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Revealing the temporal dynamics of subsurface temperature in a wetland using time-lapse geophysics

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SUMMARY

There is growing recognition of the need to understand the subsurface hydrological mechanisms within wetlands, given their potentially significant role in the hydrological and biogeochemical function of catchments, as well as their effects on the wetland habitat itself. Conventional subsurface hydrological sampling and monitoring techniques are often limited in such environments because of the invasive nature of such approaches and the sensitivity of the environment. In this study we use ground penetrating radar (GPR) and electrical resistivity tomography (ERT) to characterise the stratigraphy at a small riparian wetland site. Then, through time-lapse ERT measurements over a 12 month period, we demonstrate how changes in resistivity may provide additional value about localised recharge. We compare direct measurements of water table depth and pore fluid electrical conductivity and temperature, with subsurface resistivity derived from the ERT measurements and reveal that temporal fluctuations in temperature of the subsurface dominates the change in resistivity over the monitored period. From this we use the ERT images of resistivity to estimate spatio-temporal changes in subsurface temperature and thus infer localised zones of groundwater recharge due to suppressed seasonal variation in temperature. Although we focus here on one 2-D vertical profile through the wetland, the results highlight the potential value of non-invasive time-lapse geoelectrical surveys for mapping 3-D thermal patterns within a wetland environment.

1. Introduction

Understanding the hydrological mechanisms within wetlands is of increasing importance given the recognition that wetlands can contribute a significant role to the hydrological and biogeochemical function of catchments. Legislation such as the European Union Water Framework Directive (2000/60/EC) and Habitats Directive (92/43/EEC), and increasing public awareness of conservation issues also contribute to the growth in perceived value of such ecosystems: a fundamental understanding of a wetland's hydrological functioning must be achieved before conservation or management practices can be put in place. Numerous studies have been carried out detailing the hydrology of individual wetland sites (for example, Gehrels and Mulamoottil, 1990; Boeye and Verheyen, 1992; Harding, 1993; Shedlock et al., 1993; Gilvear et al., 1997; Andersen, 2004), most of which have relied on small-scale measurements, for example cored samples to describe the local structure, and point measurements of hydrological and hydrochemical states (for example, from piezometers).

As in other areas of subsurface hydrology, there is growing appreciation that geophysical methods can provide additional supporting information about hydrostratigraphy and hydrological states in wetlands over larger scales and with improved spatial resolution compared to conventional measurements. Many geophysical techniques also permit much less invasive investigations of the subsurface, which may be important in protected/conserved areas (as is the case in many wetland environments). A number of geophysical studies of wetlands (including peat bogs) have previously been carried out, but to date, most have focussed on structural characterisation (Slater and Reeve, 2002; Comas et al., 2004; Kettridge et al., 2008), although a number of recent studies have attempted to use time-lapse geophysical methods to reveal production and emission of biogenic gasses in peatlands (Comas et al., 2008; Slater et al., 2007). Here we demonstrate how time-lapse geophysical methods can also provide additional information about the hydrological mechanisms within a wetland. This is achieved through interpreted changes in the spatial distribution of subsurface temperature in the wetland soil, computed directly from time-lapse electrical resistivity measurements made on the wetland surface.

Although it is widely acknowledged that temperature is an important state variable with broad hydrological and

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hydrochemical value, the last decade has seen a growth in the appreciation of the value of temperature measurements within subsurface hydrological systems (see Anderson (2005) for a comprehensive review of the use of temperature measurements in subsurface hydrology). The increasing availability of low-cost local temperature sensors, development of new methods for hydrological interpretation of temperature time series (Stonestrom and Constantz, 2003; Hatch et al., 2006; Keery et al., 2007) and the utilisation of fibre optic-based technology for distributed temperature measurements (for example, Tyler et al., 2009) have all contributed to this renewed interest in temperature as a key hydrological measurement. Fibre optic distributed temperature sensors (DTS) offer impressive spatial sampling over kilometres lengths but this is limited to sensitivity only within close proximity to the cable. While this may be adequate for the determination of areas of significant upwelling in the vicinity of the cable placement, which may be effective in some groundwater-surface water studies (for example, Selker et al., 2006), they can only be utilised for subsurface temperature measurement by installation along wells (for example, Vogt et al., 2010), which offers little advantage over conventional thermistor sensor technology other than enhanced resolution of vertical temperature gradients. It is the variation in temperature of the subsurface (not the ground surface) that potentially offers more hydrological value, and in this study we infer changes in subsurface temperature in a distributed manner through ground-based electrical resistivity surveys.

