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Discrete wetland groundwater discharges revealed with a three-dimensional temperature model and botanical indicators (Boxford, UK)

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Abstract

Wetlands provide unique goods and services, as habitats of high biodiversity. Hydrology is the principal control on wetland functioning, hence understanding the water source is fundamental. However, groundwater inflows may be discrete and easily missed. Research techniques are required with low cost and minimal impact in sensitive settings. In this study, the effectiveness of using a three-dimensional (3D) temperature model and botanical indicators to characterise groundwater discharge is explored at the CEH (Centre for Ecology and Hydrology) River Lambourn Observatory, Boxford, UK. This comprises a 10-ha lowland riparian wetland, designated for its scientific interest and conservation value. Temperature data were collected in winter at multiple depths down to 0.9 m over approximately 3.6 ha and transformed into a 3D model via ordinary kriging. Anomalous warm zones indicated distinct areas of groundwater upwelling which were concurrent with relic channel structures. Lateral heat propagation from the channels was minimal and restricted to within 5–10 m. Vertical temperature sections within the channels suggest varying degrees of groundwater discharge along their length. Hydrochemical analysis showed warmer peat waters were akin to deeper aquifer waters, confirming the temperature anomalies as areas of groundwater discharge. Subsequently, a targeted vegetation survey identified *Carex paniculata* as an indicator of groundwater discharge. The upwelling groundwater contains high concentrations of nitrate which is considered to support the spatially restricted growth of *Carex paniculata* against a background of poor fen communities located in reducing higher-phosphate waters.

Keywords

Wetlands, groundwater/surface-water relations, temperature, biological indicator, UK

1. Introduction

Wetlands serve important environmental, cultural and economic functions. Particularly sensitive to environmental change, groundwater dependent wetland ecosystems are identified as priority habitats under the European Habitats Directive (EEC, 1992). Consequently, there is a growing realisation of the need for sustainable wetland management (Maltby and Acreman, 2011). The establishment and maintenance of wetlands depends primarily on hydrology (Mitsch and Gosselink, 2007), which is a key control on vegetation (Baldwin, et al., 2001; Wheeler, et al., 2009), fauna (Ausden, et al., 2001; McMenamin, et al., 2008) and biogeochemical cycling (Lischeid, et al., 2007; McClain, et al., 2003).

Groundwater discharge to riparian wetlands can be a significant component of the water balance (Krause and Bronstert, 2005). However, groundwater influxes are typically complex and spatially heterogeneous (Hunt, et al., 1996; Lowry, et al., 2007); being dependent upon topographical, geological and climatic factors (Sophocleous, 2002; Winter, 1999). Investigative techniques are required that can capture processes at a high spatial resolution. Such techniques should be non-destructive and minimally invasive due to the sensitivity of many wetland environments. Furthermore, resource restrictions often compel economical approaches.

Temperature is a useful natural groundwater tracer which can identify small-scale zones of groundwater discharge (Anderson, 2005; Conant, 2004). A significant body of research is centred around identifying and quantifying localised groundwater flux in the hyporheic zone (Briggs, et al., 2012; Constantz, et al., 1994; Hannah, et al., 2009; Keery, et al., 2007; Krause, et al., 2012; Schmidt, et al., 2007). Small-scale variability in temperature has been considered along the horizontal plane of a cross-fault ditch (Bense and Kooi, 2004). However, applications to wetlands are fewer, with temperature observations in such studies also restricted to a limited number of point measurements (Bravo, et al., 2002; Hunt, et al., 1996).

Botanical indicators of groundwater also have the potential to provide a cost-effective means of site characterisation (Lewis, 2012). However, links between phreatophytes (plants which draw water from the water table) and groundwater discharge are more established in arid and semi-arid regions than more humid regions (Batelaan, et al., 2003). Plants have been regarded as indicators of groundwater discharge in the Netherlands (Grootjans, et al., 1988; Klijn and Witte, 1999; Lucassen, et al., 2006; Schot, et al., 1988; van Diggelen, et al., 1988; Wassen, et al., 1988; Wierda, et al., 1997) and Minnesota, USA (Almendinger and Leete, 1998; Batelaan, et al., 2003; Glaser, et al., 1990; Goslee, et al., 1997; Rosenberry, et al., 2000). Research in the UK has focussed on general water requirements of wetland plant communities and species (Gowing, et al., 2002; Newbold and Mountford, 1997; Wheeler, et al., 2009). Specifically, botanical indicators for groundwater are not defined in the UK.

This paper aims to demonstrate the potential of 3D temperature models in effective and economical conceptualisation of groundwater/surface-water interaction, with a focus on lowland riparian wetlands. The potential of botanical indicators of groundwater discharge is also further explored.

2. Study Area

2.1. Site description

The Centre for Ecology and Hydrology (CEH) River Lambourn Observatory (51.445° N 1.384° W) encompasses *c.*10 ha of riparian wetland bordering a 600 m reach of the River Lambourn (Figure 1). The wetland and River Lambourn are designated as a Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC), due to their importance for *Vertigo moulinsiana* (Desmoulin's whorl snail), *Lampetra planeri* (brook lamprey) and *Cottus gobio* (bullhead). This is in addition to the river habitat (Annex 1 habitat from EU Habitat Directive: Water courses of plain to montane levels with *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation) and terrestrial plant communities (MG8 vegetation community of the UK National Vegetation Classification (Rodwell, 1991)).

The site is underlain by the Seaford Chalk Formation, a uniform soft to medium-hard chalk with frequent flint nodules, which dips at 1-2° to the southeast (Allen, et al., 2010). Up to 9.1 m of river terrace deposits and alluvium overlie the Chalk, and consist primarily of coarse gravels. These are on average 4-5 m thick with local thickening and thinning. In their lower layers there is often a high proportion of reworked chalk material. Additionally, a discontinuous layer of highly weathered and low permeability 'putty chalk' (Younger, 1989) approximately 5 m thick exists between the gravel-chalk interface and coherent chalk bedrock. The alluvial cover overlying the gravels ranges up to 2.7 m thick, mostly consisting of peat, with intermixed occurrences of silt, sand and gravel (Allen, et al., 2010). Within the wetland, these deposits are typically around a metre thick (Chambers, et al., 2014).

The site is located 13 km downstream from the ephemeral source of the River Lambourn at Lynch Wood, Lambourn (51.512° N, 1.529° W). The river drains the Chalk of the Berkshire Downs and is characterised by a large baseflow component. At Shaw, 5 km downstream of the observatory, the river has a base flow index of 0.96 and mean discharge of 1.73 m^3/s

(Marsh and Hannaford, 2008). The wetlands to the west of the river are dissected by the Westbrook Channel, which separates the site into a northern and southern meadow.

Historic maps dating back to the 1880s show a network of predominantly linear conduits, sluices and aqueducts characteristic of a managed water meadow system (Everard, 2005). In particular, a channel through the north meadow displays a sinuosity and irregularity indicative of natural origin. Most of these channels have naturally infilled and are absent from current maps.

