Groundwater–Surface Water Interaction: Process Understanding, Conceptualization and Modelling
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The role of alluvial valley deposits in groundwater–surface water exchange in a Chalk river

CORINNA ABESSER[1], PAUL SHAND[1,2], DAREN GOODDY[1] & DENIS PEACH[1]

1 *British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB, UK*
cabe@bgs.ac.uk

2 *CSIRO, Land and Water, Adelaide, Australia*

Abstract To understand the processes of surface water–groundwater exchange in Chalk catchments, a detailed hydrogeochemical study was carried out in the Lambourn catchment in southeast England. Monthly monitoring of river flow and groundwater levels and water chemistry has highlighted a large degree of heterogeneity at the river-corridor scale. The data suggest an irregular connection between the river, the alluvial deposits, and the Chalk aquifer at the study site. The groundwaters in the alluvial gravels represent a mixture of river water and deeper (Chalk) groundwaters, but simple two-component mixing is inconsistent with the data, and additional processes are required to explain the hydrogeochemistry in the alluvial deposits. It is concluded that the alluvial gravels form an important control on surface water–groundwater interactions at the study site and that the alluvial gravel deposits provide an important lateral flow pathway for pollutant transport along the river valley corridor.

Key words groundwater–surface water interactions; alluvial deposits; Chalk; River Lambourn; LOCAR

INTRODUCTION

The Chalk aquifer and Chalk rivers of southern England provide an important water resource, and sustain surface water ecosystems and their associated diverse flora and fauna. River flows are mostly sustained by groundwater discharge from the Chalk aquifer, which contributes as much as 80–95% of total flow (Sear *et al.*, 1999). Many Chalk rivers have been impacted by point-source and diffuse pollution from agricultural and other anthropogenic sources (Neal *et al.*, 2004). However, little knowledge is available on how these pollutants are transported to the river, and significant uncertainties exist in our understanding of the interaction between river and groundwater systems. In particular, the role of alluvial valley deposits needs to be considered, as they represent pathways of preferential flow through the catchment that further complicate the pattern of pollutant flux and surface water–groundwater exchange. Understanding these processes will have wider implications in terms of water resource development, control of pollution, sustainability of river ecosystems, as well as flooding, and will also be beneficial to many other areas of Europe such as France, Belgium, Denmark, Germany and Poland, which have large Chalk or calcareous aquifer systems.

The study presented here is part of the Lowland Catchment Research (LOCAR) thematic programme which was initiated to advance the scientific understanding of permeable lowland catchments in the UK (Wheater & Peach, 2004). The study site is located in the catchment of the River Lambourn in southeast England, which covers an area of 234 km^2 in the West Berkshire Downs. The Chalk is the principal aquifer in the study area and the River Lambourn exhibits many characteristics of Chalk groundwater-dominated river systems. River flow is mostly sustained by groundwater discharge, which on average, contributes around 96% of total flow (Gustard *et al.*, 1992). Hydrological studies in the catchment have shown that flow accretion in the River Lambourn is not uniform (Grapes *et al.*, 2005; Griffiths *et al.*, 2006), and appears to be controlled by the underlying geology (e.g. sub-horizontal features in the chalk) (Bradford, 2002), as well as by catchment topography, in particular the location of the dry valleys (Grapes *et al.*, 2005). In addition, Quaternary sediments and alluvial deposits cover the Chalk in the river valleys and provide linear, high storage and sometimes high permeability aquifers (Wheater *et al.*, 2007). These laterally extensive, alluvial gravel aquifers vary considerably in thickness and lithology. They are responsible for the development of local (and laterally discontinuous) flow systems in the valley bottoms (Grapes *et al.*, 2006), and hence contribute to the complex pattern of flow accretion and surface water–groundwater exchange. It is widely accepted that these alluvial deposits influence sub-surface flow pathways through the flood plain (Grapes *et al.*, 2006), and recent studies suggest that a direct connection may exist to the river (Griffiths *et al.*, 2006). However, *how* and *where* groundwater is exchanged across the alluvial–bedrock interface and/or the alluvial–river interface remains uncertain. Such knowledge is important to establish potential pathways of pollutant inputs to the river-system and to understand and quantify the likely response-time between a pollutant entering the system and its subsequent emergence in the surface waters.

In this paper we present a hydrochemical approach, which uses hydrometric data in conjunction with geochemical and atmospheric tracer data to infer groundwater flow paths within the alluvial gravels, and to assess the extent of surface water—groundwater interactions in the flood plain at our study site adjacent to the River Lambourn.

