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Identification of flow pathways along hillslopes using electrical resistivity tomography (ERT)

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Abstract Hillslope processes are crucial as they define how fast water reaches the stream, how long water is stored in soil and groundwater systems, and which hydrochemical composition the water has when reaching the stream. In this paper the potential of electrical resistivity tomography (ERT) to identify flow pathways at the hillslope scale is demonstrated. This technique was used at two hillslopes (drained by a spring at the bottom) in addition to previously applied tracer methods that enabled the quantification of the runoff components during flood events. The structure of the soil and drift cover could be mapped using ERT and, consequently, the source areas of shallow and deep groundwater could be identified. Thus, the potential of a multi-technical approach (hydrometry, tracers and geophysics) is clearly demonstrated.

Key words Black Forest Mountains; electrical resistivity tomography (ERT); flow pathways; runoff generation

INTRODUCTION

Hillslope processes mainly define the hydrological and hydrochemical response of small catchments (Anderson & Burt 1990; McDonnell & Tanaka 2001). These processes define how fast the water reaches the stream, how long water is stored in soil and groundwater systems, and what hydrochemical composition the water has when reaching the stream. There is much nonlinear coherence with numerous feedback mechanisms occurs, which makes the prediction of the hydrological response extremely difficult. Using natural tracers, it has been recently demonstrated that the retention of water in a small catchment can be very long (e.g. Kirchner *et al.*, 2000). However, where and how the water is stored for so long, while the hydrodynamic reaction can be very quick (cf. “hydrological paradox”, Kirchner, 2003), is not completely understood (e.g. Uhlenbrook *et al.*, 2003). It appears that new experimental techniques need to be developed to gain a better understanding, in particular of subsurface flow processes. The latest developments in hydrogeophysics (Rubin & Hubbard, 2005), in combination with classical hydrometric methods and tracer methods, might be a step forward.

The objective of this paper is to demonstrate the potential of electrical resistivity tomography (ERT) to identify flow pathways at the hillslope scale. In particular, how valuable this information is for exploring runoff generation processes was investigated, if additional tracer methods for the quantification of the runoff components were previously applied.

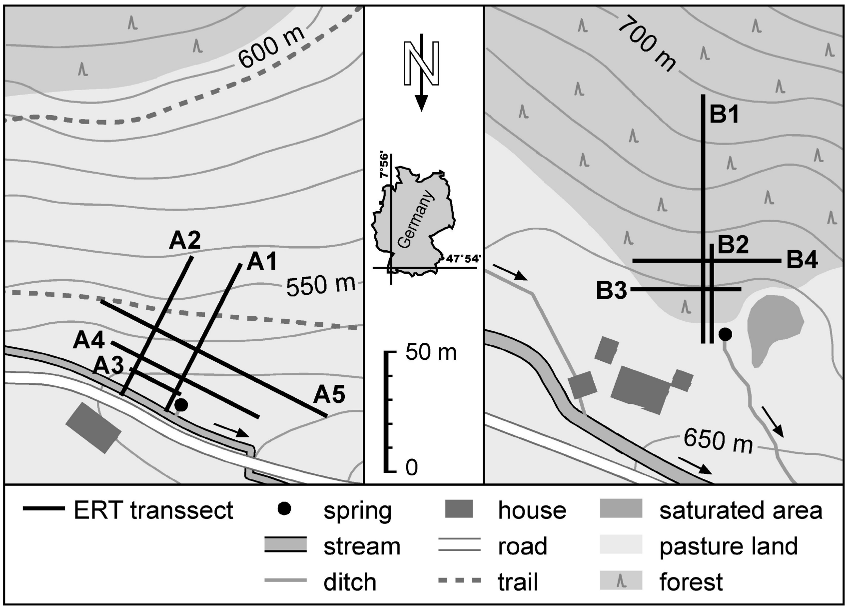

Fig. 1 Maps of the test sites of spring A and B. The black lines show the locations of the transects that were investigated using ERT (A1-A5 and B1-B4).

STUDY SITES

Two hillslopes located in the Brugga catchment, southern Black Forest Mountains, Germany, were investigated (Fig. 1). The bedrock consists of gneiss and is covered by a glacial and periglacial drift of varying depths (0–10 m). Brown soils (cambisol) have mainly developed on this drift cover. Both test sites are steep with a mean slope of 24° and 16° for the lower hillslope at spring A and spring B, respectively. Both springs at the toe of the hillslope initiate a little creek, which is directly connected to the next stream. The land use differs at both sites and is dominated by pasture land and spruce forest for spring A and spring B, respectively.