2.2. Initial conceptual model

Wetland water levels have been inferred to be principally controlled by the River Lambourn and Westbrook stage (Atkins, 2005; Musgrave, 2006; Old, et al., 2014). Groundwater contributions are regarded as more significant in the south meadow, though the possibility of groundwater upwellings at the northernmost extent of the site has been suggested from hydrochemical analysis (Musgrave, 2006). Such deductions were, however, based on an arbitrarily positioned transect and cluster of randomly located piezometers in each meadow.

The low permeability ‘putty’ chalk is considered to act as a confining layer to the Chalk aquifer, and its uneven distribution has implications for exchange between groundwater and surface water (Chambers, et al., 2014). Studies at a nearby site 100 m upstream of the Observatory, part of the Lowland Catchment Research (LOCAR) programme (Wheater, et al., 2007), have indicated variable hydraulic connection between the Chalk, gravels and surface water (Abesser, et al., 2008; Allen, et al., 2010; Lapworth, et al., 2009). The extent of the interaction remains unclear.

3. Methods

3.1. 3D peat temperature model

Temperature of the peat was characterised in daylight hours over five days in February 2013 when the difference in surface temperature and groundwater temperature was expected to be pronounced. The north meadow was surveyed between 11-13th February and the south meadow between 18-19th February. An Oakton™ Type T thermocouple probe connected to a thermocouple thermometer was inserted into the peat at 1056 locations on an approximate 5 m x 5 m grid (Figure 2a). These were georeferenced with differential GPS (dGPS). Measurements were taken at depths of 0.15, 0.30, 0.45, 0.60, 0.75, and 0.90 m below ground level (bgl) resulting in a total of 5109 temperature measurements, with the peat less than 0.90 m thick in places. Dense scrub and watercourse boundaries confined the survey extent.

Temperature data were imported into the 3D visualisation and analysis application Paradigm SKUA 2011.3™. This is a powerful modelling package widely used in the earth sciences, allowing the integration and analysis of borehole, geophysical and other subsurface data. A 3D grid was constructed which encapsulated the temperature measurement points and had cell dimensions of 1 x 1 m in the horizontal plane and 0.05 m in the vertical direction. The north and south meadows were kept separate. The grid was positioned so that the temperature measurement points coincided with the centre of grid cells. It was deformed to align each layer of cells parallel to the undulating surface topography. Measured temperature values were assigned to the grid cell in which they occurred and, following variogram modelling (Figure 2b), were interpolated throughout the gridded volume using ordinary kriging (Webster and Oliver, 2007).

The spherical 3D variogram model was estimated within Paradigm SKUA 2011.3™ by the method of moments. The software includes the capability to include anisotropy in the variogram model. This is where the expected squared difference between a pair of observations is a function of both the length and the direction of the vector which separates the measurement locations. In contrast, isotopic models assume that the variogram is purely a function of the length of the vector.

In the horizontal plane, any directional-dependence appeared to be caused by a single feature in the northern meadow. The temperature was less variable parallel to this than perpendicular to it. Since the feature dissected the meadow, it was not possible to represent this anisotropy by a geometric distortion (stretching or contraction) of the variogram range in a single direction. Any attempt to do so would have led to artefacts in the predicted temperature surface. There was a clear difference between the variograms in the horizontal and vertical planes. Therefore the estimated model was isotropic in the horizontal plane with geometric anisotropy in the vertical plane (Webster and Oliver, 2007). The estimated spherical variograms are shown in Figure 2b. The estimated nugget and sill variances are 0.01 $(^{o}C)^{2}$ and 0.52 $(^{o}C)^{2}$, respectively. The range of the model is 35.5 m in the horizontal direction and 0.3 m in the vertical direction.

3.2. Site instrumentation

An existing gridded piezometer array was numbered 1-13 (Figure 1). Supplemental piezometers were added in May 2013 to target observed temperature anomalies (locations 14-19; Figure 1). All locations comprise separate peat and gravel piezometers, with the exception of location 8 where the peat was too thin to complete an installation. Gravel piezometers are screened approximately 2.5-3.5 m bgl whilst peat piezometers are screened across the entire peat thickness. Chalk boreholes are also located at sites 3, 20 and 21; these are screened at 9.5-10.0, 8.0-9.0 and 5.0-6.0 m bgl, respectively.

Groundwater heads are routinely measured manually by dipping observed water levels. Moreover, gravel groundwater temperatures are monitored every five minutes using either In-Situ Level Troll® 500s or SWS Divers® installed to a consistent depth of 3 m bgl in piezometers 1-13. The River Lambourn temperature is measured every 15 minutes at monitoring site SW1, with a Druck® PDCR 1830 (Figure 1). Channel stage is regularly observed at four stage boards along the River Lambourn (a-d) and two in the Westbrook (e-f). Continuous 15 minute averaged air temperature data and subsurface temperature at 0.1, 0.3 and 0.5 m depths are recorded at an automatic weather station (AWS) using CS215™ and 107-LC™ temperature sensors, respectively.

3.3. Water sampling and analysis

Groundwater samples were collected in May 2013 from all gravel and chalk piezometers once stable field measurements were obtained for dissolved oxygen (DO), pH, specific electrical conductance (SEC), redox potential (Eh) and temperature. These measurements were collected using Mettler-Toledo™ probes contained within a flow-through cell to inhibit any contact with the atmosphere. Samples from all peat piezometers were obtained following a single purge, as the transmissivity of the peat was too low to sustain continuous abstraction with a peristaltic pump (0.1-0.5 l/min) in piezometers 1-13. Hence, only field measurements of pH and SEC were collected in the peat. Surface water samples were also obtained from the River Lambourn at SW1 and Westbrook at SW2 (Figure 1).

Laboratory sample preparation and analysis were performed following the procedures outlined by Neal, et al. (2011). Major anions and dissolved metals were determined via Dionex™ liquid chromatography and ICP-OES, respectively. Alkalinity was determined by titration with hydrochloric acid. Dissolved organic carbon (DOC) analysis was undertaken with a Thermalox™ C analyser following acidification and sparging. Total phosphorus (TP) was determined by the method of Eisenreich, et al. (1975). Soluble reactive phosphate (SRP) and ammonium-nitrogen were determined colorimetrically.

3.4. Linking vegetation coverage to hydrology

Vegetation species were identified at a subset of the temperature survey positions to identify potential botanical indicators of groundwater upwelling. The temperature survey positions were selected by stratified random sampling (De Gruijter, et al., 2006) where the strata comprised deciles of the observed temperature at 0.15 m depth (Table 1). Twelve of the positions within each stratum were selected at random. Vegetation species were identified at these 120 locations in addition to the locations of the paired piezometers.

