
Interaction between groundwater, the hyporheic zone and a Chalk stream: a case study from the River Lambourn, UK

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Abstract Understanding the processes controlling groundwater/surface-water interaction is essential for effective resource management and for protecting sensitive ecosystems. Through intensive monitoring of Chalk groundwater, shallow gravel groundwater and surface water in the River Lambourn, UK, using a combination of hydrochemical and hydrophysical techniques, a complex pattern of interactions has been elucidated. The river is broadly in hydraulic contact with the streambed sediments and adjacent gravels and sands, but these deposits are mainly hydraulically separate from the underlying Chalk at the site. The hydraulic relationship between the river and underlying alluvium is variable, involving components of groundwater flow both parallel and transverse to the river and with both effluent and influent behaviour seen. While the gravel aquifer is significant in controlling groundwater/surface-water interaction, its importance as a route for flow down the catchment is likely to be modest compared with river discharge. The hydrological complexity revealed in a geological setting typical of lowland UK Chalk streams has implications both for investigation methods and for management such as in the setting of environmental objectives in the European Water Framework Directive.

Keywords Groundwater/surface-water interaction · Hyporheic zone · Potentiometric head · Chalk · Water quality · UK

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Introduction

The importance of groundwater–surface water (GW–SW) processes has been appreciated for some time (Winter et al. 1998). Understanding such processes is important for a number of reasons which may vary depending on the hydrology, landuse, ecological sensitivity and management of a particular system: to determine the sustainable limits of abstraction in a water sensitive system (Cook et al. 2003); to understand the hydrological function of the river plain during extreme events (Krause and Bronstert 2007); to assess the function of the riparian zone in regulating biogeochemical processes (Hill 1996; Lapworth et al. 2008).

Historically much GW–SW process work in the UK has focussed on upland catchments (e.g. Soulsby et al. 2002); however, there has been a growing focus on the hydrological function of permeable aquifers (Wheater and Peach 2004) due in part to a lack of fundamental understanding of GW–SW processes in these systems and the increasing management pressures on lowland aquifers. The Chalk is an important European aquifer and occurs in a number of countries around the North Sea, namely the UK, France, Belgium, the Netherlands, Germany, Denmark and Sweden. It forms the most important groundwater resource in the UK and the contribution to river flow from groundwater in Chalk catchments is very significant, in some cases as high as 95% (Sear et al. 1999) sustaining river flow even during periods of reduced rainfall. An understanding of the mechanisms of GW–SW interaction in these catchments is therefore important for the management of both the surface and groundwater systems. A greater understanding of GW–SW process is also required in light of the European Water Framework Directive (Council of European Communities 2000), which demands that all surface water bodies achieve targets for good chemical and ecological status and necessitates a holistic approach to the management of catchment hydrology. Recent studies have highlighted the complexity of GW–SW processes both in terms of spatial scales and temporal variability (Krause et al. 2007; Grapes et al. 2005; Griffiths et al. 2006) and have shown that the traditional classification of a particular river reach as either gaining or losing are over-simplistic.

There are a range of approaches available to understand GW–SW processes, including hydrochemistry (Tetzlaff and

Soulsby 2008; Mencio and Mas-Pla 2008), fluorescence properties of organic matter (Lapworth et al. 2009), colloidal transport (D.J. Lapworth, British Geological Survey, unpublished data, 2009), physical parameters, e.g. temperature and potentiometric heads (Keery et al. 2007; Schmidt et al. 2007; McGlynn et al. 1999), and process oriented modelling approaches (Krause et al. 2007). Each of the methods have advantages and drawbacks which can often be site specific, so choosing the best method(s) for a particular site is not straightforward. In most situations, a combination of several techniques is required to understand the complex hydrological processes. The present paper provides a unique data set for a lowland Chalk catchment using both hydrochemical and potentiometric head data to investigate interaction between groundwater and surface water. The paper focuses on the mixing processes between shallow piezometers directly beneath the stream and shallow piezometers adjacent to the stream within the framework of a conceptualised regional groundwater flow model.

Study site and geological setting

The study site is located in rural Berkshire at Boxford on the River Lambourn (Fig. 1). This is a predominantly groundwater-fed river, with a baseflow index of 0.96 (Marsh and Hannaford 2008), which drains part of the Chalk of the Berkshire Downs in the southern UK. The river rises near to

the town of Lambourn and flows in a south-easterly direction to join the River Kennet at Newbury. The Kennet then flows generally eastwards to join the River Thames. The Lambourn exhibits bourne (seasonal) behaviour in its upper reaches and, near to its junction with the Kennet, has a mean flow of $1.73 \text{ m}^3/\text{s}$ (Marsh and Hannaford 2008). It is known that the River Lambourn, in common with a number of other Chalk rivers does not gain or lose uniformly over its length (Grapes et al. 2005) but tends to accrete flow over distinct sections, probably resulting from groundwater flow through discrete fractures or fracture systems.

The study site was developed from a previous observation site set up as part of the Lowland Catchment Research (LOCAR) programme (Wheater and Peach 2004). It is located 12.75 km downstream from the source of the river at Lynch Wood, Lambourn. A number of boreholes were drilled during the LOCAR investigations and these have been subsequently added to.

A detailed account of the geology of the Pang-Lambourn catchment is given by Aldiss and Royse (2002). Briefly, the catchment comprises Chalk (Upper Cretaceous) underlain by a thin layer of Upper Greensand (Lower Cretaceous) in hydraulic continuity, and sealed beneath by mudrocks of Jurassic age. The Chalk is overlain by Palaeogene deposits and superficial drift from the Quaternary.

The River Lambourn flows SE along a mostly linear, possibly joint-controlled, valley incised into the Chalk of the Berkshire Downs (Fig. 1). The Boxford site is located

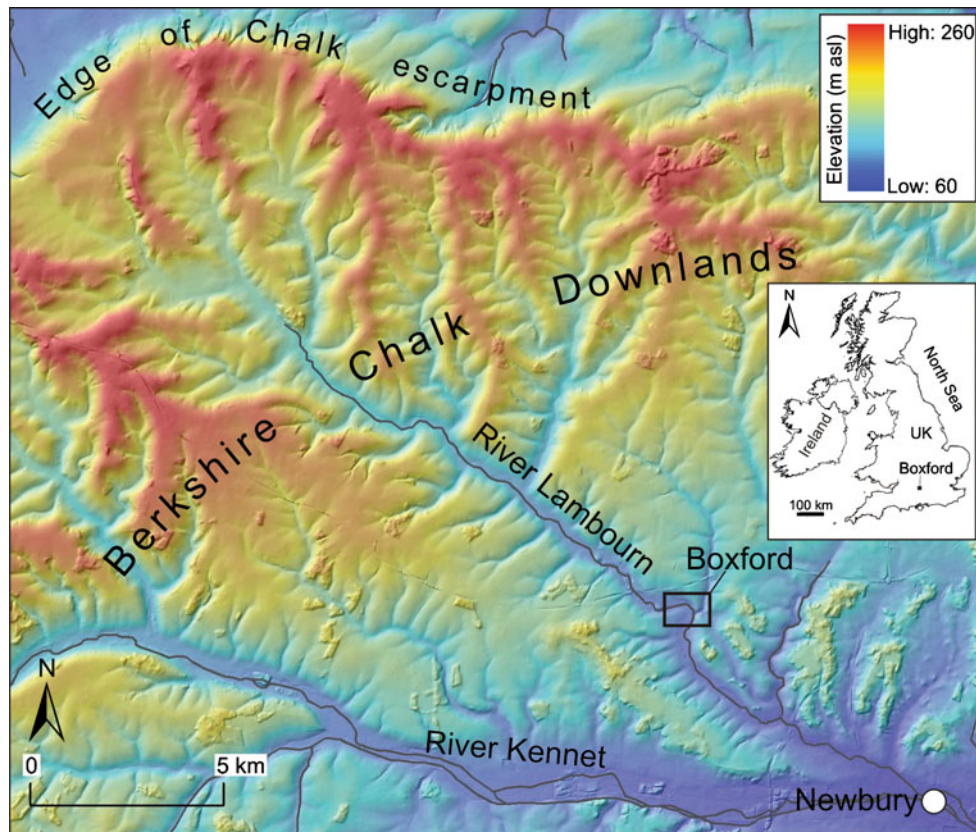


Fig. 1 Location of the Boxford area, UK (NEXTMap Britain elevation data from Intermap Technologies. OS data ©Crown Copyright. All rights reserved. BGS 100017897/2009)

in the lower part of the River Lambourn at one of two conspicuous valley bends (Fig. 2). The Chalk Group ranges up to 242 m thick in the Berkshire Downs and dips at 1–2° SE away from the steep escarpment which marks its northern boundary. A range of Quaternary and younger superficial deposits partially cover the Chalk including clay-with-flints on interfluvial and river terrace deposits, head and alluvium on valley floors.

At Boxford, the River Lambourn is cut into the Seaford Chalk Formation (Upper Chalk), a uniform soft-to-medium-hard Chalk with many flint nodules and a few laterally continuous tabular flints and clay-rich Chalks (Fig. 2). Chalk bedding dips at low angles (1–2°) across the river valley from NW to SE. Boreholes drilled at the site along the northern margin of the valley show that the River Lambourn and its floodplain is separated from the Chalk by up to 7.5 m of river terrace deposits and alluvium (Fig. 3). Such river terrace deposits and alluvium are common in Chalk valleys.