METHODS: ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

Electrical resistivity surveys have been made for decades in hydrogeology and geotechnical investigations (Loke, 2003); more recently it has been used to solve problems in environmental hydrology (e.g. Kemna *et al.*, 2000; Bentley & Gharibi, 2004). The subsurface resistivity is mainly related to various geological and hydrological parameters: the lithology (rock and grain sizes, porosity, and mineralogy), the fluid content (solutes) and the degree of water saturation (cf. Archie's law, applicable in particular for media with low clay content as it is the case at the study site; Loke 2003). The determination of the resistivity goes back to Ohm's law, which describes the relations between the current density, the electrical field (voltage) and the resistivity. For mapping the electrical resistivity of the subsurface, an electrical current is injected into the ground through two current electrodes and the resulting voltage difference is measured at two potential electrodes. 2-D surveys and recently even 3-D surveys are using multi-electrode resistivity surveying instruments and fast inversion software to map the electrical resistivity of the subsurface.

In this study the resistivity surveys were carried out using the Syscal Junior Switch System with 24 electrodes and two multi-core cables (spacing between the electrodes varied between 1 to 5 m). The electrodes were set along hillslope transects, and a roll along procedure (installing half of the electrodes at the end of the transect as soon as the first half of the electrodes are free) enabled investigation of transects with more than 24 electrodes. The 2-D Wenner configuration was used as the electrical array. The measured pseudosections (apparent resistivity) were processed with a 2-D inverse numerical modelling technique (software: RES2DINV) to give the estimated true resistivities of the subsurface (for further details see e.g. Loke, 2003).

RESULTS AND DISCUSSION

The spring discharges at both sites were monitored continuously for several years and precipitation (10-min intervals) was measured during some events with two rain gauges that were close to the springs. There were clear differences between the springs' hydrographs and between their chemical and isotopic responses to rainfall events. Spring A is characterized by slow and delayed runoff behaviour (Fig. 2). In contrast, the time lag of the runoff response at spring B is shorter, the peak discharge is higher and its maximum is reached about 2 days earlier. The runoff recession is considerably steeper at spring B than at spring A. However, despite the rapid runoff response, spring B also shows a fairly constant discharge of 0.3 L s^{-1} during summer droughts, which suggests that the spring is fed by at least two runoff components, a long-lasting base flow component and a dynamic storm flow component.

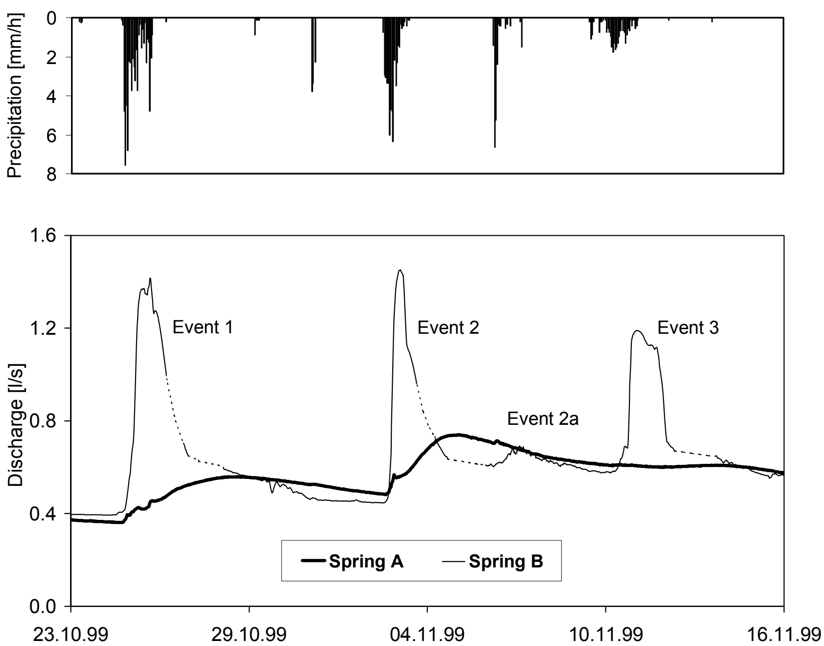

Fig. 2 Precipitation and discharge at both springs during the investigation period. Dotted lines represent interpolations of missing data (due to technical problems).