The survey was conducted with a 2 m^2 quadrat in July 2013 when stands were mature enough to allow easier identification. Each quadrat was aligned north-south and located at its southwest corner using dGPS. For each quadrat, individual species and their percentage cover were indentified. These results were then used to allocate the location to a particular community of the National Vegetation Classification (NVC) (Rodwell, 1991) using the TABLEFIT procedure (Hill, 1996). This establishes the degree of agreement between species coverage in each quadrat and the association tables in British plant communities. Only where goodness of fit values where at least 50 % were samples allocated. Further, the positions of all *Carex paniculata,* easily recognisable in dense tussocks up to 1.5 m tall and 1 m in diameter, were recorded and matched to the local temperature decile.

4. Results

4.1. Temperature

4.1.1 3D peat temperature model

Overall temperature ranges between 2.1 and 10.3°C in the peat, with a mean temperature of 6.4 °C (σ = 1.7 °C). In the north meadow the mean temperature was 6.5 °C (σ = 1.76 °C). In the south, mean temperature was lower at 6.0 °C (σ = 1.32 °C). The model shows discrete warm temperature anomalies (>9 °C) which correlate with historical channels (Figure 3), which have infilled and are no longer present (Figure 1). In the north meadow the anomalies largely correspond to the path of the sinuous relic channel, whilst the main anomaly in the south meadow lies within a relic channel draining to the Westbrook. The anomalies are tightly constrained with heat only propagating 5-10 m laterally from the channel centre.

Temperature gradients vary widely across the site, and cross-sections through the model show they are relatively constant with depth at some of the strongest temperature anomalies (Figure 3c). Overall the mean temperature increases from 4.7 °C at 0.15 m to 7.9 °C at 0.9 m, while σ drops from 1.3 to 0.9 °C. The decreasing σ with depth reflects a decreasing range from between 2.1 °C and 10.0 at 0.15 m, down to between 5.7 and 10.3 °C at 0.9 m.

A warm temperature anomaly is located at the source of the main relic channel in the north meadow, with further anomalies spread along its course (Figure 3d). Anomalies within the peat frequently extend toward the surface, but then gradually dissipate with distance. Greatest changes in temperature occur at shallow depths. Below 0.7 m warm anomalies are persistent along the entire channel length before dispersing at around 370 m from the source.

4.1.2 Logged air, river, peat and gravel temperature

Air temperature ranges during the peat temperature surveys were -0.3 to 2.6 °C and -5.0 to 10.6 °C for the north and south meadows respectively (Figure 4). These fluctuations were significantly dampened through the peat depth, with total variations of only 0.8, 0.3, and 0.1 °C at 0.1, 0.3 and 0.5 m bgl, respectively.

Groundwater temperature within the gravels ranged from 9.4 to 10.2 °C between piezometers in the north meadow, with the exception of piezometer 6 which was around 7.3 °C. There appears to be a temperature gradient across the meadow with the warmest water located further north. Within the south meadow the gravel groundwater was cooler at 8.3 to 9.0 °C.

The River Lambourn temperature varied between 7.7 and 8.2 °C, with a mean of 7.9 °C, during the north meadow survey. During the south meadow survey the variation was 7.3 to 9.4 °C, with a mean of 8.4 °C.

4.2. Piezometric surface elevations (heads)

Vertical upward head gradients from gravel to peat persist at sites 14-19 (Figure 5), which are drilled into the relic channels containing the warm temperature anomalies. Upward gradients also exist at sites 5 and 12, which are in close proximity to these channels. Elsewhere predominantly downward gradients are present. Within the north meadow, there also appear to be higher groundwater heads in the peat and gravels in the vicinity of the relic channel. Chalk heads are higher than adjacent gravel and peat heads in the north meadow, but lower in the south meadow.

Peat and gravel heads are significantly higher than the adjacent River Lambourn and Westbrook levels in the north meadow. In the south meadow, there is no significant gradient towards Westbrook. In general groundwater head contours follow a south-westerly direction at an overall gradient of 0.003 in peat, gravel, and chalk (Figure 5).

4.3. Hydrochemistry

Water chemistry from the peat piezometers falls into three distinct groups, initially distinguished on the basis of their SEC (Figure 6). Group 1 comprises piezometers 14-19 targeting the temperature anomalies, where peat water chemistry is akin to the chalk waters. Group 3 encompasses piezometers 1 and 4-13 where peat waters are characterised by elevated alkalinity, Ca, DOC, Si, NH_4, TP, SRP, Fe and Mn, whilst they are depleted with respect to SO_4 and NO_3. Group 2 includes piezometers 2 and 3 which are considered intermediate waters between Groups 1 and 2. pH does not vary between groups with a mean of 7.1, 7.0 and 7.1 for Groups 1, 2 and 3, respectively.

There are strong positive correlations between alkalinity, DOC and Ca in Group 3 (Figure 7). Group 1 and chalk waters, in contrast, are clustered, with Group 2 waters falling between. Gravel groundwater is reasonably well-mixed across the site, although alkalinity, TP and NO_3 show some variation between groups. The gravel waters show a similarity to chalk waters. Nevertheless, in places, the gravel waters display occasional characteristics of Group 3 peat waters. This is most notable at piezometer 6 which has comparably high SEC (0.7 mS/cm) and alkalinity (6.3 mEq/l), high concentrations of Ca (132.8 mg/l), DOC (5.7 mg/l), Si (8.9 mg/l), Mn (0.1 mg/l), and is depleted in SO_4 (4.3 mg/l) and NO_3 (2.6 mg/l).

4.4. Vegetation coverage

In terms of NVC plant communities the S28 *Phalaris arundinacea* tall-herb fen community dominates the site (Table S1 of the electronic supplementary material (ESM)). Other prevalent communities include the OV24 *Urtica dioica – Galium aparine* community, OV26 *Epilobium hirsutum* community, S7 *Carex acutiformis* swamp, S6 *Carex riparia* swamp, and S5 *Glyceria maxima* swamp. These communities are all distributed evenly across the temperature deciles. Plant communities unclassified by the TABLEFIT procedure are also distributed evenly. Small samples of the communities S23 *Other water-margin vegetation*, and W6 *Alnus glutinosa - Urtica dioica* woodland are observed in the warmest decile.

Amongst individual species, *Glyceria maxima*, *Carex acutiformis*, *Urtica dioica*, *Phalaris arundinacea*, *Iris pseudacorus* and *Galium aparine* prevail (Table S2 of the ESM). These show no preference for areas with temperature anomalies. Where species appear to show an affinity to areas with warmer temperatures, such as *Salix triandra*, *Salix fragilis*, *Carex paniculata*, *Caltha palustris*, *Typha latifolia* and *Lamium album*, sample numbers are limited (1-3 locations). *Poa trivialis* appears to show the converse preference towards cooler areas, but based on only four samples.

The exhaustive *Carex paniculata* survey identified 55 of 59 individuals located in temperature deciles 9 and 10 (Figure 8). Furthermore, *Carex paniculata* were abundant in areas of the north meadow, but restricted to only a single individual in the south meadow.

5. Discussion

5.1. Groundwater discharge

Warm temperature anomalies in this winter survey are considered to relate to areas of groundwater discharge. This is supported by groundwater head and hydrochemical data which indicate vertical upward head gradients towards the peat, and peat water chemistry representative of chalk waters in such areas. Discrete areas of groundwater discharge into infilled relic channels occur within both the north and south meadows.