River terrace deposits are primarily coarse-grained gravels with typically 50% of clasts ranging from 25–100 mm in size. Sand, silt and clay do not generally comprise more than 5% of the deposit, although locally thin beds of sandy gravel are developed. The gravels are typically 3–4 m thick, although there is local thickening (e.g. borehole C) and thinning (e.g. N15) which suggests an irregular erosion surface on the top of the Chalk (Fig. 3). The gravels are composed predominantly of rounded flint clasts; however, the basal 1–2 m often includes a high proportion of reworked Chalk material which may have been incorporated into the river terrace deposits during downcutting and erosion. The Chalk clasts are often highly degraded and may have a significant hydrogeological impact by occluding porosity and significantly reducing the permeability of the gravels adjacent to the underlying Chalk. In addition, the upper part of the Chalk is commonly of a structureless ‘putty’ type

which also is likely to have low permeability. In the subsequent hydrogeological discussion, the term ‘gravels’ is used to encompass the arenaceous, mainly coarse-grained, lithologies forming the river terrace deposits. The hydraulic conductivity of the gravels, estimated using the Hazen formula (Freeze and Cherry 1979) from grain-size data obtained from borehole X (Fig. 3), ranges from 200 to 7,800 m/day, with the coarsest gravels giving values of 4,600 and 7,800 m/day.

The alluvial cover on the underlying gravels ranges up to 2.7 m thick and comprises a mosaic of peat, clay, silt, sand and gravel generally intermixed in variable proportions. Laterally, the alluvium merges with clay-rich head and slope-wash deposited on the valley flanks. The transmissivity of the unconfined Chalk aquifer in the Berkshire Downs is considered to decrease from around 2,000 m²/day in valley bottoms to around 50 m²/day under interfluvial, with storage coefficients of around 0.015–0.03 in the valleys and around 0.005 under interfluvial (Allen et al. 1997).

In the catchment, the Chalk matrix porosity generally decreases linearly with depth from about 45% near ground surface, to less than 25% at 100 m bgl (below ground level). This is consistent with previously reported depth trends in Chalk matrix porosity (Bloomfield et al. 1995) and reflects the diagenetic grade and maximum burial depth of the Chalk. Variations from this overall trend reflect primary lithological variations such as the presence of marls and hardgrounds.

Investigations at the study site

Site instrumentation

The site has been studied principally by means of piezometers emplaced in purpose-drilled boreholes, mainly on the northern bank of the river (Fig. 4). Open boreholes have also been used and, in addition, several

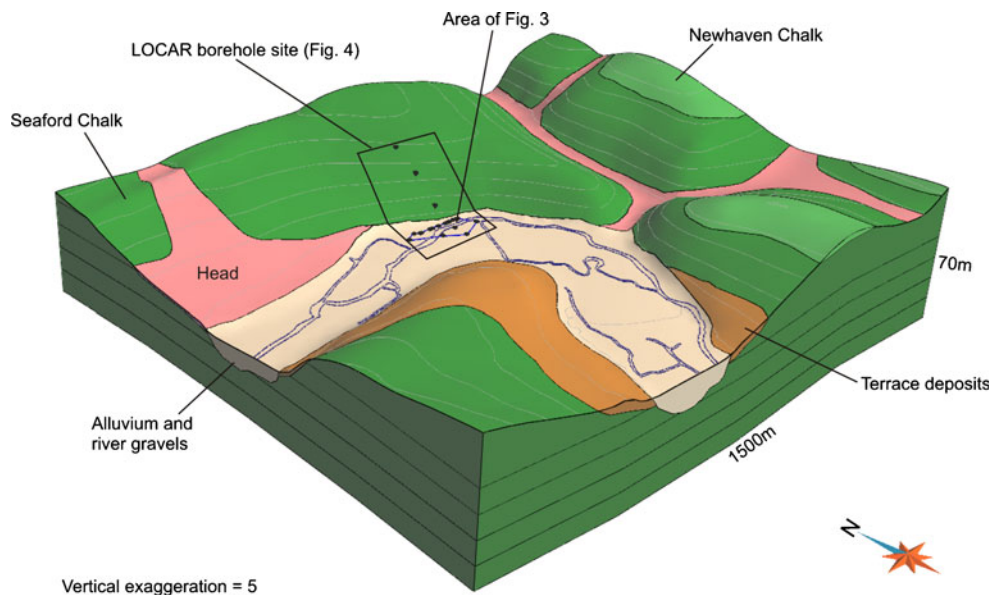


Fig. 2 Boxford area block geology (NEXTMap Britain elevation data from Intermap Technologies. OS data ©Crown Copyright. All rights reserved. BGS 100017897/2009)

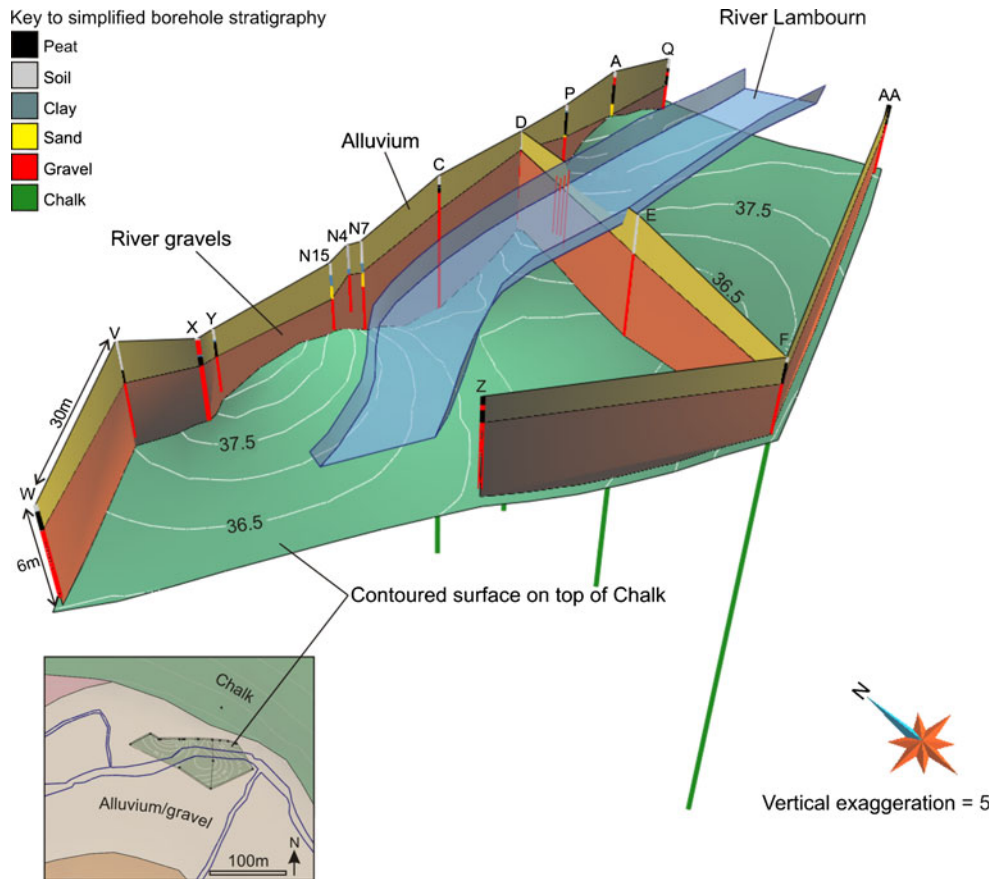


Fig. 3 Boxford research site geology (from Allen and Allen 2008). OS data ©Crown Copyright. All rights reserved. BGS 100017897/2009. Borehole sites labelled A, AA, C, etc

piezometers have been emplaced directly into the river bed. Borehole drilling and piezometer emplacement was carried out at various times between 2002 and 2008. Prior to 2005, all installations, and the data obtained from them, were part of the NERC LOCAR thematic research programme. Details of the installations are given in Table 1. The piezometers and boreholes were completed either in the Chalk aquifer or in the overlying alluvial sands and gravels. At a number of locations, piezometers were emplaced in both units, and, in several cases, multiple piezometers were installed in the Chalk at different depths (or the borehole annulus was used).

Groundwater heads at the study site were monitored by directly dipping water levels and in many cases by using TROLL or Diver pressure loggers installed in the piezometers or open boreholes. For a number of piezometers, data are available from late 2002 to 2008.

Water sampling and analysis

Table 1 lists the sampling sites (piezometers and river samples), response zones for the piezometers and the relevant lithology. Sampling for chemical analysis was carried out at the study site in two separate phases, the first entailing sampling on a variable basis at intervals from 1 to 6 months between October 2003 and March 2008, and

a second phase of fortnightly sampling between June 2007 and May 2008.

Groundwater samples were collected using a submersible pump following prolonged purging. Unstable parameters (dissolved oxygen, pH, alkalinity, redox potential and specific electrical conductivity) were measured on-site in flow cells and allowed to stabilise prior to measurement. Samples for inorganic chemical analysis were filtered through a 0.45- μm cellulose nitrate membrane into sterile containers and stored refrigerated in the dark. An aliquot of sample was acidified (1% vol/vol) with nitric acid (Aristar grade) for cation analysis.

Hydrochemical analysis was carried out by ion chromatography (for anions), and inductively coupled plasma-optical emission spectroscopy (ICP-OES) for cations. All inorganic analysis was verified using the AQUACHECK (Aquacheck Ltd) inter-laboratory proficiency-testing scheme.