STUDY AREA

The Lambourn catchment is underlain by the Chalk Group of Upper Cretaceous age, which represents the principal aquifer of the region. It is a fractured dual-porosity aquifer consisting of a micro-porous, high porosity matrix, intersected by a well-developed fracture system. Groundwater flow is dominated by a preferentially enlarged (secondary) component of the fracture system. The development of these enlarged fractures is generally greater in areas of significant groundwater flux and, hence, transmissivity in the Chalk tends to be greater in the valleys than at the interfluve. In the valley bottom, the flood plain and near-stream areas, the Chalk is covered by alluvium comprising a weathered and flint-rich carbonate sediment. The alluvial deposits are underlain by gravels (flint clasts of variable size) overlying clay-rich, variably weathered “putty chalk” (Wheater *et al.*, 2007), although the spatial distribution of the latter is still unclear. These river valley deposits potentially represent laterally extensive, alluvial gravel aquifers. Their hydraulic conductivity may vary considerably with depth, but also laterally, due to high (local) variability in the thickness of the gravels and their lithology (Grapes *et al.*, 2006).

The River Lambourn is fed by the Chalk aquifer and is characterised by a semi-natural flow regime (influenced by intermittent inputs from sewage treatment works) with maximum mean monthly flows during the spring (1.39 m^3/s, March 2005), coinciding with maximum groundwater levels, and minimum mean monthly flows in autumn (0.75 m^3/s, October 2005) (NRFA, 2007). The mean annual flow in the Lambourn (measured at Shaw SU 470 682) is 1.73 m^3/s (1962–2005; (NRFA, 2007) with a baseflow index of 0.96 (Gustard *et al.*, 1992).

METHODS AND MATERIALS

Instrumentation at the site consists of 8 boreholes located on either side of the River Lambourn (Fig. 1). The boreholes are located along the flood plain of the river (A, C, D, E, F), including a forested wetland (E, F), as well as on the Chalk outcrop (G, H and I), arranged along two main transects: transect 1 (A-D-C) parallel to the river (in the flood plain) and transect 2 (G-I-H-D-E-F) perpendicular to, and across, the river (from the interfluve to a wetland south of the river). All boreholes, except for F, are equipped with 2 piezometers, installed at different depths within the aquifers (see Table 1), providing a total of 15 groundwater sampling points for the hydrochemical investigations. An additional three piezometers (N4, N7, N15) were installed in the flood plain of the river in line with the transect 1 (Adams *et al.*, 2003, Fig. 1).

Sampling was carried out using submersible pumps and included on-site measurements of temperature, specific electrical conductance (SEC) and alkalinity (by titration), as well as pH, dissolved oxygen (DO) and redox potential (Eh). The latter parameters were measured in a flow-through cell. Prior to sampling, a minimum of 2–3 well volumes was removed from the piezometers and samples were collected after on-site readings of temperature, conductivity, pH, DO and Eh had stabilised.

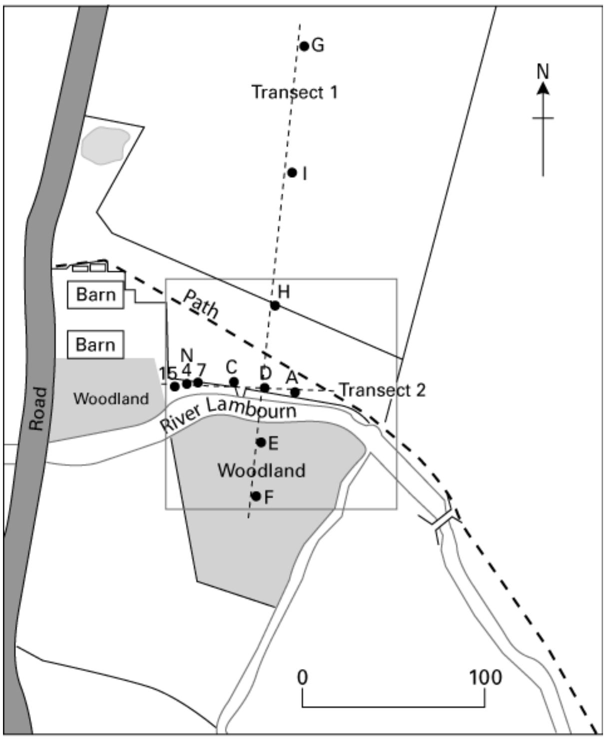

Fig. 1 Borehole installations at the study site.