In the north meadow, peat and gravel groundwater heads are consistently higher than the river and Westbrook stages. These heads are likely to be supported by upwelling groundwater from the Chalk. This is borne out by warmer temperatures in both the peat and gravels. The heads around the main relic channel indicate this is likely to be the focus of upwelling. Such small-scale variations in gravel head have also been noted 100 m upstream of the wetland where they were attributed to probable upwelling of chalk waters associated with geological heterogeneities (Allen, et al., 2010). An absence of either relatively impermeable putty chalk at the chalk surface, or reworked chalk towards the base of the gravel matrix, would account for these observations (Figure 9).

The warm temperature anomaly within the sinuous relic channel of the north meadow is maintained at depth, yet loses constancy towards the surface. This is likely to be a result of groundwater discharge of varying magnitudes. However, during hydrochemical sampling when the peat was saturated across the site, piezometers away from the channel pumped with intermittent flow. Peat piezometers within the channel, however, sustained continuous abstraction indicating a higher permeability. Hence, localised upwellings and resultant increases in hydraulic head would promote preferential lateral flow through more permeable sediments of the relic channel. The observed heat transport could then encompass an element of lateral advection induced by relic channel flow.

Hydrochemical evidence suggests some lateral groundwater movement away from the vicinity of relic channels. This is supported by the intermediate group 2 waters contained within peat piezometers 2 and 3. Peat piezometer 3 is located down gradient of the northern relic channel, from which water is likely to have at least partially originated given the lack of upward hydraulic gradient at the site itself. A relic channel exists 5-8 m southwest of piezometer 2, yet beyond the survey extent.

At a distance of approximately 370 m along the relic channel temperature anomalies cease. Further south there is a large inversion in the vertical head gradient indicating the potential for downward movement of peat waters into the gravels. Downwelling of peat waters within this vicinity is further supported by hydrochemical and temperature data at gravel piezometer 6.

In the south meadow, the main warm anomaly is contained within a minor relic channel within 30 m of the Westbrook. This anomaly is relatively cooler compared to those in the north meadow indicating less significant groundwater discharge. Moreover, there is no significant gradient between the groundwater and surface waters. Therefore groundwater is not considered to be a major control on peat heads in the south meadow. Heads are likely to be supported by river stage and/or rainfall.

5.2. Biogeochemical wetland processes

The wetland appears to be acting as a highly dynamic biogeochemical reactor (Prior and Johnes, 2002). Upwelling areas are delivering waters rich in NO_3 and SO_4, which are removed away from the temperature anomalies through reductive bacterial processes (Figure 9). On the other hand, the upwelling waters are depleted with respective to SRP and TP. Nevertheless, SRP concentrations ($\bar{x}$ = 53.1 μg/l, σ = 76.4 μg/l) suggest that P is not a limiting nutrient for the wetland ecosystem. These biogeochemical processes and nutrient fluxes create distinct chemical environments, which have implications for ecological response.

The reductive processes and chemical observations can be explained through equations 1 to 6. High alkalinity and reducing conditions away from the upwelling waters may be explained in part through the oxidation of organic matter:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \quad (1)$$

This dissociates to:

$$CO_2 + H_2O \rightarrow HCO_3 + H^+ \quad (2)$$

The free proton is then able to liberate calcium from the calcite in the peaty matrix:

$CaCO_3 + H^+ \rightarrow HCO^-_3 + Ca^{2+}$ (3)

The much lower NO_3 concentrations away from the upwelling waters provide some evidence for denitrification:

$5CH_2O + 4NO_3^- \rightarrow 2N_2 + 4HCO_3^- + CO_2 + H_2O$ (4)

and nitrate reduction to ammonia (DNRA) with higher NH_4^+ and DOC concentrations:

$4NO_3^- + 4H_2 + 2H^+ \rightarrow 3H_2O + NH_4^+$ (5)

which both further contribute to the alkalinity. Although a number of studies have supported the premise that high organic carbon availability favours DNRA over denitrification (Megonigal, et al., 2003), the higher proportion of NH_4^+ is likely due to mineralisation of organic N in the peat. Denitrification could also produce N_2O as the final product.

Similarly, lower SO_4 concentrations could be from bacterial sulphate reduction:

$2CH_2O + SO_4^- \rightarrow H_2S + 2HCO_3^-$ (6)

which, again, add to an increase in the alkalinity. Similar sequences of redox chemistry have been observed in other calcium carbonate environments when stimulated by high loadings of organic carbon (Gooddy, et al., 2002).

5.3. Botanical indicators of groundwater discharge

The NVC plant communities identified for the site are species poor and collectively typical of mesotrophic to eutrophic soils and waters. There is little discernible preference to water source as indicated by temperature. Some individual species seem to correspond to areas of groundwater discharge in the main vegetation survey, but sample numbers are low. These include *Caltha palustris* which has been recognised elsewhere as a possible indicator of groundwater discharge (Klijn and Witte, 1999; Rosenberry, et al., 2000; Wierda, et al., 1997).

The affiliation of *Carex paniculata* to warm temperature anomalies is marked. An explicit association between the presence of the species and temperature is, however, doubtful. *Carex paniculata* is part of a widespread European temperate element in the UK flora, as defined by Preston and Hill (1997). There is little suggestion that the species has a tight temperature requirement, though Ellenberg (1988) has it as an “indicator of fairly warm conditions from lowland to high mountain sites, but especially in submontane to temperate regions”. The occurrence of this sedge is more likely to be determined by other factors linked to the temperature pattern.

The upwelling areas deliver waters relatively low in minerals Ca, Si, Fe and Mn, and nutrients TP and SRP, yet rich in NO_3 and SO_4 (Figure 9). A preference for *Carex paniculata* to Ca poor groundwater with higher NO_3 and SO_4 concentrations has been shown on the Pleistocene sands of central and northeast Netherlands (Grootjans, et al., 1988; Wassen, et al., 1988). Furthermore, *Carex paniculata* has been shown to prefer waters with low Ca and relatively high NH_4 concentrations on the gravel deposits of the River Meuse in southeast Netherlands (Lucassen et al., 2006). However, groundwater Ca concentrations are higher across the study site, given its setting within a chalk valley, than those found in the Netherlands, by around 30-70 mg/l, as are Si concentrations by 3 mg/l. Fe and Mn concentrations are comparatively lower, by around 1-12 mg/l and 1.7 mg/l, respectively.

