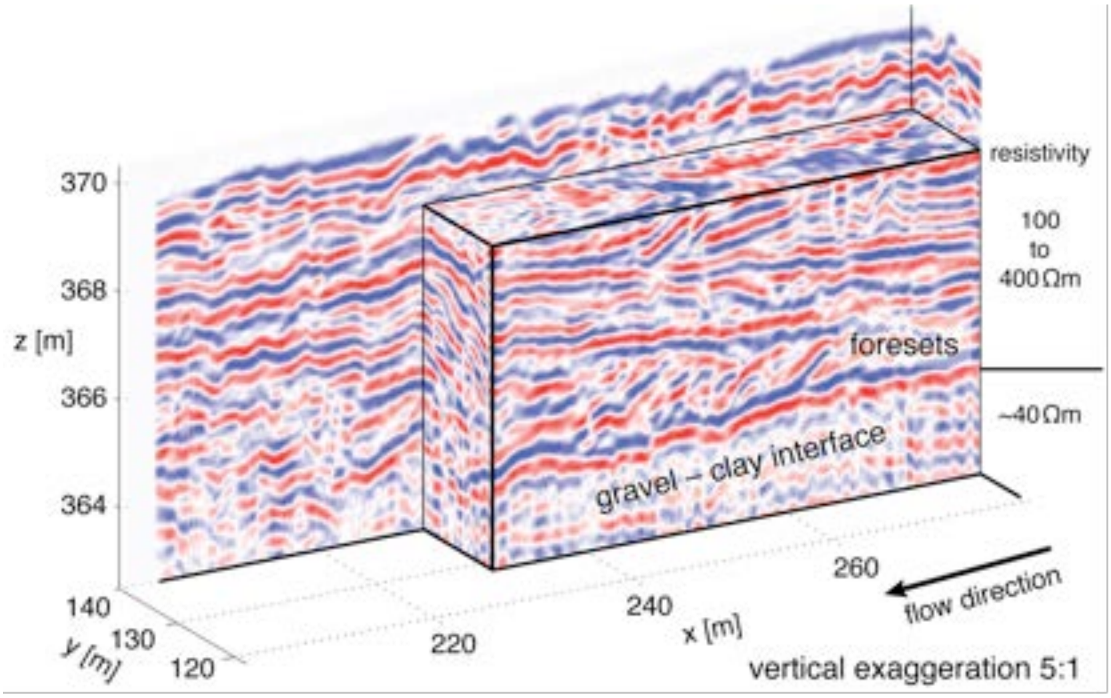

***Figure** 7 Chair plot of processed GPR data acquired across the western part of the gravel bar within the restored site. Resistivities shown on the right side of the model represent average values for the gravel- and clay-rich layers derived from an inversion of 3-D surface ERT data constrained by the boundaries defined by the GPR data. Location of the site is shown in Figure 1.*