Table 1 Borehole details at study site (GWL = groundwater level).

Transect 1 (N–S)			Transect 2 (E–W)		
Bh no.	Response zone	Lithology	Bh no.	Response zone	Lithology
I2	30.0–35.0 m	Chalk			
I1	37.1–52.3 m	Chalk	N15	GWL–15 m	Chalk
G2	27.63–100 m	Chalk	N4	GWL–4 m	Gravel
G1	18.0–26.5 m	Chalk	N7	GWL–7 m	Putty Chalk
H2	20.0–24.0 m	Chalk	C2	3.8–4.8 m	Gravel
H1	25.0–30.0 m	Chalk	C1	11.4–23.9 m	Chalk
D	See transect 2		D2	0.7–3.8 m	Gravel
E2	0–4.7 m	Gravel	D1	10.7–25.1 m	Chalk
E1	11.5–25.2 m	Chalk	A2	0–1.8 m	Sand
F	10.1–34.0 m	Chalk	A1	13.2–24.0 m	Chalk

At each piezometer, samples for the analysis of major and trace elements were collected in nalgene© bottles and filtered through a 0.45-µm filter. Samples for dissolved organic carbon (DOC) were filtered through a 0.45-µm silver-membrane filter and collected in Cr-acid washed glass vials. At 3-monthly intervals, samples for the measurement of atmospheric trace gases CFC and SF_6 were collected from piezometers and the river, following the displacement method described in Oster *et al.* (1996). Unfiltered samples were collected into glass bottles contained within metal canisters in order to avoid atmospheric contact and to ensure that the sample was protected from atmospheric contamination by a jacket of the same water.

Analyses of major cations and sulphate were carried out by ICP OES and analysis of anion species (Cl, Br, I, F) by automated colorimetry. Trace elements were analysed by ICP MS. Concentrations of CFCs and SF_6 were measured by gas chromatography with an electron capture detector after pre-concentration by cryogenic methods, based on the methods of Oster *et al.* (1996) and Busenberg & Plummer (2000), respectively.

RESULTS

Hydrology

Figures 2 and 3 show manually dipped water levels in the boreholes of transect 1 and transect 2, respectively, together with a proxy river stage (the proxy river stage was based on stage measurements, provided by the Environment Agency of England and Wales, upstream and downstream of the study site and related to the elevation of the river level close to borehole D). The plots illustrate that groundwater levels along transect 1 decline towards the river, although the calculated hydraulic gradient is very low (4.2 m km^{-1}). Along transect 2, the groundwater levels measured in the Chalk (N7, N15, A1, C1, and D1) are very similar and follow the same temporal trends. Median groundwater levels in these boreholes ranged between 91.1 and 91.4 m aOD during the sampling period and are generally higher than the (proxy) water level of the river which averages around 91.0 m aOD. Median groundwater levels in the alluvial gravels, recorded in piezometers N4, C2 and D2, are consistently lower (90.8–91.0 m aOD) than those in the Chalk. Hydraulically, this indicates a potential for water from the Chalk to recharge the riparian gravels. However, the consistent differences in water levels between the gravels and the Chalk (~0.45 m) suggest that the connectivity between these units at the study site is poor. This is confirmed by Fig. 4 where water levels for the Chalk and the gravels are plotted against each other. It shows that water levels within the individual (hydro)geological units, e.g. within the Chalk, Fig. 4(a), as well as within the gravels, Fig. 4(b), correlate well with each other, but significant scatter occurs between the units (Fig. 4(c). It is therefore unlikely that sizeable exchange of water between the gravels and the Chalk occurs at the study site. In piezometer A2, however, groundwater levels are more similar to the Chalk level (Fig. 3). This piezometer is also installed in alluvium but here deposits consists of thin sands (directly overlying the Chalk) as opposed to the gravel deposits (overlying "putty" chalk) as present in N4, C2 and D2. The good correlation between water level changes in A2 and in the Chalk (D1) is illustrated in Fig. 4(d) and suggests that the alluvial sands are better connected to the Chalk than the gravels.