At this site, it is considered that nutrient rather than mineral supply is likely to be the limiting factor for *Carex paniculata,* particularly given it is a sizeable species with high nutrient demands. Furthermore, it is plausible that NO_3, rather than P, is the limiting nutrient for *Carex paniculata* distribution. Addition of N to calcareous fens has been shown to increase the biomass of some *Carex* species, without changing the species composition (Pauli, et al., 2002). Increased P has also been found to promote the growth of poor fen species, especially more competitive grasses, to the exclusion of other species (Hoek, et al., 2004). These findings are consistent with evidence of *Carex paniculata* surrounded by a variety of poor fen species to situations with the influx of base-rich groundwater and eutrophication

(Rodwell, 1991; Sinker, 1962). This suggests the species may have potential as an indicator of groundwater discharge across lowland chalk wetlands, as chalk groundwater is generally high in NO_3 throughout much of Western Europe due to historical agricultural loadings (Aguilar, et al., 2007; Wang, et al., 2012).

The value of *Carex paniculata* as an indicator species lies in its use for initial hydrological site appraisals and directing further study. The presence of the species or of groundwater does not guarantee the other, despite the majority of stands found in the groundwater dependent north meadow. Rather, tussocks of *Carex paniculata* indicate adjacent conditions arising from a distinct chemical environment. These may result from groundwater discharge in a particular geological context or from another supply mechanism (Wheeler, 1999). Furthermore, other factors than water source are influential, principally light availability (Goslee, et al., 1997), along with soil conditions, air quality and seed availability. Supporting information is invariably required. Wider areas may be characterised as potential areas of groundwater discharge, although it is not possible to delineate discrete areas by vegetation alone.

5.4. Value and limitations of a high resolution 3D temperature model

A detailed 3D temperature model could be a useful precursor to the targeted deployment of sensor arrays. One-dimensional vertical temperature arrays are becoming increasingly commonplace as a means of estimating groundwater fluxes (Anibas, et al., 2009; Voytek, et al., 2013). Such estimates require profile time series to solve analytical flux representations (Briggs, et al., 2012; Hatch, et al., 2006). Sensors could be positioned to sample temperature gradients representatively across an entire site to estimate total groundwater influx. Furthermore, their deployment could also be based upon an understanding of the flow field, which is important to avoid misinterpretation of temperature time series (Cuthbert and Mackay, 2013). For example, at this site there is evidence for non-vertical flows which have been considered the greatest source for error when implementing 1D solutions (Lautz, 2010).

Temperature data may be gathered simply and economically over large areas. In this study the total equipment cost was GBP 250 and a team of two covered 0.1 ha/hour. Limitations of the technique include the need for a high water table elevation and penetrable soils, although these are often distinguishing features of wetlands. Furthermore, it is possible that groundwater discharge may exhibit seasonality or dynamically respond to intense precipitation events, which would not be captured in a single temperature survey.

Other approaches to detect groundwater upwelling include water budgeting (Acreman and Miller, 2006), intrusive investigation, and remote sensing by thermal or multispectral imaging (Becker, 2006). Water budgeting lacks spatial definition and requires quantifiable boundary flows which are often not applicable to wetlands. Standard intrusive exploratory techniques include drilling and trial pitting which are disruptive to sensitive ecosystems and are spatially restricted (Baines, et al., 2002). The influence of air temperature at the ground surface renders remote sensing uncertain, as groundwater temperature signals are seen to fade noticeably in the upper 0.5 m. Moreover, commonly used satellite techniques do not possess the requisite spatial resolution and have limited penetration of the subsurface (Becker, 2006). The method presented is able to encapsulate the necessary scale, depth and resolution with minimal intrusive impact.

6. Conclusions

A high spatial resolution 3D temperature model provides a rapid, economical tool for detailed investigation with minimal intrusive impact. It is applicable worldwide provided there is a sufficient contrast between air and groundwater temperatures at the time of the study. The temperature model, here, delineates discrete areas of groundwater discharge in areas which had not previously been considered to be groundwater dependent, with implications for future sustainable management of the site. The lateral continuity of the temperature anomalies revealed upwelling was generally associated with infilled relic channel structures. Such features are likely to be widespread within riparian lowland wetlands given the dynamic nature of river channels and could be pivotal in the hydrological conceptualisation of many sites. Furthermore, vertical temperature sections within the relic channels indicate the magnitude of groundwater discharge varies along their length.

A temperature model is an effective precursor to the targeted installation of more costly monitoring, e.g. an array of piezometers in this instance. Such targeted piezometer arrays should be favoured in these heterogeneous riparian settings where data from dense random clusters or gridded arrays have been demonstrated to be insufficient for successful site characterisation.

The new site conceptualisation also revealed the prevalence of *Carex paniculata* in areas of deeper groundwater upwelling suggesting that it could be a useful botanical indicator of groundwater dependence. This correlation is considered to be a result of the relatively NO_3 and SO_4 rich, Ca and P poor, waters associated with the deeper groundwater, as opposed to a causal link to temperature itself. *Carex paniculata* is likely limited by N rather than P. Surrounding reducing waters low in NO_3 and SO_4 and high in P promote poor fen communities. A need for hydrochemical or hydrogeological supporting information limits the use of *Carex paniculata* as an indicator species to preliminary site walkovers. Nevertheless, in similar geological settings the species may help determine further investigative requirements.