Results: physical hydrogeology

In boreholes where multiple piezometers were installed into the Chalk (Table 1), the measured hydraulic heads did not indicate a clearly discernable vertical head gradient within the aquifer. Therefore, to a first approximation, potentiometric values from a single Chalk piezometer at

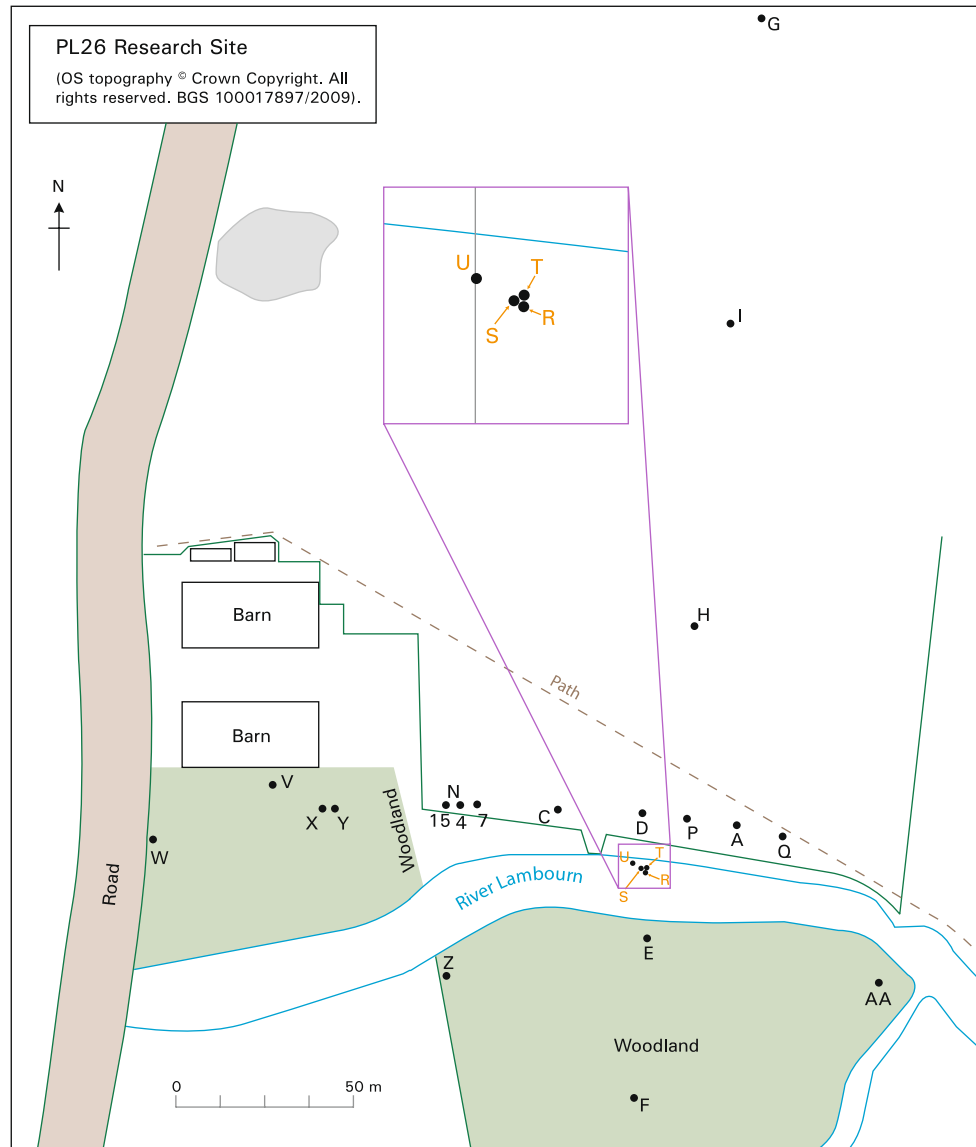


Fig. 4 Boxford research site borehole and piezometer location map. Borehole sites labelled in *black*, river piezometers (*R,S,T*) and river stilling well (*U*) labelled in *orange*

any depth are taken to represent the potentiometric state of the Chalk aquifer at that location (at least over the depth range of the investigation). Using this assumption, the horizontal components of flow in the Chalk may be assessed from the piezometer data. Chalk head data are mainly available along a N–S transect running across the river from borehole G in the north to borehole F to the south (a distance approaching 250 m). Figure 5 illustrates piezometer and borehole water levels along the transect on a number of occasions, varying from drought conditions (July–August 2005) to a period of high groundwater level (May 2008). The data indicate a southerly groundwater gradient, and therefore a component of Chalk groundwater flow, both towards the river, and continuing beyond, to the south. The hydraulic gradient increases with increasing head, but is not uniform over the section, tending to flatten in the vicinity of the river and to steepen over the southernmost portion. Chalk heads around the river are significantly higher than

the level of the river surface (ranging up to about 0.3 m during wet periods), suggesting a lack of hydraulic continuity between the aquifer and the river. Data from Chalk piezometers and boreholes away from the N–S section show an inconsistent spatial pattern, probably because of the limited spread of such installations along the bank. Temporal head variations increase away from the river to the north; the total range over the monitored period (from daily average data) increases from around 0.8 m in borehole C near to the river to 1.4 m at borehole G.

The regional gradient of the potentiometric surface of the Chalk aquifer in the Lambourn Valley around the study site is broadly to the south east, i.e. along the line of the valley and has a value of around 0.0035 at low groundwater levels (August 1976 data). The component of Chalk hydraulic gradient measured along the N–S transect generally varies between 0.003–0.004, depending on groundwater level and thus is broadly consistent with the regional value.

Table 1 Boxford research site installation information

Site ID	Installation type	Year completed	Response zone (m bgl unless indicated)	Lithology
Gravel groundwaters				
PL26A2	Piezometer	2002	wt-1.78	Sand
PL26C2	Piezometer	2002	wt-4.8	Gravel
PL26D2	Piezometer	2002	wt-3.8	Gravel
PL26E2	Piezometer	2002	wt-4.7	Gravel
PL26N4	Borehole	2003	2.66–3.63	Gravel
PL26P	Piezometer	2007	1.6–3.3	Gravel/sand
PL26Q	Piezometer	2007	1.4–2.5	Sandy gravel
PL26V	Piezometer	2008	2.30–5.30	Gravel
PL26W	Piezometer	2008	1.50–5.56	Gravel
PL26Y	Piezometer	2008	1.50–3.55	Gravel
PL26Z	Piezometer	2008	1.50–5.90	Gravel
PL26AA	Piezometer	2008	1.00–3.58	Gravel
Chalk groundwaters				
PL26A1	Piezometer	2002	13.2–25.0	Chalk
PL26C1	Piezometer	2002	11.4–25	Chalk
PL26D1	Piezometer	2002	10.7–25.35	Chalk
PL26E1	Piezometer	2002	11.15–25.2	Chalk
PL26F	Borehole	2002	10.86–34.0	Chalk
PL26G1	Piezometer	2002	50.5–100.0 ^a	Chalk
PL26G2	Piezometer	2002	27.63–48.5 ^a	Chalk
PL26G3	Annulus	2002	18–26.5	Chalk
PL26H1	Piezometer	2002	25.03–30.0	Chalk
PL26H2	Piezometer	2002	20.0–24.0	Chalk
PL26H3	Annulus	2002	2.2–19.0	Chalk
PL26I1	Piezometer	2002	39.4–52.3	Chalk
PL26I2	Piezometer	2002	30.0–35.0	Chalk
PL26I3	Annulus	2002	15.0–29.0	Chalk
PL26N7	Borehole	2003	6.9–7.83	Putty Chalk
PL26N15	Borehole	2003	6.6–15.4	Chalk
PL26X	Piezometer	2008	6.3–9.7	Chalk
River bed groundwaters				
PL26R	Piezometer	2007	0.4–0.6 ^b	Gravel
PL26S	Piezometer	2007	1.4–1.6 ^b	Gravel
PL26T	Piezometer	2007	2.4–2.6 ^b	Gravel
Surface waters				
R. Lambourn	Stilling well	2007		

wt water table

^a Seal between PL26G1 and PL26G2 probably breached

^b Metres below river bed

These data suggest, therefore, that groundwater flows in the Chalk at the site probably follow the regional NW–SE trend, but apparently have little interaction with the river (either directly, or via the intervening gravels). After flowing under the river, such groundwaters presumably continue

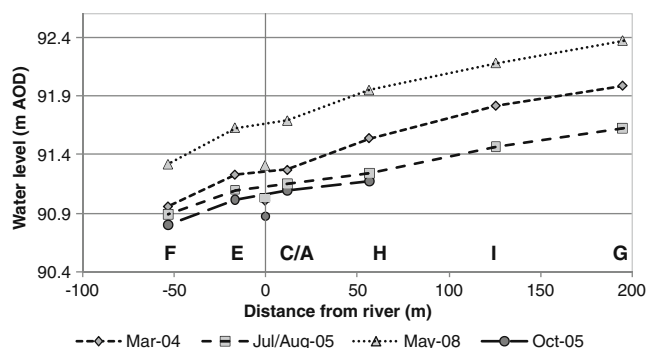


Fig. 5 Chalk potentiometric levels along N–S transect between boreholes *G* and *F*. Piezometer C1–A1 average used because D1 was not reliable at high heads. River is at zero line with river level indicated (2005 river levels are approximate)

along the valley bottom, rising to recharge the overlying alluvium or entering the stream further down the valley. It may be noted that the disparity between the Chalk groundwater flow direction and the direction of river flow at the site is a result of the location of the study site on a bend in the river, thus the W–E direction of river flow is a local variation in the general NW–SE flow of the River Lambourn.