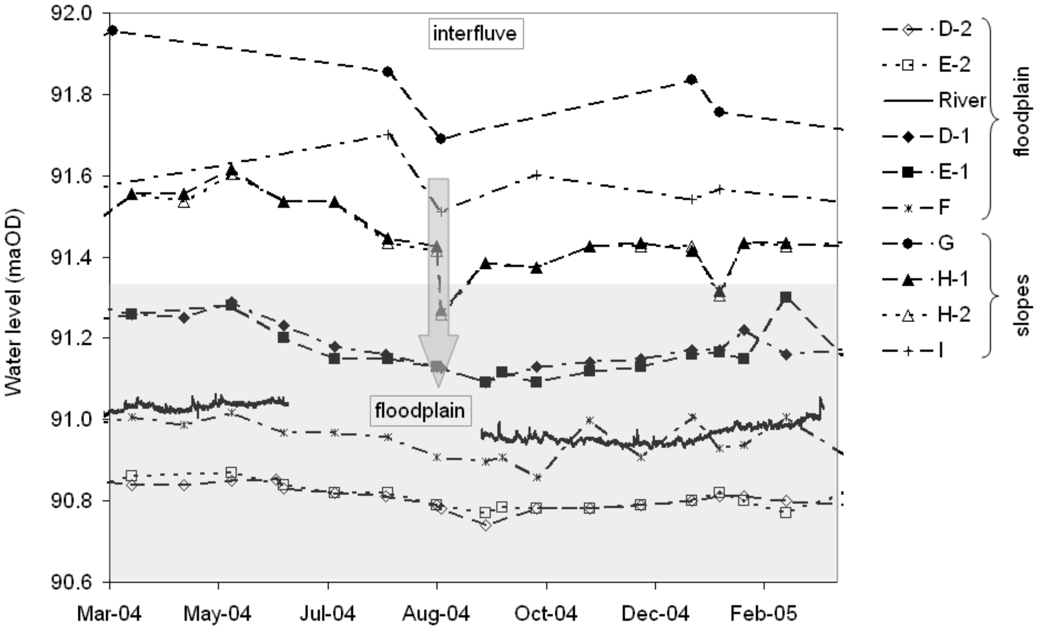

Fig. 2 Water levels along transect 1 (N–S, from interfluve to flood plain).

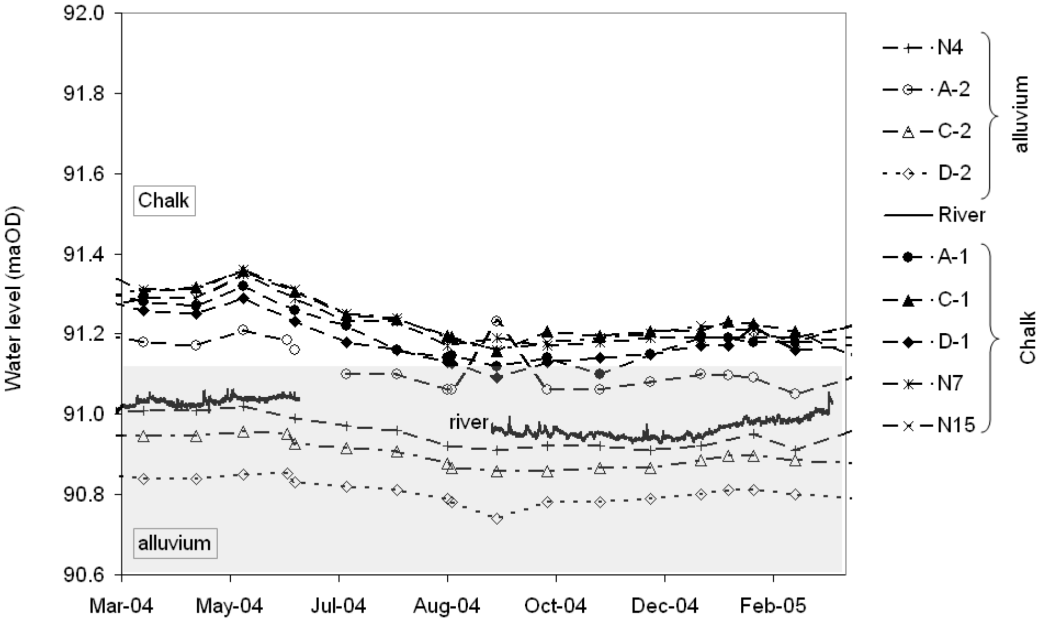

Fig. 3 Water levels along transect 2 (E–W, in flood plain parallel to river).