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Figures

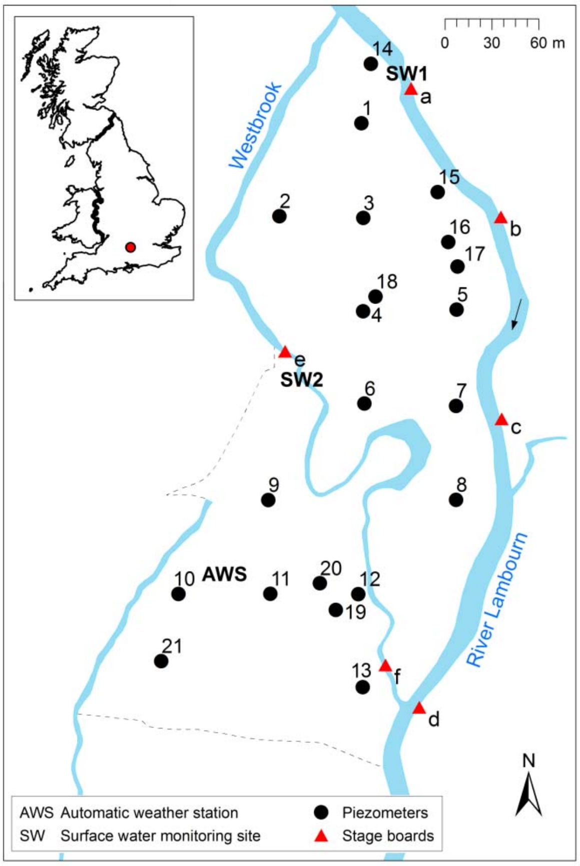

Fig. 1 CEH River Lambourn Observatory with instrumentation network

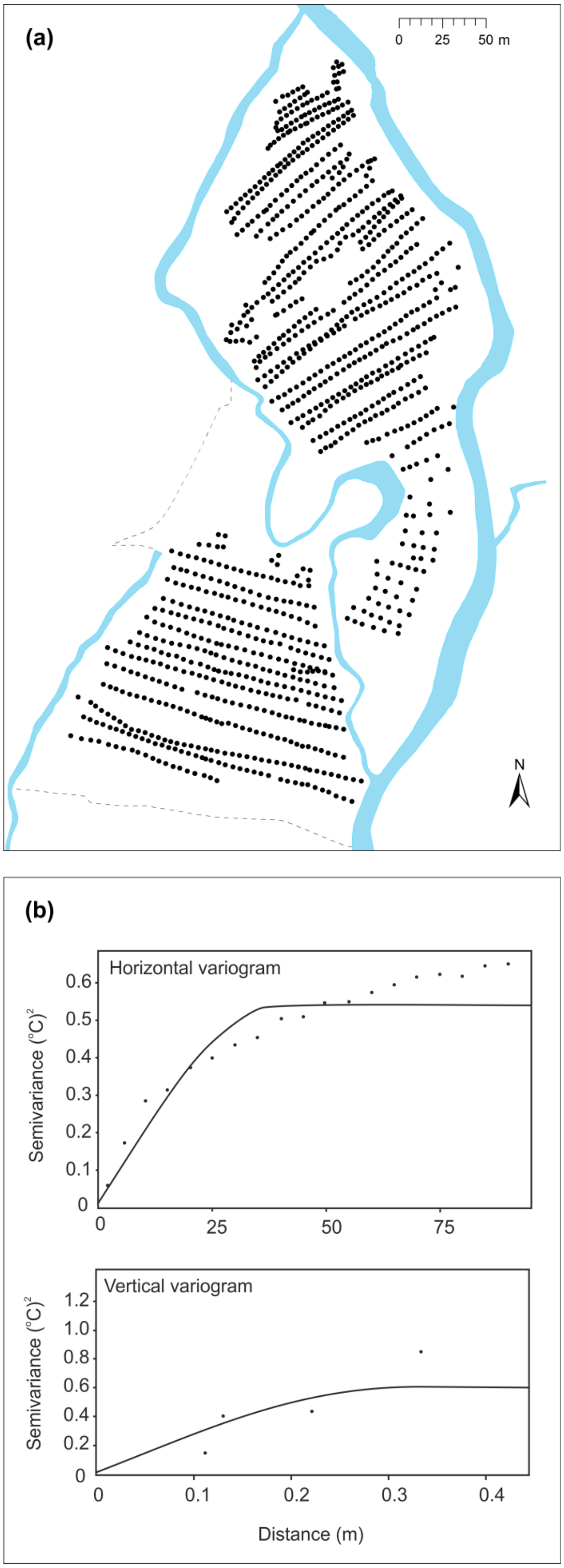

Fig. 2 (a) Locations of 1056 peat temperature profiles (b) Variograms in the horizontal and vertical directions

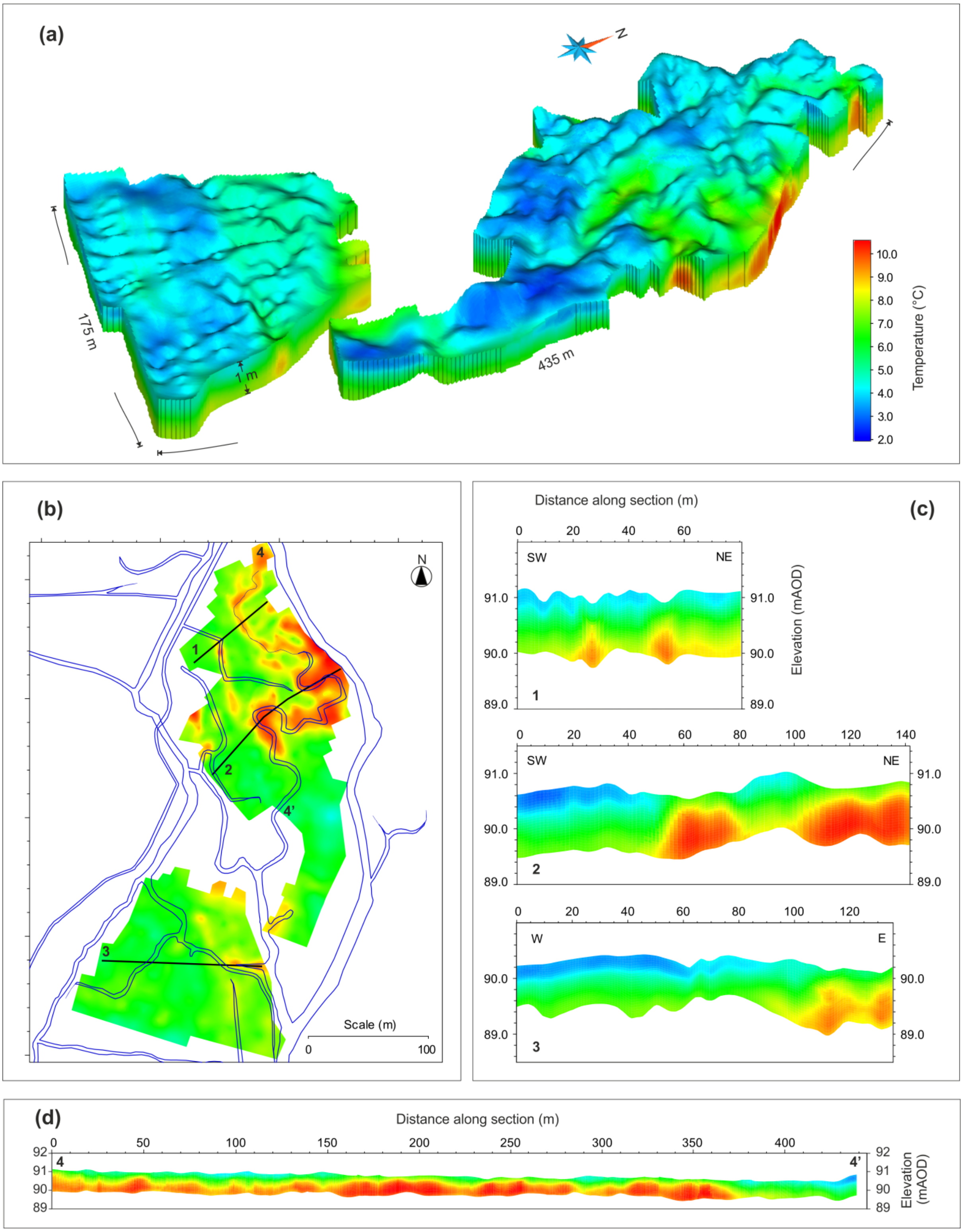

Fig. 3 Subsurface temperature across wetland: (a) 3D temperature model with X20 vertical exaggeration, (b) plan view of temperature at 0.7 m bgl with historical channel layout from 1882 displayed, (c) temperature cross-sections across wetland, and (d) cross-section along infilled relic channel in north meadow.