The flattening of the hydraulic gradient in the vicinity of the river could imply an increase in permeability in the Chalk under and near to the river; or, alternatively, leakage from the Chalk towards the river. Given the high head difference between the Chalk and the river, the former explanation is currently considered to be the most likely. This would be consistent with the common perception of high Chalk transmissivities under valleys (Allen et al. 1997)

Heads in the gravels are consistently lower than those in the underlying Chalk (Abesser et al. 2008) and tend to have a smaller to similar range of variation. Figure 6 illustrates head variations in paired piezometers in the gravels and the underlying Chalk at the site for two periods; during a drought and in a wet period. Also shown

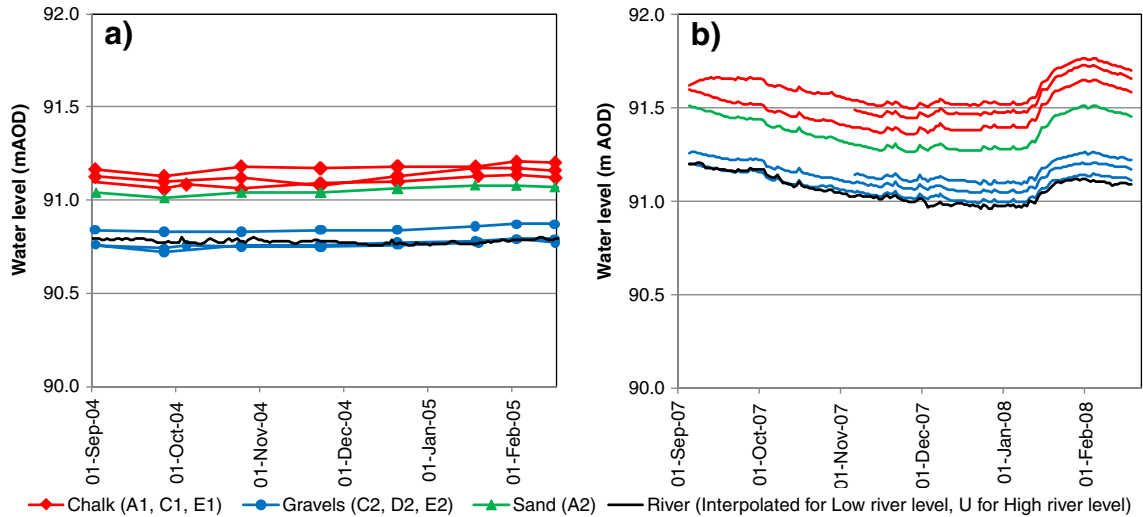


Fig. 6 Head variations in river bank piezometers at the study site for periods of **a** low and **b** high river level

are river levels; levels taken from the stilling well U are shown for the wet period and a surrogate level, obtained as an average of upstream and downstream measurements, is used during the earlier drought period when there was no stilling well at the study site. The data indicate that hydraulic heads in the gravels are lower than those in the underlying Chalk at the site, during both wet and dry periods, with differences commonly of the order of 0.3–0.4 m, implying that there is generally poor hydraulic connection between the gravels and the underlying Chalk in the vicinity of the river. An exception, however, is borehole A, where no gravels are present and the Chalk is overlain by sand. Heads in a piezometer emplaced within the sand (A2), while lower than those in the underlying Chalk, tend to follow the Chalk heads more closely than at other locations.

Figure 7 shows gravel heads measured in piezometers at a time of high groundwater levels (13 May 2008). On the north bank of the river, the values tend to decrease with proximity to the river and, generally, downstream, suggesting that there are groundwater flow components in these directions. Values on the southern bank also decrease downstream. However, the pattern of the

hydraulic head is somewhat complex; for example, the area of anomalously high gravel head associated with borehole A is also seen to affect borehole Q. The reason for this anomaly is unknown, but given the shallow depth to Chalk at borehole A, it is considered likely that upflow from the Chalk to the overlying sediments occurs in the vicinity of this borehole. It is also possible that the gravel body to the east of borehole A is hydraulically separate from the gravels to the west and from the river to the south, given the differences in head. Figure 7 has not been contoured since this would imply a contiguous potentiometric surface, which has not been established.

The hydraulic relationship between the river and the adjacent and underlying gravels can strictly only be compared for piezometers close to the river stilling well, given that the river level gradient is not known in detail. Figure 7 indicates that on the northern bank, gravel heads adjacent to the river near to the stilling well (piezometers C2, D2, P) are all slightly higher than the river (of the order of 50 mm), while on the southern bank, piezometer E2 is at a similar head to the river. The figure also suggests that hydraulic heads in the piezometers below the river bed are similar to that of the river, with indications of a small

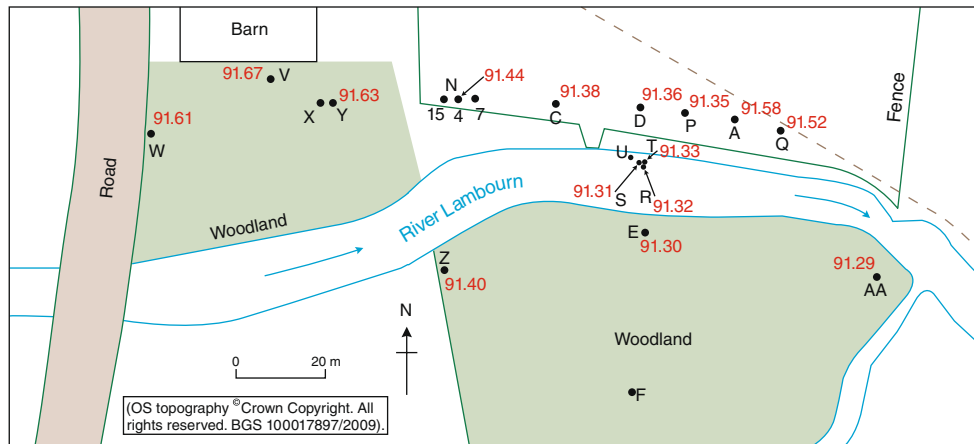


Fig. 7 Gravel groundwater levels at the research site on 13 May 2008 (southern section of Fig. 4). Levels are in red. The dashed line is the path

increase in hydraulic head with depth. To a first approximation, therefore, these data suggest that the river in this area has hydraulic continuity with the underlying and bank-side gravels (though as noted previously, this may not extend to the gravels penetrated by piezometer Q).

When river level time-series data from the stilling well (U) are compared with data from adjacent bank-side gravel piezometers (using daily pressure logger averages), it is seen that the gravels on the northern bank nearly always maintain a higher head than the river, implying southerly flow towards the river. In addition, for piezometers D2 and P, closest to the stilling well, there is a tendency for the gravel–river head difference to increase as river levels fall. Data from the gravel piezometer E2, on the southern bank of the river, shows a higher head (by a few centimetres) than the river at low river stages, but at high river levels, there is evidence that this gradient reverses, with gravel levels reaching a few centimetres below those in the river. Hydraulic heads in the northern bank gravel piezometer D2 and the southern bank piezometer E2 are generally similar, but there are indications of a small southerly head gradient, particularly at high groundwater levels.

The most direct indication of the hydraulic relationship between the river and the underlying gravels should be obtained from the river-bed piezometers R, S and T. Hydraulic head data from these piezometers are shown in Fig. 8 over the period May 2007 to February 2008. The figure indicates that heads generally increase in the order U–R–S–T; that is, in the order of increasing depth beneath the river and, thus, indicate the potential for upward flow. This is consistent with previous potentiometric measurements at shallow depths in the river bed (Pretty et al. 2006). There is some indication from the pressure logger data that the magnitude of the upward head gradient decreases with increasing river stage—a similar relationship to that observed in the bank-side gravel piezometers.

These observations from the river stilling well, the nearby gravel piezometers on the bank-side and in the river bed suggest complex hydraulic interactions between

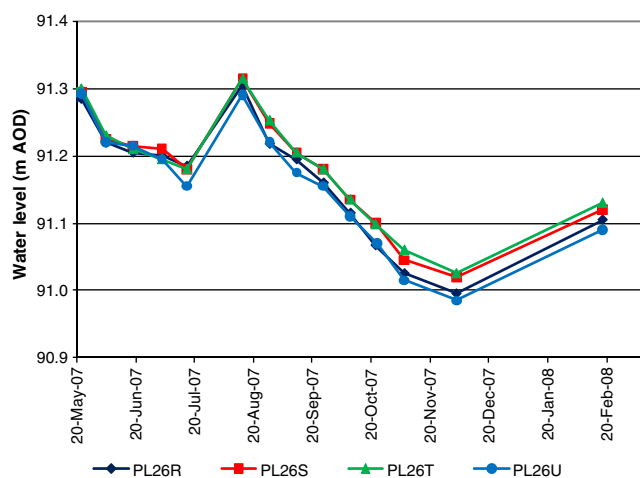


Fig. 8 Dipped water levels in gravel piezometers under the river (R, S, T) and in the river stilling well (U)

the gravels and the river. They imply that, at low river levels, the river tends to receive flow from the gravels on both banks, whereas at high stages, the river receives water from the northern bank only, while losing water to the gravels lying to the south. Upward flows occur within the gravels beneath the river and there is some evidence that these are greatest at low river levels, with a similar potential variation in bank-side inflows. What cannot be determined from the available evidence is the magnitude of these potential flows, since permeabilities, and particularly river-bed permeabilities, remain unknown. However, the indication that upward hydraulic gradients are greatest at low river levels might suggest that the gravel groundwater system is to a degree independent of the surface system, i.e. that bed permeability is low (compared to that of the gravels)

In addition to these groundwater/river interactions, the head data suggest that gravel groundwaters in the area of the stilling well also have a component of flow under the river in a southerly direction at high river levels. This is reasonable since the thickness of the gravel aquifer is not significantly reduced by the presence of the river.

Results: hydrochemistry

Three reservoirs of water with certain differences in hydrochemical quality exist at Boxford: the river, the gravels, and the Chalk. This allows possible hydraulic links between them to be examined in terms of binary or ternary mixing. These links are assessed in two ways: firstly by reviewing long-term data from boreholes containing gravel and Chalk piezometers pairs, and secondly by examining the more detailed record from the river-bed piezometers collected over the course of 1 year.