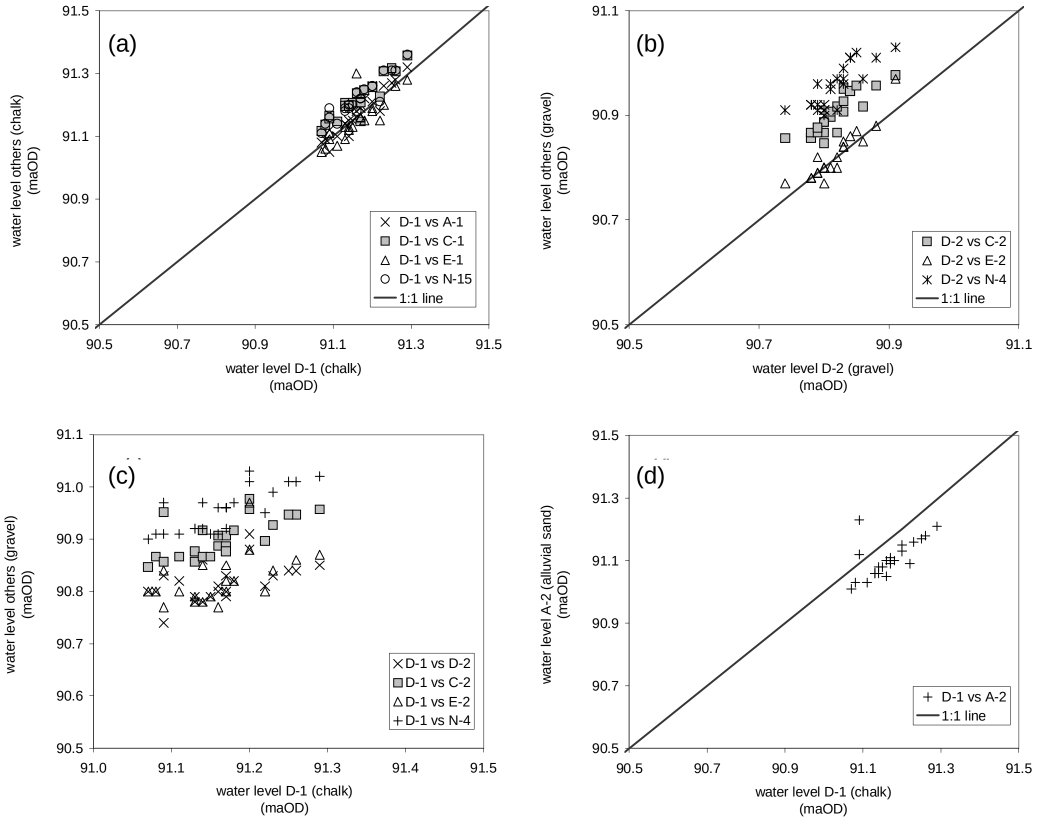

Fig. 4 Interrelationship between water levels at study site.

The proxy river level falls within the upper range of the alluvial groundwater levels (Fig. 3) suggesting that the river is broadly in hydraulic contact with the alluvial gravels. There are consistent water level differences within the gravels with water levels declining in the direction of river flow from N4 to D2. The gradient within the gravels is considerably steeper than the average gradient of the river at the site (estimated from upstream and downstream stage measurements). This suggests that the connection between the gravels and the river is not continuous and implies that areas of little or no connectivity exist along the river (parallel to transect 2), although the head variation may also reflect variation in transmissivity in the gravels.

Amendments to the head measurements resulting from a recent survey mean that the above findings differ from the previous conclusions of Wheater *et al.* (2006, 2007) who suggested that the connectivity between the gravels and the river at the study site is uniformly poor.

Geochemistry

Concentrations of selected elements are plotted against time in Fig. 5. For clarity, the data have been plotted separately for transect 1 and transect 2 and river concentrations are given in each graph for reference.

The dominant major elements, such as Ca, as well as HCO_3 (not shown) in the groundwater display little variation and are typically higher than in the river. Concentrations in the gravels are similar to those in the underlying Chalk, although, at times concentrations are lower and more similar to those in the river. The lower concentrations coincide with higher water levels in the boreholes, suggesting dilution of groundwater at high flows. The relationship (not shown) is more obvious for HCO_3 than for Ca, which also shows very high concentrations (greater than those in the Chalk) in the gravels near the farm (Fig. 5(a)), thus indicating that Ca sources additional to bedrock weathering exist in the catchment (probably inputs from adjacent farm).