The hydrochemical responses and tracer investigations are discussed in further detail in Uhlenbrook *et al.* (2005). In general, it could be shown that at spring A, a two-component hydrograph separation using dissolved silica could be carried out: the two components were interpreted as direct runoff (rain water) and groundwater (hypothesis one). The fraction of the direct runoff was only about 3% during three investigated events. This small proportion of direct runoff could be explained by water flowing along preferential pathways (i.e. root channels, earthworm channels, etc.). The rest of the spring water was delivered from groundwater, which could not be separated further into different groundwater components. At spring B, a three-component separation using dissolved silica and deuterium was calculated. The three components were interpreted as: (a) direct runoff (same formation processes as at spring A) as well as the (b) shallow, and (c) deep groundwater. Shallow groundwater contributed a small proportion of base flow prior to the events, and became the major component during the peak of the event. The importance of shallow groundwater at the study site was already shown by Uhlenbrook *et al.* (2002). The fractions of the runoff components during three investigated events for the direct runoff, shallow and deep groundwater amounted to 10, 50 and 40%, respectively. The dynamic contributions of the shallow groundwater were consistent during the observed floods events. To summarize, both springs are dominated by groundwater components during floods, but spring B has a dynamic component that dominates during flood runoff generation and causes a much more dynamic runoff response.

The ERT measurements were all carried out during similar moisture contents in summer 2004. They clearly demonstrate the different soil and drift covers as well as the location of phreatic zones at the two sites (Figs 3 and 4). However, the differences were not evident from the surface characteristics and the previously available information of the soils and geology. The distribution of the ohmmeter values (i.e. unit of the electrical resistivity) at the hillslope of spring A indicate a relatively thick and homogeneous zone (values >1000 Ωm; unsaturated zone) above the groundwater table (values <500 Ωm; backup with many other measurements in the area) that feeds the spring. This groundwater body seem to reach 30 m upslope a depth of more than 10 m (Fig. 3, A1). It can be concluded that the infiltrating rainwater needs to pass the unsaturated zone before it reaches the lateral flowing groundwater, and then it increases the groundwater table and causes a displacement of groundwater at the spring outlet. A shallow groundwater body could not be detected at this site and rapid lateral subsurface flow was not evident (cf. tracer data). In contrast, at spring B a significantly higher range of resistivity values was observed near the soil surface a few tens of metres uphill. The high values indicate a more heterogeneous subsurface structure, including coarser bedrock material (boulders) that is highly conductive. Areas of lower resistivities (<500 Ωm) could be found at the location of the spring and also 60 m upslope relatively close to the surface (Fig. 4, B1). It can be concluded that infiltrating rainwater can reach the shallow hillslope groundwater quicker, and accordingly causes groundwater displacement at the spring outlet. Further field investigations, including digging and drilling at some locations are necessary but technically difficult. The detection of the shallow and inclined groundwater body at spring B fits nicely to the results of the hydrograph separation using dissolved silica and environmental isotopes, which indicated a highly dynamic shallow groundwater body.