Long-term monitoring of the bank-side piezometer pairs and the River Lambourn

The basis of an overview of the long-term monitoring of gravel and Chalk piezometer pairs A, C, D and E between October 2003 and March 2008 is provided by Table 2. Concurrent data for the river are included. The table includes field-measured parameters and a range of major, minor and trace inorganic determinands. It also includes standard deviations and the maximum and minimum values noted for each determinand during the monitoring period. The standard deviations provide an indication of typical variation with time. This ranges from <5% for Ca and Mg, and generally <10% for the remainder of the major ions, although SO₄ is slightly more variable than the others. Maximum and minimum deviations from the average values range from <±10% of the average for Ca, usually <±10% for Mg, but up to +77/–45% for other major ions, and sometimes greater percentages for minor ions. The largest deviations from the mean tended to be shown by the maxima rather than the minima. The Chalk

Table 2 Summary of hydrochemical data from the Boxford riverbank piezometer pairs for the period 2003–2008, with data for the river, N boreholes and H1 (Chalk baseline) over the same period. Maximum and minimum values are provided. *av* average; *sd* standard deviation; *DO* dissolved oxygen; *SEC* specific electrical conductivity; *WT* water table

BH No.	Resp. zone m bgl	No. of samples	T °C	pH	DO mg/L	SEC µS/cm	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO ₃ mg/L	Cl mg/L	SO ₄ mg/L	NO ₃ -N mg/L	Si mg/L	Ba µg/L	Br µg/L	F µg/L	Pot µg/L	Sr µg/L
Gravel																				
A2 av	WT-1.78	38	11.0	7.04	7.87	601	117	1.87	8.28	1.01	302	14.9	11.2	6.46	8.10	39.5	53	138	38	293
A2 sd			0.8	0.07	1.20	55	4.4	0.08	0.56	0.20	12	1.1	1.2	0.42	0.32	10.9	15	18	11	20
A2 max			13.2	7.15	11.94	651	127	2.10	9.78	1.70	347	20.5	15.1	7.79	8.88	74.7	106	200	55	352
A2 min			9.8	6.83	4.38	299	106	1.68	7.13	0.79	277	12.6	9.0	5.56	7.39	25.4	28	99	20	257
C2 av	WT-4.8	24	10.7	7.09	8.27	618	116	1.83	9.61	0.98	299	17.5	12.7	6.87	8.24	19.2	54	125	39	301
C2 sd			0.68	0.05	1.27	27	4.1	0.06	0.54	0.05	13	1.8	1.0	0.28	0.37	1.2	13	15	14	16
C2 max			11.8	7.17	11.91	664	123	1.93	10.9	1.08	316	21.5	14.5	8.24	8.97	22.8	100	152	72	336
C2 min			8.1	6.94	4.82	566	108	1.61	8.58	0.80	259	13.9	10.6	6.35	7.60	17.4	28	97	20	272
D2 av	WT-3.8	38	10.7	7.09	8.54	603	116	1.80	8.73	0.93	295	16.1	11.4	6.61	8.31	20.4	49	133	37	295
D2 sd			0.53	0.07	1.10	20	4.0	0.04	0.38	0.06	10	1.2	1.3	0.31	0.33	2.0	10	22	11	20
D2 max			12.2	7.37	10.86	650	122	1.92	9.98	1.09	311	21.5	14.0	8.02	9.10	24.8	83	200	59	355
D2 min			9.0	6.95	4.75	574	107	1.70	8.11	0.82	268	13.2	6.3	5.97	7.60	16.5	33	97	17	249
E2 av	WT-4.7	24	10.5	7.10	7.28	630	115	1.90	12.3	1.24	302	22.4	12.2	6.46	7.94	28.0	53	135	33	300
E2 sd			0.50	0.07	1.63	27	4.9	0.09	1.66	0.23	38	4.2	1.1	0.36	0.34	12.1	11	22	11	15
E2 max			11.6	7.23	11.3	704	125	2.29	17.1	2.20	438	31.6	14.6	7.79	8.54	79.8	74	200	51	329
E2 min			9.4	6.92	2.17	570	104	1.76	10.8	1.04	192	16.6	11.6	5.82	6.82	20.9	30	100	13	272
Grand average			10.7	7.1	8.0	613	116	1.8	9.7	1.0	300	17.7	11.9	6.60	8.15	26.8	52	133	37	297
Chalk																				
A1 av	13.25–25	38	10.7	7.06	8.33	588	115	1.77	8.27	1.00	302	14.6	7.33	5.98	8.75	22.0	49	137	37	302
A1 sd			0.33	0.07	1.12	55	3.8	0.05	0.37	0.08	32	1.4	1.2	0.34	0.41	2.6	8	19	10	19
A1 max			11.5	7.22	12.1	647	122	1.87	9.17	1.37	323	16.4	8.5	6.40	9.64	28.7	71	200	57	363
A1 min			10.0	6.88	4.69	283	104	1.65	7.82	0.89	275	12.2	6.0	5.63	7.85	18.0	30	100	16	267
C1 av	11.4–25	24	10.7	7.10	8.15	602	114	1.80	9.28	1.02	296	16.9	8.77	6.30	8.85	20.0	61	134	38	308
C1 sd			0.50	0.05	1.32	25	3.8	0.05	0.39	0.06	12	1.5	1.3	0.39	0.39	1.8	10	22	9.3	17
C1 max			11.9	7.17	11.69	640	123	1.87	9.95	1.12	305	18.9	9.7	6.69	9.88	23.7	343	200	65	339
C1 min			9.8	6.96	4.22	553	105	1.62	8.54	0.87	266	14.3	8.1	6.01	8.15	18.8	20	100	14	272
D1 av	10.7–25.35	38	10.7	7.09	8.25	583	114	1.77	8.41	1.01	297	14.9	7.79	6.04	8.88	21.3	50	137	35	303
D1 sd			0.44	0.05	1.08	55	3.9	0.06	0.62	0.07	22	1.8	1.3	0.38	0.42	1.5	13	23	11	14
D1 max			11.7	7.24	10.7	635	121	1.86	9.13	1.15	315	16.4	10.0	6.49	9.60	26.1	82	200	52	344
D1 min			9.5	6.96	4.63	281	106	1.60	7.82	0.89	261	12.2	6.3	5.60	8.20	17.5	36	87	14	251
E1 av	1.152–25.2	24	10.4	7.10	7.99	601	114	1.78	8.85	1.03	295	16.2	8.15	6.20	8.83	20.0	48	133	39	300
E1 sd			0.48	0.07	0.99	24	4.0	0.06	0.35	0.05	7.9	1.6	1.2	0.42	0.50	1.3	13	20	13	16
E1 max			11.6	7.28	10.86	645	120	1.85	9.59	1.20	308	18.1	9.0	6.70	9.62	22.4	82	200	67	327
E1 min			8.9	6.93	6.33	576	106	1.63	8.22	0.87	204	13.6	7.2	5.79	8.10	16.7	25	100	16	281
Grand average			10.6	7.09	8.18	594	114	1.78	8.70	1.02	297	15.7	8.01	6.13	8.83	20.8	52	135	37	303
Others																				
River av		38	10.9	7.93	10.6	554	108	1.62	8.39	1.52	271	16.8	12.6	7.13	7.80	18.2	41	115	82	251
River sd			2.5	0.15	1.40	54	4.0	0.06	0.75	0.24	20	1.6	1.8	0.47	0.50	3.7	8	24	43	17
River max			15.1	8.28	14.0	611	115	1.75	10.4	2.30	292	21.4	17	8.42	8.84	33.6	59	200	277	295
River min			6.4	7.63	8.05	267	95	1.37	6.96	1.08	175	13.4	9	6.30	6.51	16.1	21	79	21	247
H1 av.	25.03–30	38	10.6	7.08	7.92	596	116	1.75	7.93	0.96	306	13.6	7.47	5.79	8.81	21.2	51	140	39	300
H1 sd			0.34	0.07	0.94	23	3.5	0.05	0.29	0.05	20.9	0.84	0.7	0.19	0.32	2.2	11	23	10	20
H1 max			11.8	7.25	9.51	640	126	1.87	8.64	1.13	327	15.3	9.7	6.32	9.62	28.6	73	200	57	364
H1 min			9.8	6.88	5.20	561	108	1.61	7.33	0.84	198	11.2	5.9	5.37	8.10	16.7	29	97	19	248
N4 av	2.66–3.63	26	11.0	7.07	7.67	677	120	2.04	15.5	2.43	303	32.0	15.4	7.35	7.97	23.0	60	132	41	313
N4 sd			0.70	0.05	1.09	30	4.2	0.051	1.66	0.39	10	4.7	0.5	0.43	1.1	1.4	11	26	14	14
N4 max			12.1	7.16	9.44	739	129	2.13	18.4	3.21	322	41.4	16.5	8.81	8.82	25.5	88	200	65	342
N4 min			9.3	6.92	4.46	627	113	1.96	12.3	1.60	286	24.5	14.1	6.79	2.96	18.8	37	96	20	280
N15 av	6.6–15.4	26	10.6	7.10	8.08	638	117	1.86	12.7	1.05	299	25.0	12.8	6.83	8.40	20.8	57	131	41	305
N15 sd			0.459	0.05	1.08	27	5.3	0.051	1.50	0.06	11	4.8	0.5	0.27	0.40	1.1	10	22	14	14
N15 max			11.7	7.20	9.62	695	128	1.99	16.5	1.21	321	38.1	14.0	7.45	9.36	23.4	88	200	70	331
N15 min			9.4	6.94	4.91	617	107	1.73	10.2	0.92	272	18.2	11.8	6.42	7.70	18.4	42	90	13	277

piezometer waters, all from 10 m bgl or deeper, are the least variable in composition.

Linkages between river level and changes in hydro-chemistry, sometimes complex, were considered in Abesser et al. (2008). The emphasis in the present paper is to deconvolve the relationships between the river, gravels and Chalk by taking simple averages from the now-sizeable datasets.

Table 2 indicates that for most determinands there is rather little difference between the gravel and Chalk pairs, either in an individual borehole or between the boreholes. Average differences exceeding 10% are seen only for Na, Cl, SO₄ and Ba (all higher in the gravels), while differences in the range 5–10% are seen for NO₃ and Si (the latter higher in the Chalk).

For reference purposes, the ‘baseline’ Chalk groundwater averages as represented by piezometer H1 are also provided in Table 2. While there are no major differences for most ions between H1 and the grand average of the Chalk piezometers, Cl is on average 14% higher in the piezometers and Na, K, SO₄ and NO₃-N are 5–10% higher.

Compared to the H1 baseline, river water is slightly higher in Na and significantly higher in dissolved O₂, K, Cl, SO₄, NO₃-N and P. Piezometer H1 on the other hand is higher in Ca, Mg, HCO₃, Si, F, Ba, Br and Sr. Some of the differences are linked to the carbonate system: with a higher pH, due to CO₂ degassing, river water is able to hold less of the alkaline earth elements Ca, Mg, Ba and Sr in solution, and HCO₃ is also lowered. Dissolved O₂ would be expected to be higher in surface waters than in groundwater. The minor elements Si and Br are acquired during water-rock interaction and are therefore higher in the H1 water, which has a mean residence time of decades (Goody et al. 2006). The higher concentrations of K, SO₄, NO₃-N and P_{tot} in the river are most likely due to a combination of agricultural runoff and treated sewage effluent.