Chloride concentrations are generally higher in the river than in both the gravel and the Chalk groundwater. However, in the boreholes near the farm (N4, N7, N15), Cl concentrations in both the gravels and the underlying Chalk are higher than in the river. Similar trends were observed for Na and K (the latter is only high in N4) and are interpreted as originating from the adjacent farm (Wheater *et al.*, 2006), which also affects the groundwater chemistry in borehole C. High Cl, K and Na concentrations are also present in the boreholes E and F, located in the wetland south of the river. This is probably related to a different source, possibly from horse manure tips upslope of the site.

Sulphate concentrations are significantly different in the gravel and in the Chalk groundwater (Fig. 5(c)). Concentrations in the gravels are >10 mg L^{-1}, similar to those in the river (range 9.48–10.6 mg L^{-1}, median 12.3 mg L^{-1}), and increase with increasing water level. Conversely, SO_4 concentrations in the Chalk are <10 mg L^{-1} (except for N15) and show little correlation with water levels in the boreholes. In the boreholes close to the farm (N4, N7, N15 and C2), and also in the shallow wetland borehole (E2), SO_4 is often higher than in the river. While these high concentrations are attributed to point source inputs from the farm and manure tips (Wheater *et al.*, 2006) it is obvious that SO_4 inputs must also be derived from diffuse sources, as indicated by its different behaviour compared to Na, K and Cl as well as by the good (positive) correlation with nitrate (NO_3-N). Nitrate concentrations in the Chalk groundwater are generally lower than in the river and in the gravels, but display similar seasonal trends in all boreholes implying that there is a similar source (although not necessarily a similar flow path) regardless of the depth of the unsaturated zone. Nitrate concentrations increase with rising water levels in all boreholes, but the trend is more pronounced in the gravels.

Atmospheric tracers

The concentrations of CFCs and SF_6 in the groundwater are given in Table 1 for the October 2004 sampling survey together with the calculated concentrations for modern air saturated water (ASW) at 10°C. The data show that all groundwater samples have a CFC-12 and SF_6 concentration below modern atmospheric concentrations, while some of the CFC-11 concentrations are above or close to modern. In the river, both CFC-12 and CFC-11 concentrations are greater than modern, hence providing a potential tracer for river water/groundwater exchange. River concentrations for SF_6 are close to atmospheric equilibrium within the error of the measurement.