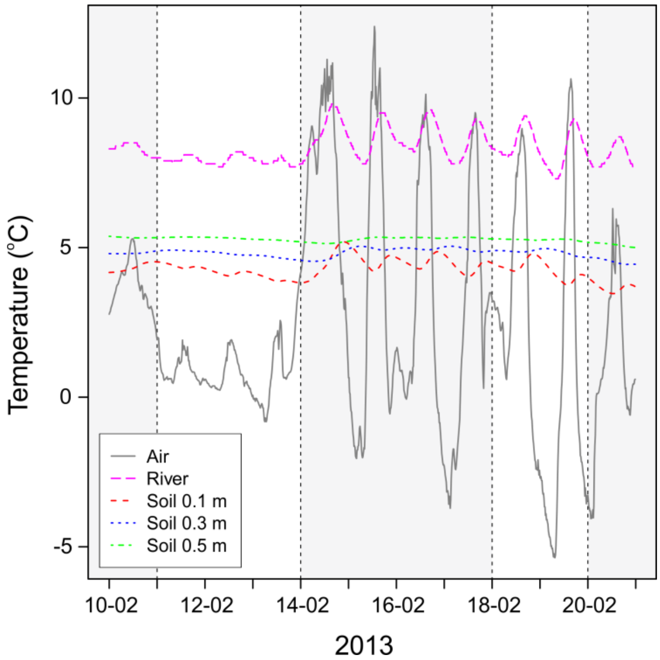

Fig. 4 River Lambourn temperature at SW1, with air and soil temperature at AWS. A grey background indicates records not relating to the period of the temperature spatial survey.

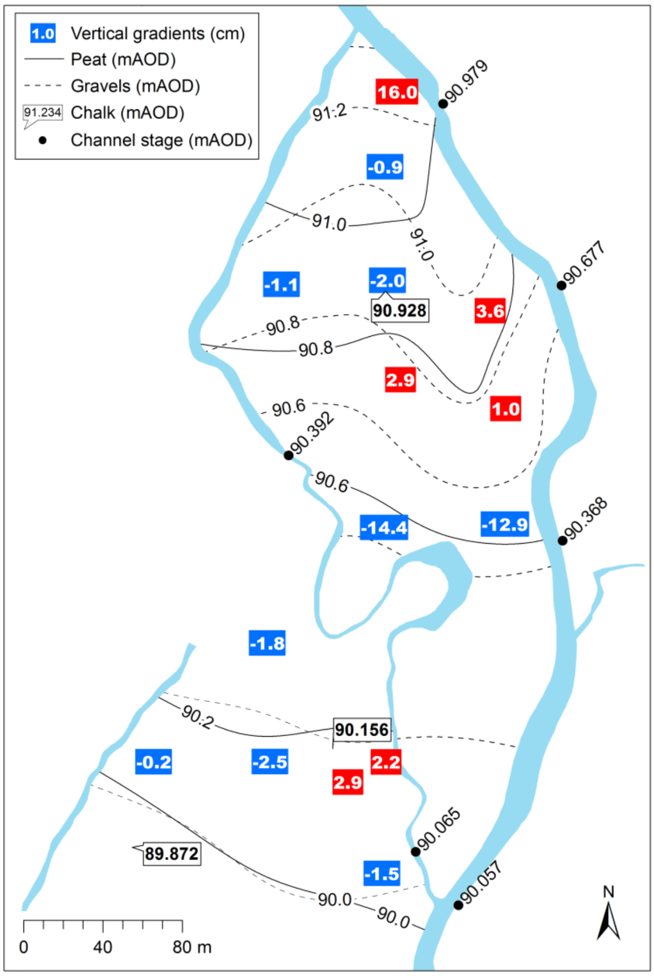

Fig. 5 Groundwater head map for peat and gravels with vertical gradients (red upward, blue downward), chalk heads, and channel stages.

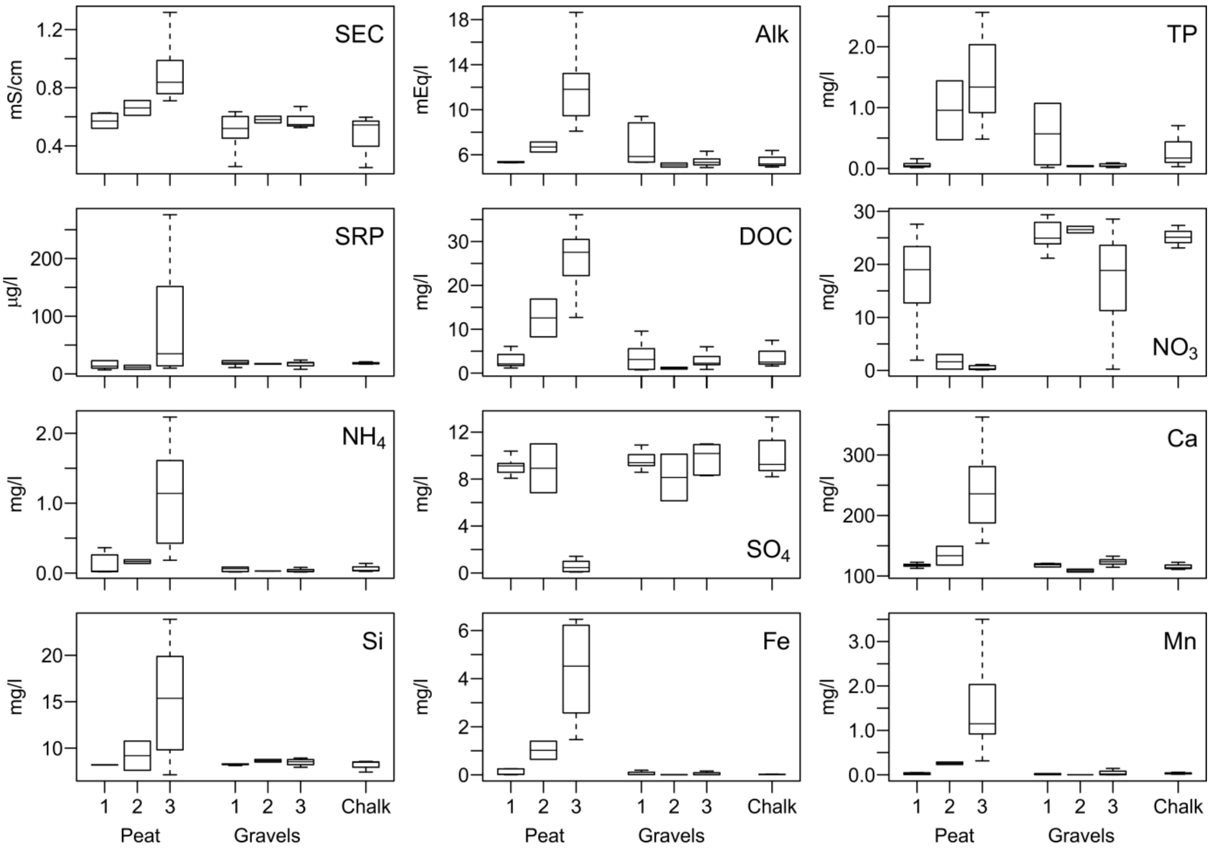

Fig. 6 Boxplots showing selected hydrochemistry of peat, gravels, and chalk. Peat and gravels are split into three groups to reflect variations in chemistry within the peat. Chalk waters encompass both groundwater and surface waters.