A likely source of excess Cl and other ions is the farming activities associated with the barns on the western side of the site (Fig. 4). Examination of the averaged analyses from the gravel borehole N4 (Table 2) shows that it exceeds the grand average of the gravel piezometers by over 10% in Ca, Mg, NO₃-N, Br and especially Na, K, Cl and SO₄. The last six of these ions are often found in effluent from farming activities, while the rises in Ca and Mg are probably caused by increased mobilisation from Chalk mixed in with the gravel by the effluent’s originally lower pH (Goody et al. 1998). The average from the Chalk borehole N15 (Table 2) shows fewer excesses greater than 10% over the grand average for the Chalk piezometers, but still has major excesses in Na, Cl and SO₄.

Therefore the potential exists for tracing water movements within and between the gravels, shallow Chalk aquifer and the river, as pointed out by Abesser et al. (2008). Figure 9 shows plots of Na, K, Cl, SO₄ and NO₃-N versus distance from N4 for the gravel and Chalk piezometers. The north-bank piezometers A, C and D are treated as a linear array, while the south-bank piezometer

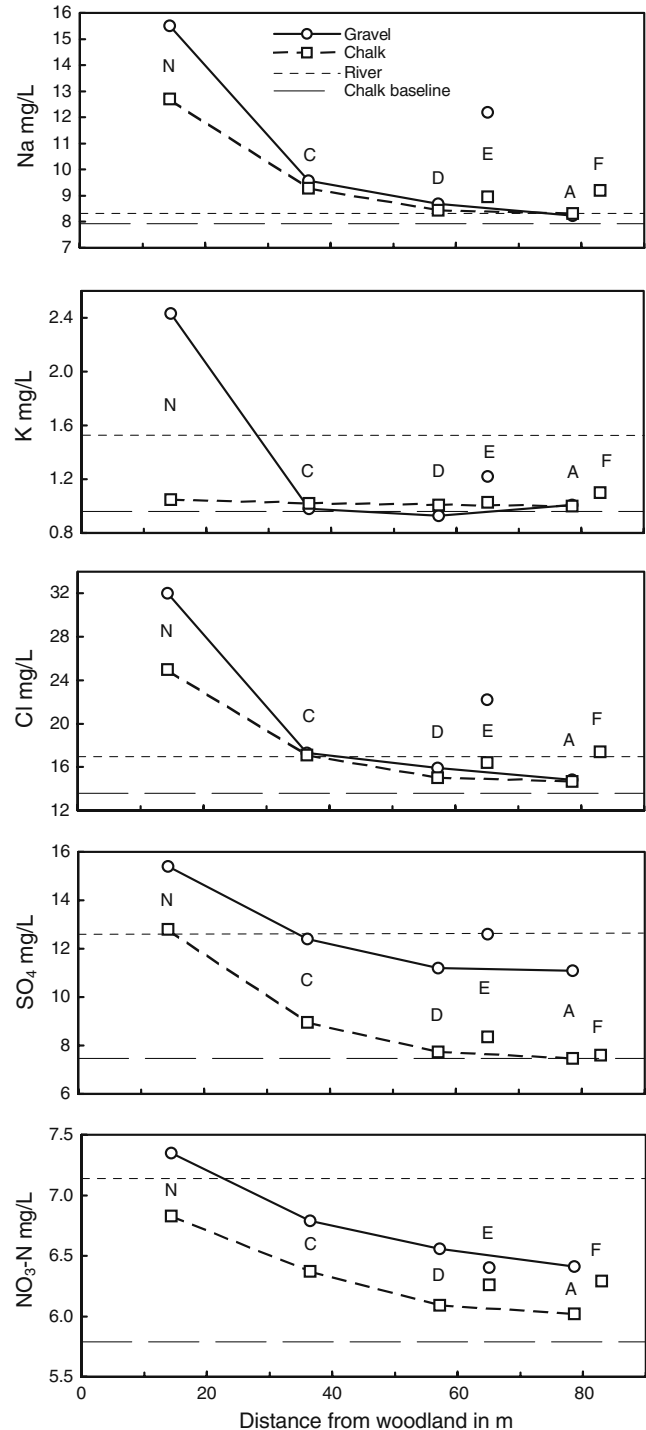


Fig. 9 Averages (2003–2008) of selected ions for groundwaters from the Boxford bank-side piezometer pairs in relation to the composition measured in the N boreholes, versus distance from the edge of the north-bank woodland (see Fig. 4). Also shown are average river and Chalk baseline compositions

E is separately superimposed. In each case, a dilution trend away from the composition in the N boreholes is apparent. However, the separation between gravel and Chalk concentrations varies: it is low for Na, K and Cl, but high for SO₄ and NO₃-N. In most instances this

appears to be linked to the concentration in the river, with a low contrast between the river and H1 for Na and Cl, but a high contrast for SO_4 and $\text{NO}_3\text{-N}$, suggesting that ternary mixing is occurring. The plot for K is an apparent anomaly, but can be explained by its tendency to sorb onto clay minerals, which are present in the gravel.

To arrive at an overall assessment for the manner in which mixing is affecting the various piezometers, a cross-plot of two conservative but varying major ions is required. Chloride is normally considered to be the most appropriate, while, in the present case, with all waters reasonably high in dissolved O_2 , SO_4 is also likely to be highly conservative. Figure 10 shows the piezometer averages on a Cl– SO_4 plot. It shows that while the waters A1, C1, D1 and E1 are very largely the product of binary mixing between N4-type water and baseline Chalk, others (A2, C2, D2, E2 and N15) are derived from ternary mixing between the three end-members, illustrating the complexity of flowpaths in the bank-side gravels.

Detailed monitoring of the hyporheic piezometers

In the river gravels, north-bank piezometers P and Q, and river-bed piezometers R, S and T (locations: Fig. 4) were monitored fortnightly for hydrochemistry over the year June 2007–May 2008 (river conditions permitting). The open river was also monitored together with stilling well U, but sampling of the latter was discontinued after a few months as there was no significant difference in water quality. The two north-bank piezometers also gave results similar to each other, so the dataset from Q is not considered further here, as P is significantly nearer to the river-bed piezometers. The river-bed piezometers were designed with narrow response zones centred on approximately 0.5 m (R), 1.5 m (S) and 2.5 m (T) below the river

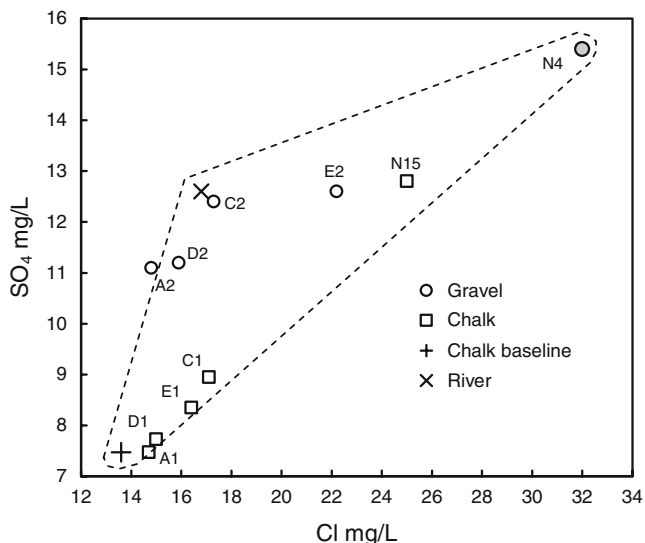


Fig. 10 Long-term (2003–2008) chloride and sulphate data for groundwaters from the Boxford bank-side piezometer pairs compared to the compositions of the *river*, the *N* boreholes and the *Chalk baseline*. The ternary mixing envelope is also shown (*dashed line*)

bed to provide sufficient resolution to understand any mixing processes taking place.

Figure 11 shows plots of field measurements of temperature, specific electrical conductivity (SEC), pH alkalinity and dissolved O_2 from June 2007 to May 2008. Also included is the N4 average and the river level record for the same period, plus the long-term average for H1, i.e. the Chalk baseline.

Unsurprisingly, river temperature fluctuates more widely than groundwater temperatures, and river water has more dissolved O_2 than the gravel waters, though these are still relatively well-oxygenated. The river also has a significantly higher pH and lower alkalinity than the gravel waters (already observed in connection with the 2003–2008 paired piezometer record) owing to CO_2 loss. Specific electrical conductivity (SEC) is also lower in the river. It may be noted here that while spot measurements of SEC match the river datalogger record well (based on the daily average of 15-min readings) throughout the year, spot measurements of temperature match less well with the datalogger record for the river during the summer. Spot temperature measurements of river water reflect short-term fluctuations due to the time of sampling and/or weather conditions, whereas the datalogger record is a daily average.

The clear correlation between river and gravel water temperature is not shown by the other parameters in Fig. 11, suggesting that propagation of seasonal temperature change is more diffusive than advective. Nevertheless, there is evidence that downward advective effects may occasionally predominate: after both the sudden flood event of July 2007 and the relatively rapid rise in river stage during the second half of January 2008, piezometer SEC values decline towards the river value for a short period of time.

More usually, because river-bed piezometer heads increase with depth (see previous section), flow potential will be directed upwards into the river rather than away from it. However, the existence of ternary mixing in the bank-side gravel revealed by Fig. 10 suggests that the hyporheic gravel as a whole is a zone of complex mixing. This seems to be reflected in the chemistry of the piezometers. Plots of selected ions (Fig. 12) show that P and the shallow river-bed piezometer R (0.5 m) are consistently the closest to the Chalk baseline while the deep piezometer T (2.5 m) is the closest to the N4 average. Meanwhile the river appears to vary relatively independently.