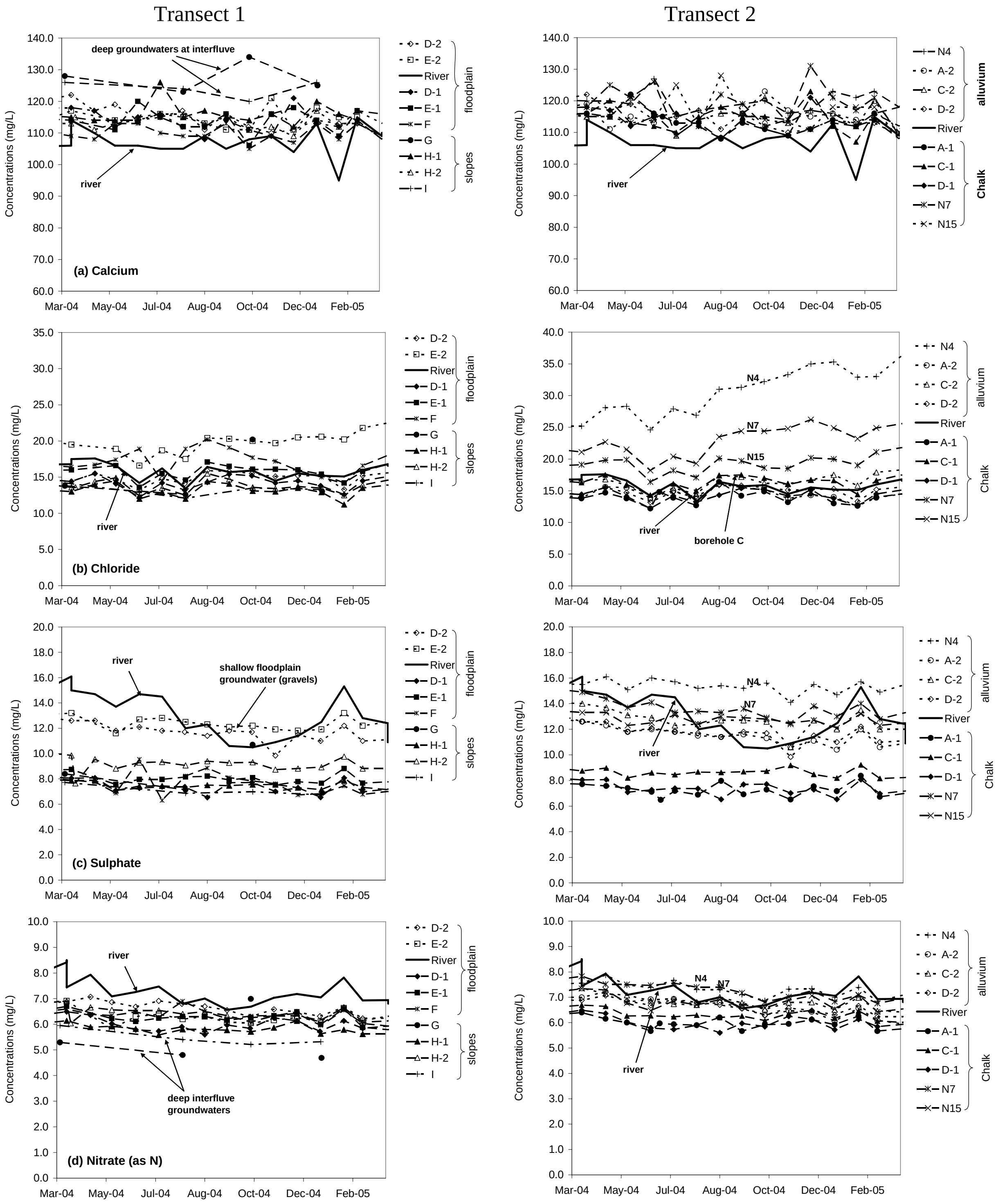

Fig. 5 Distribution of Ca, Cl, SO_4 and NO_3-N in the groundwaters of transect 1 and transect 2.

The data suggest that the groundwaters in the deep boreholes near the interfluve do not contain a modern recharge component and have been recharged between 16 years (1988) to 23 years (1984) ago (calculated from SF_6 and CFC-12 data, Gooddy *et al.*, 2006). In contrast, the deeper groundwater, mid-slope between the river and the interfluve (H1, H2) shows mixing of an older groundwater component (from upgradient) with more recent (modern) recharge (Gooddy *et al.*, 2006). The mixing proportion of the modern component increases in the flood plain and the chemical signature of the gravel groundwaters indicates the presence of a river component (higher CFC-11 concentrations) although this varies with time. In the piezometers at site A2 (sand above chalk), CFC-11 concentrations are generally smaller than in the gravels or in the river and similar to mid-slope Chalk groundwaters (borehole H), suggesting that interaction with the river is limited and that mixing with Chalk groundwater and modern recharge predominates. The CFC data also show that there is a "river component" (higher CFC-11) in the Chalk groundwater beneath the gravels, suggesting that surface water–groundwater interactions are not restricted to near-surface horizons.

Table 2 CFC-12, CFC-11 and SF6 concentrations for transect 1and 2 measured in October 2004 at the study site (ASW = modern-air saturated water).

	Transect 1 (N-S)				**Transect 2 (E-W)**		
Piezometer	**CFC-12** pmol/L	**CFC-11** pmol/L	**SF_6** fmol/L	**Piezometer**	**CFC-12** pmol/L	**CFC-11** pmol/L	**SF_6** fmol/L
I1	3.26	3.17	1.11	N15	2.51	5.37	0.88
I1	3.48	3.37	1.30	N4	2.59	6.19	1.00
G	1.83		2.50	N7	2.63	4.78	1.10
H2	2.63	4.85	0.86	C2	2.61	4.88	1.00
H1	2.84	4.43	1.22	C1	2.70	6.21	1.35
D2	2.63	4.88	0.93	D2	2.63	4.88	1.11
D1	2.50	5.43	0.45	D1	2.50	5.43	0.86
River	4.03	8.97	0.85	A2	2.58	4.00	2.63
E2	2.45	5.07	0.97	A1	2.51	4.10	1.54
E1	2.45	5.59	0.64	River	4.03	8.97	2.50
F	2.23	5.78	0.62				
ASW at 10ºC (calculated)	2.97	5.40	2.30				