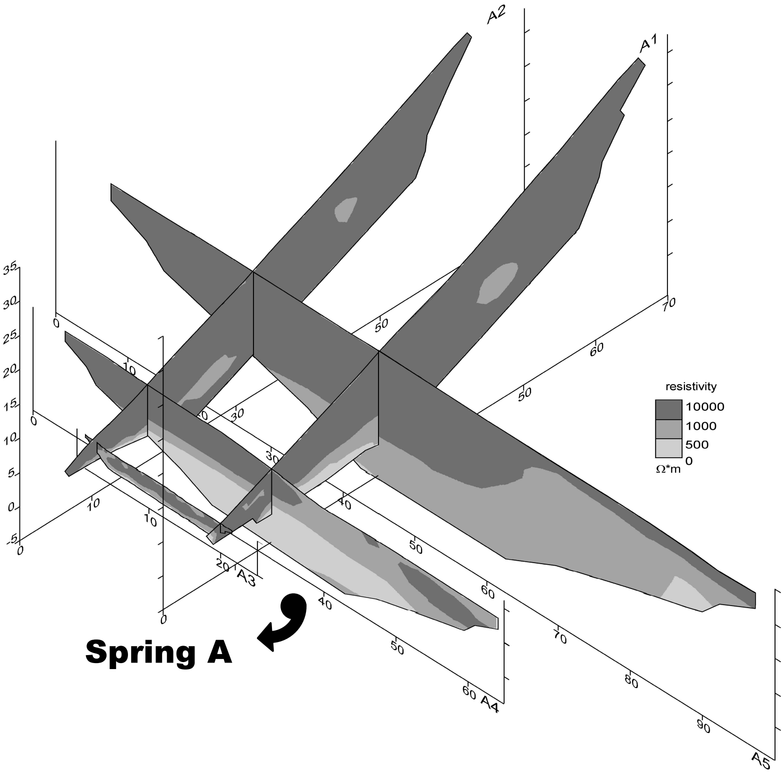

Fig. 3 Results of the 2-D electrical resistivity tomography surveys at the hillslope of spring A using Wenner 2-D configurations; see Fig. 1 for the location of the transects.

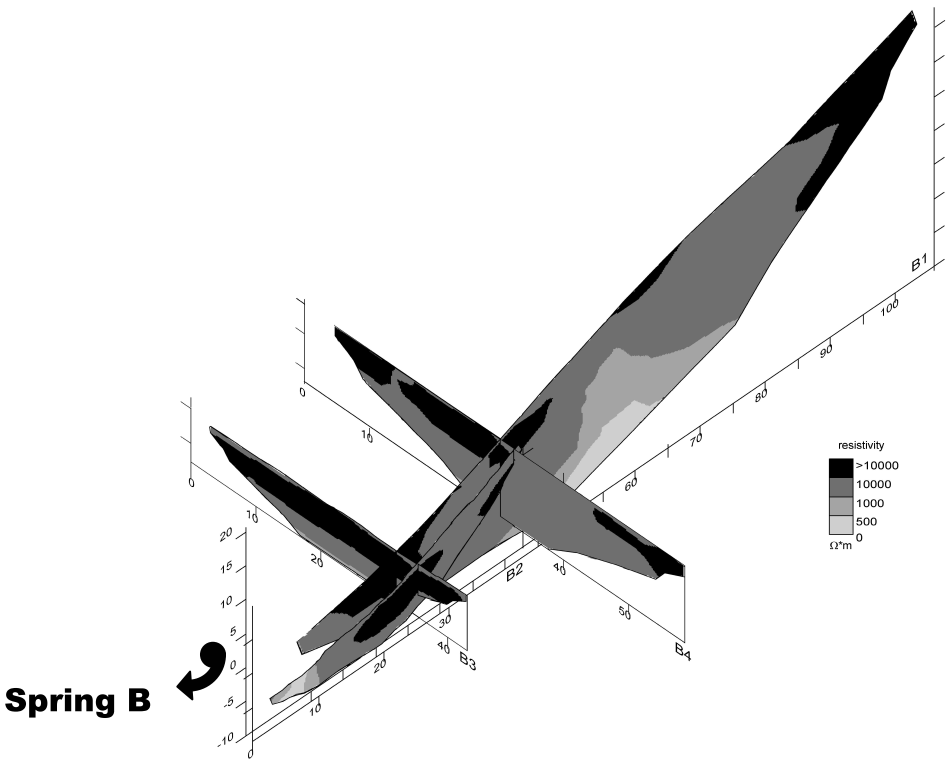

Fig. 4 Results of the 2-D electrical resistivity tomography surveys at the hillslope of spring B using Wenner 2-D configurations; see Fig. 1 for the location of the transects.

CONCLUSIONS

As shown for the two investigated hillslope/spring systems, the hydrological processes and flow pathways in mountainous landscapes can be very diverse, even on relatively adjacent and similar steep hillslopes. This spatial heterogeneity of hillslope processes appears to be closely related to the highly variable soil and drift structure (first order control) overlain by land use, vegetation patterns and topography (second order controls). Of course all controls are related to each other. ERT surveys proved very useful at that scale and provided further insights into the structure of the soil, the origin of runoff components and flow pathways, thus, into the runoff generation processes. Additional knowledge of the geology and soils is needed to interpret the ERT measurements. The method is particularly useful if further hydrometric data like rainfall, runoff and tracer data are available for the hillslope scale. It is felt that for larger areas (>1–100m) the resolution for the available technique is getting too coarse to identify important structure in the subsoil.

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