The behaviour of the river-bed piezometers can be examined in more detail via averaged profiles of a range of parameters (Fig. 13). Here the Chalk groundwater baseline is indicated only where it does not fall within the N4 compositional range, thus it is not shown for temperature, dissolved oxygen or total phosphorus (P_{tot}). With the exception of temperature, which in the river and shallow subsurface is ultimately controlled by mean annual air temperature, all the profiles show changes. Some of these, i.e. dissolved O_2 and SEC, are not especially diagnostic as they would be expected to differ

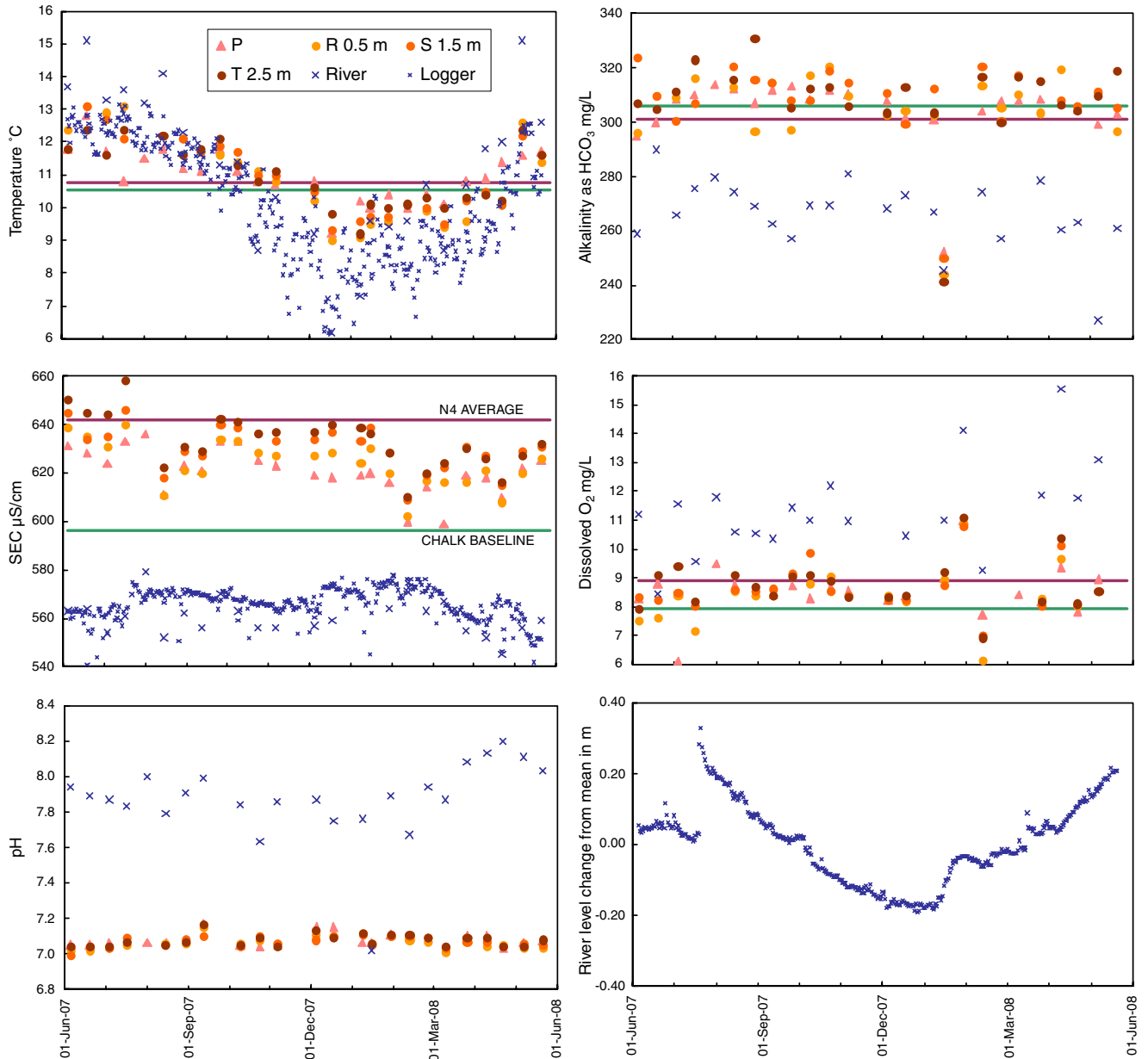


Fig. 11 Plots of variations in the field-measured parameters *temperature*, specific electrical conductivity (*SEC*), *pH*, *alkalinity* and *dissolved O₂* in the Boxford river-bed piezometers, bank-side piezometer *P* and the River Lambourn, over the period June 2007–May 2008. Also shown are daily-average *temperature*, *SEC* and *river level* data obtained from dataloggers. Key as shown for *temperature* plot. Average compositions for *N4* over the same period and the long-term *Chalk baseline* are indicated where appropriate

between the river and groundwater. However, for the Na, Cl, SO₄ and NO₃-N profiles the changes can be interpreted in terms of mixing. None of the gradients is truly vertical between T (2.5 m) and R (0.5 m), which would be the case if the system were dominated by upward flow. Instead, the profile shapes appear to be affected by two different processes: mixing between N4 and Chalk baseline waters for the section from T to R, then a much sharper, probably largely diffusional gradient between R and the river (this is also the case for P_{tot}, which is a rare case where the river exceeds N4 in average concentration). Thus a reversal of slope occurs in cases where the average composition of the river lies nearer to N4 than the Chalk baseline (i.e. SO₄ and NO₃-N).

The zone of more significant mixing between the river and groundwater (the hyporheic zone in the strict ecological sense) must therefore lie above the level of Piezometer R at this particular location. This would accord with the findings of detailed hyporheic sampling nearby during 2004 (Pretty et al. 2006) which suggested that most mixing occurs in the uppermost 0.2 m of the profile (Fig. 14).

Comparison of the hyporheic piezometers with the gravel–Chalk piezometer pairs

On two occasions during the year-long monitoring of the river-bed piezometers, the gravel–Chalk piezometer pairs

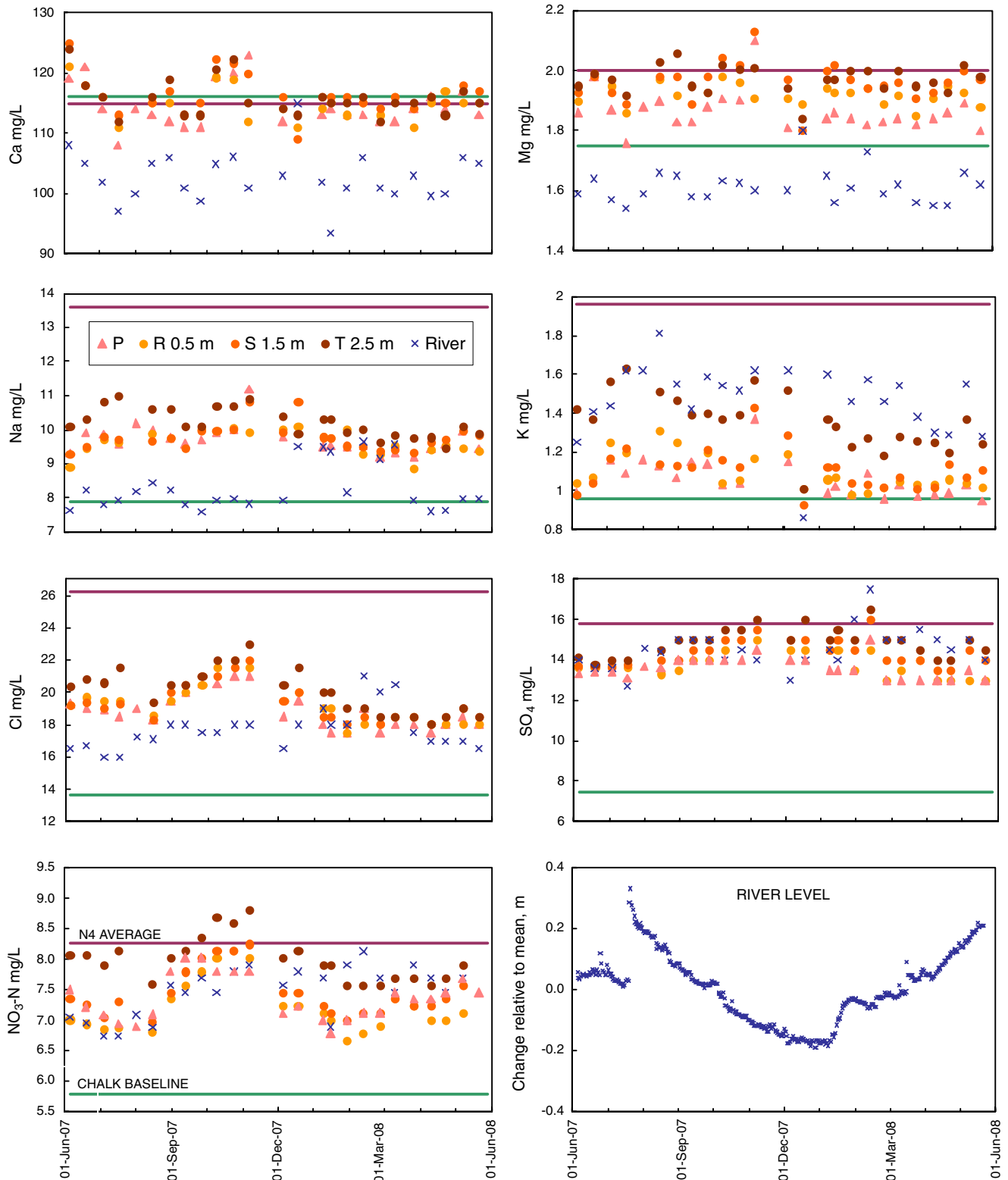


Fig. 12 Plots of changes in major ions in the Boxford river-bed piezometers, bank-side piezometer P and the river, over the period June 2007–May 2008. Key as shown for *Na* plot. Average compositions for *N4* over the same period and the long-term *Chalk baseline* are indicated for each ion. Daily-average *river level* data are also shown

were sampled (24 October 2007 and 10 March 2008). Figure 15a and b show respectively October and March versions of the Cl–SO₄ plot first shown in Fig. 10 with data from all piezometers added.