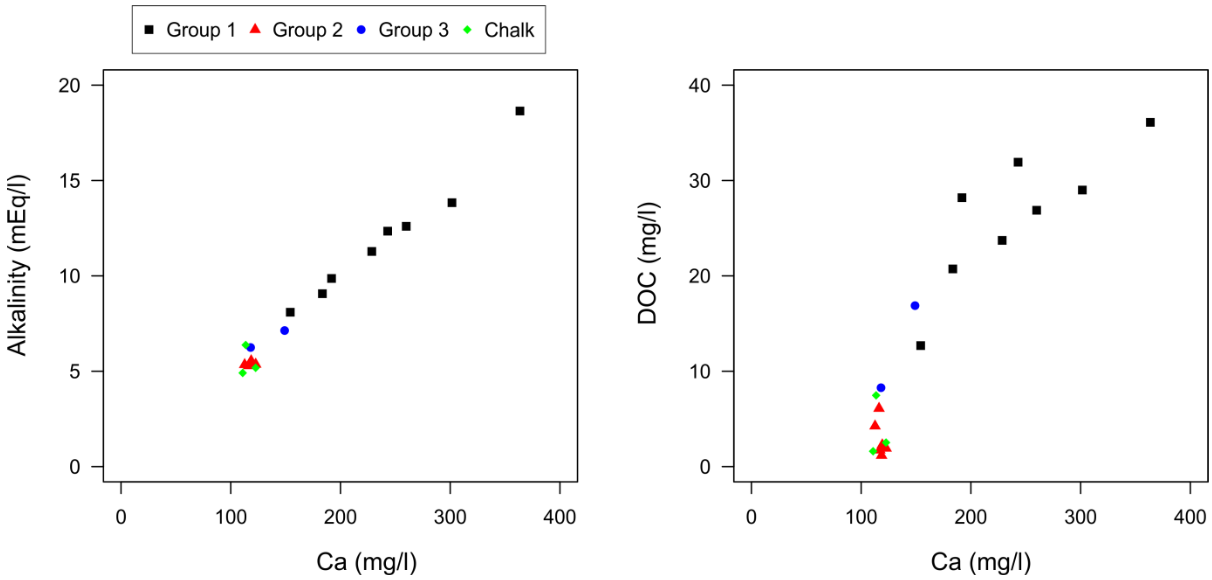

Fig. 7 Grouped peat and chalk water concentrations of Ca against Alkalinity and DOC.

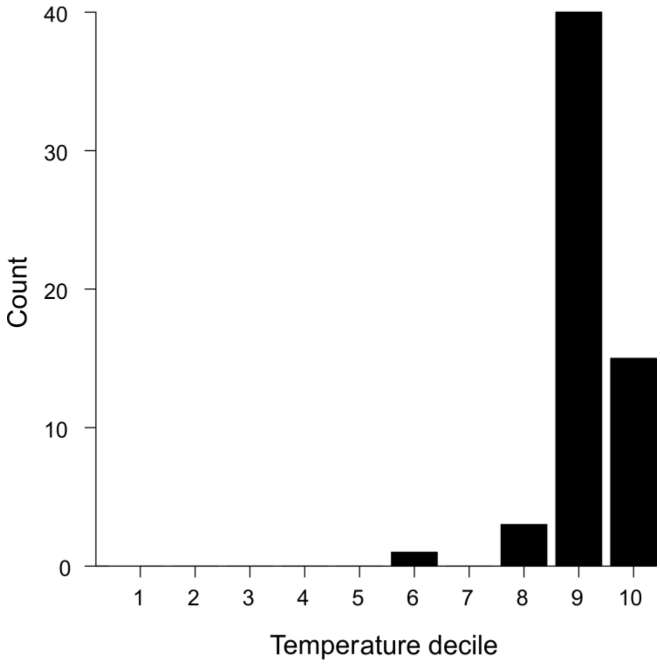

Fig. 8 Distribution of Carex paniculata occurrence across temperature deciles.

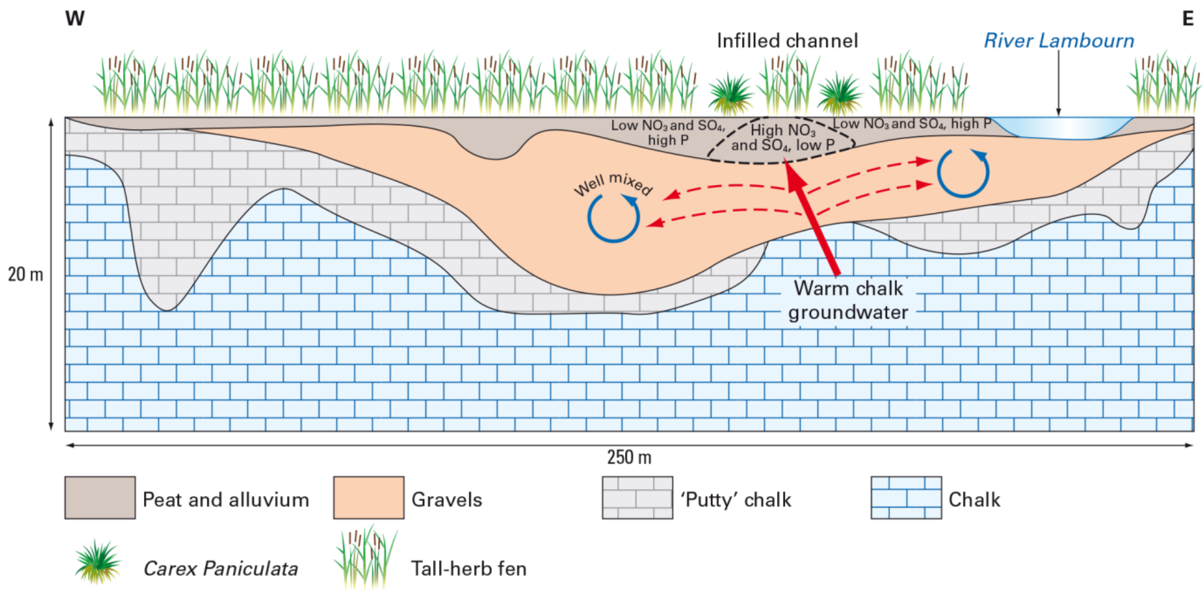

Fig. 9 Conceptual vertical section through the Observatory.

Table 1 Boundaries of temperature deciles.

Decile		1	2	3	4	5	6	7	8	9	10
Temperature	Min	0	3.4	3.7	4.0	4.2	4.4	4.6	4.9	5.5	6.8
range (°C)	Max	3.39	3.69	3.99	4.19	4.39	4.59	4.89	5.49	6.79	10.0