DISCUSSION AND CONCLUSIONS

The groundwater head measurements in the Chalk piezometers along transect 1 indicate a component of regional flow (N–S) with a shallow hydraulic gradient towards the river. Near the river (transect 2), where alluvium (mostly gravels) overlies the Chalk, a local flow system is observed. Here, the high upward gradient beneath the flood plain suggests groundwater discharge from the Chalk into the gravels, although significant exchange between the gravels and the Chalk at the study site is unlikely, as indicated by the consistent difference in water levels. The poor connectivity to the Chalk may be due to the presence of heavily weathered chalk beneath the gravels, but "windows" of better connectivity exist where alluvial sands (rather than gravels) are present (Wheater *et al.*, 2006). The gravels appear to be broadly in hydraulic contact with the river, but postulated head differences between the gravels and the river suggest local variability in the connection between the gravels and the river. The question of where and how the gravels are connected to the river is not yet clear as the lack of appropriate river level data at the study site (at the time of writing) prevented a definite assessment.

The differences in hydraulic head within the gravels suggest a component of hydraulic gradient parallel to the river, although it is unclear if and how much flow occurs. It is also likely that these head differences are due to poor connectivity within the gravels caused by the presence of hydraulically unconnected gravel deposits and/or low permeability horizons within the gravels.

The hydrochemical data indicate a degree of heterogeneity in the groundwater composition at the study site, temporally as well as spatially. The chemical signature of the gravel groundwater is similar to the groundwater in the Chalk for determinands such as Ca, Mg and HCO_3 but the decrease in element concentrations with rising water levels suggest dilution of the gravel groundwater (Chalk component) at high flows, with a river component. For other determinands, such as SO_4 and NO_3, concentrations in the gravels are more closely related to those in the river and concentrations increase as water levels rise. Such behaviour again confirms that river water (high SO_4, NO_3) enters the gravels during periods of increased runoff although recharge of soil waters may also contribute to the observed signature.

The presence of a river component in the gravels is also evident from the atmospheric tracer (CFC, SF_6) data. High concentrations (>modern) of CFC-11 indicate that groundwaters near the river are influenced by recharge from the river (which contains above modern concentrations). The data suggest a three-component system for the gravels consisting of: (1) Chalk groundwater flowing towards the river, (2) direct rainfall recharge, and (3) river water. However, this simple mixing model cannot explain the hydrochemistry of the gravel groundwater near the farm where concentrations of elements such as Na, Cl, K, SO_4 are often higher than in the river (component 3), the underlying Chalk (component 1) or the rainfall recharge (component 2). The high concentrations of these elements are likely to be associated with the nearby farm, probably from animal waste or fertilizer storage. This affects elements such as Ca and Mg (usually associated with bedrock sources/weathering) and possibly also NO_3 and SO_4 (mostly associated with diffuse river/catchment inputs), hence complicating the interpretation of the hydrochemical pattern. At the same time, however, the contamination, in particular the high Cl concentrations, provides a good tracer for groundwater movement. It indicates that a flow pathway exists from the surface into the gravels and into the underlying Chalk, and also implies a longitudinal (i.e. parallel to the river) component of groundwater movement in the gravels and in the underlying Chalk.

The above findings are important as it is implied that the exchange of surface water and groundwater is not restricted to near-surface horizons, but also affects the underlying Chalk groundwater. These interactions are governed not only by the Chalk/river connectivity, but also by the superficial geology. In particular, the presence and lithology of the alluvial gravels and sands is important as this determines where recharge/discharge areas (and hence interaction between the river, the gravels and the Chalk) occur. The findings also suggest that the gravels, as well as the underlying Chalk provide a lateral pathway for groundwater flow down-valley (parallel to the river). This is particularly important from the perspective of pollutant transport and broadens previous conceptualisations which refer to the gravels only as a potential conduit of down-valley groundwater flow (Griffiths *et al.*, 2006).

The sampling period spans low recharge conditions during the winter of 2004 and even lower in winter 2005. Hence, the system response at high recharge conditions and high groundwater heads is still unknown. Such information is increasingly important if we are to understand the response of such catchments to future climate change. Prolonged periods of above average precipitation produce high groundwater levels and as a result, flow pathways and connectivity between the Chalk, the alluvial gravels and the river may change, as suggested by Mullinger *et al.* (2007) and Grapes *et al.* (2006). It is, therefore essential that monitoring at the site is continued to include a range of high and low recharge conditions, as well as more intensive rainfall-event monitoring in order to better understand the temporal dynamics of surface water–groundwater exchange at the study site.

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