The electrical resistivity of a porous medium is a function of many properties and states, such as porosity, structure (organisation of the medium), clay content, water content, pore fluid salinity and temperature. Consequently, the measurement of resistivity is often ambiguous unless variation in resistivity is dominated by one of these properties or states. In hydrostratigraphic surveys, resistivity can prove to be effective where different lithologies are characterised by differences in porosity and/or structure. Resistivity can also be effective for monitoring changes in a hydrological state, such as water content (for example, Zhou et al., 2001; Michot et al., 2003; French and Binley, 2004), if the changes are dominated by changes in the particular state (or if the changes due to other states can be accounted for).

Electrical resistivity tomography (ERT) is the generic term used for the method for determination of the subsurface resistivity distribution from multiple electrical resistance measurements made using a quadrapole arrangement of electrodes. The electrodes are commonly placed on the ground surface; by varying the location and spacing of the electrode quadrapole a 2-D or 3-D image of the resistivity can be developed (see, for example, Binley and Kemna, 2005). Although the temperature effect on resistivity is widely known (for example, Schön, 2004; Rein et al., 2004) only a few attempts have explicitly accounted for subsurface temperature variation in ERT-derived images of resistivity (for example, Hauck, 2002; Hayley et al., 2009), in these cases as a means of removing the temperature effect. In a wetland environment we may expect relatively minor changes in fluid saturation over time and thus, provided the influence of changes in salinity is minimal (unlike in, for example, a coastal wetland), the temporal changes in resistivity may indicate temperature fluctuation. Since this can be achieved within a spatial map of resistivity, we may be able to infer spatial variation in temperature associated with, for example, localised vertical or lateral recharge in a groundwater-fed wetland. Here we demonstrate this approach, using a case study based on a small wetland within the floodplain of the Chalk-fed River Lambourn in Berkshire, UK.

2. Site description

The River Lambourn is a tributary of the River Kennet (Fig. 1). It has a catchment area of approximately 234 km^2 and is located in the Berkshire Downs, UK. The catchment is in an area of unconfined Chalk and is groundwater dominated. The floodplain is designated as a Special Area of Conservation (SAC) under the Habitats Directive (92/43/EEC) due to the habitat it provides for *Vertigo moulinsiana* (Desmoulins whorl snail), and the study area is also within the Boxford Water Meadows Site of Special Scientific Interest, designated for its wetland habitats. The Boxford wetland is located on the floodplain adjacent to the river in a rural area approximately 15 km downstream of the source of the River Lambourn. The study was carried out on a small area of floodplain of approximately 60 m by 60 m, to the east of the river. The area is dominated by tall herbaceous vegetation. Prior and Johnes (2002) and Musgrave (2006) provide more information on the ecological setting of the site, while Grapes et al. (2006) give a hydrogeological context for the floodplain wetlands within the River Lambourn catchment.

A small stream forms within the wetland and enters the River Lambourn at the downstream end of the site, as shown in Fig. 2. The stream is shallow (approximately 10 cm or less) and vegetation-filled, with an indistinct structure. Flow surveys in the River Lambourn upstream and downstream of the wetland stream show a consistent increase in flow downstream of the wetland stream. This is predominantly attributed to the stream inflow, although flow cannot always be observed on the surface during summer months, and the accretion in river flow may be therefore partly attributable to more diffuse inputs from the wetland. Although there is not always flow at the surface, the channel surface remains consistently moist through the summer and the vegetation communities indicate an increased wetness in the vicinity of the channel.

The site is located at the mouth of a dry valley. A number of similar valleys occur along the catchment, and are thought to

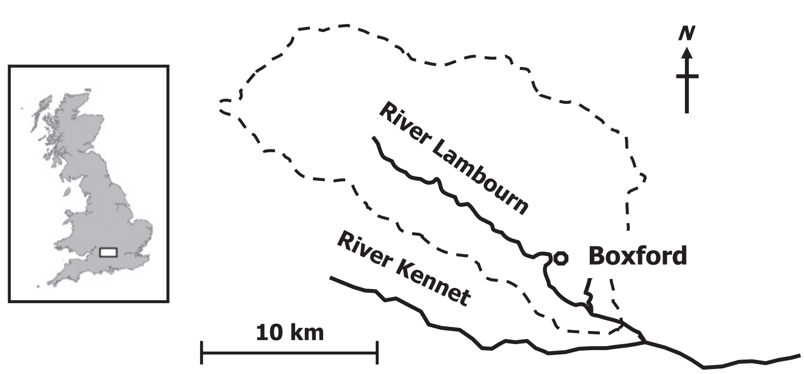

Fig. 1. Location of field site with the catchment of the River Lambourn (topographic catchment boundaries of the River Lambourn are shown by the broken line).