In the autumn (Fig. 15a) the situation is similar to that for the long-term averages shown in Fig. 10. There is a good separation between the river, *N4* and *Chalk baseline* compositions. As before, the *Chalk piezometers* show

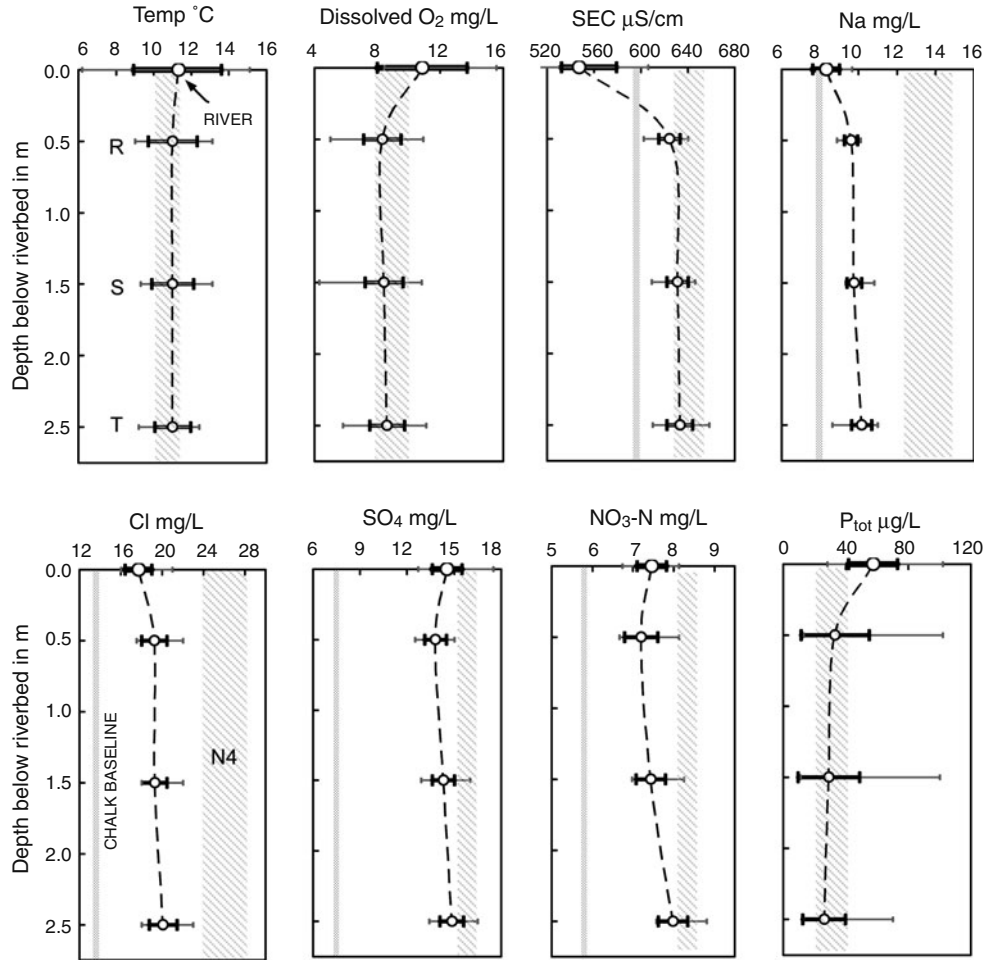


Fig. 13 Averaged profiles for selected determinands from the Boxford river-bed piezometers R, S and T, sampled over the year June 2007–May 2008, and shown in relation to the river composition. The key is indicated in the Temp profile. To illustrate the variation in each dataset, *standard deviation and maximum–minimum bars* are shown. Also shown in the Cl profile is the standard deviation band for the dataset from borehole N4 over the same period, and the long-term *Chalk baseline* where this falls outside the N4 range (i.e. it is not indicated for temperature, dissolved O₂ or P_{tot})

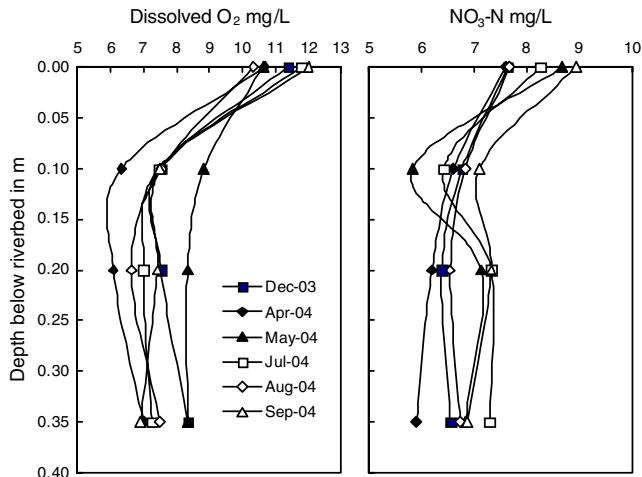


Fig. 14 Sequential plots of dissolved O₂ and NO₃-N from the shallow river-bed gravel at Boxford, showing steepest gradients in the uppermost 0.2 metres. Based on data from Pretty et al. (2006)

evidence of mixing with N4-type water. N15 has a lower N4-type component than before, but also less of a river water component. The bank-side gravel piezometers A–C have shown the greatest change, moving towards E2 in composition and therefore having almost equal proportions of river, N4 and Chalk groundwater. This is the situation for P also. The river-bed piezometers contain progressively less Chalk-type water in the order from R downwards.

In the spring, the situation has changed (Fig. 15b). The most obvious difference is the lower SO₄ concentration for N4, and now (unlike the autumn and the earlier plot in Fig. 10), some of the samples fall outside the putative mixing triangle. The reason for this is presumably related to a lag between changes in N4 or river water composition and the compositions measured in the various piezometers. Both the autumn and spring plots show N4 and river compositions for earlier fortnightly samplings. While there is little change over the preceding 6 weeks in the autumn, there are relatively large changes in the spring, and going back 4–6 weeks would provide better inclusion of the

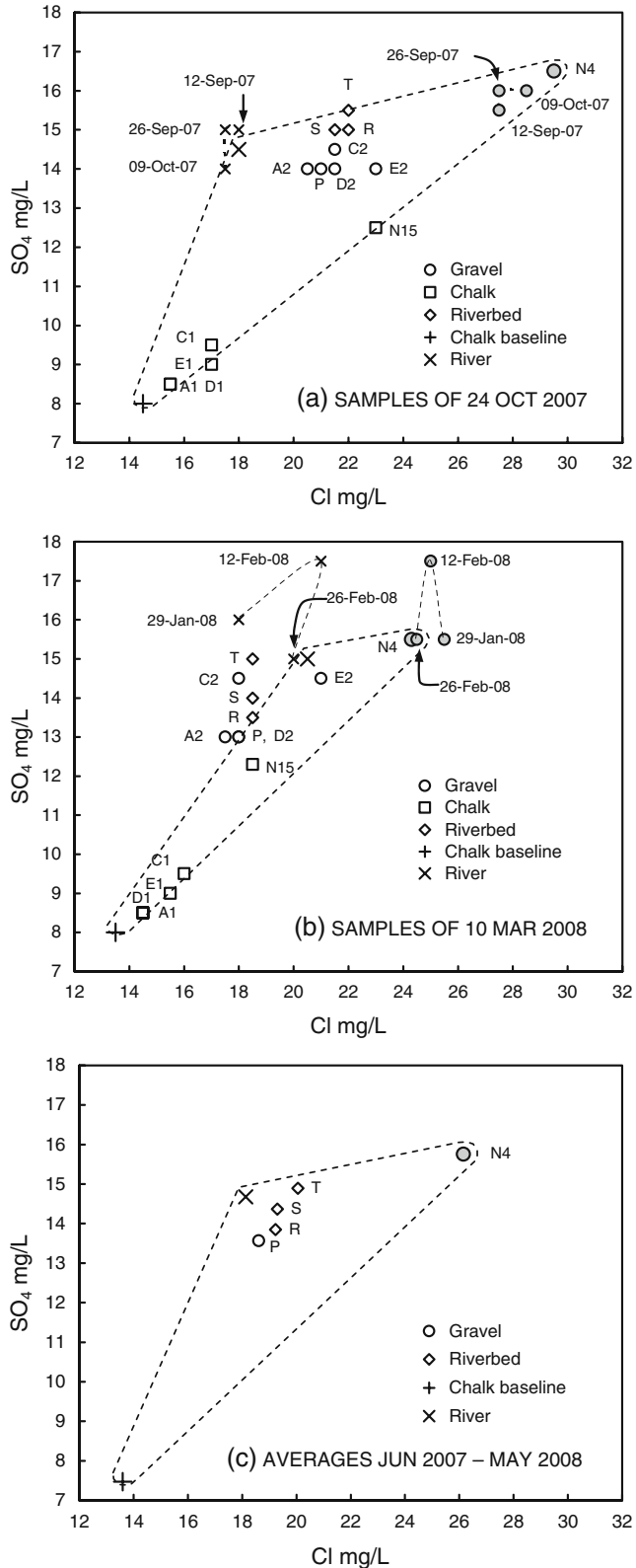


Fig. 15 Plots of chloride vs. sulphate concentrations for waters from Boxford riverbank and riverbed piezometers, showing mixing relationships in **a** autumn 2007, **b** spring 2008, and **c** for the whole 12-month period of monitoring (some piezometers omitted for clarity)

data. Equally, however, it is clear that interpretation of the proportions of each end-member in individual samples would vary depending on whether the 29 January or 12 February compositions for N4 and the river were used.

One solution to this is to use the long-term average approach previously adopted in Fig. 10. For clarity, Fig 15c shows only the recent piezometers P, R, S and T, plus the river and N4, together with the long-term average for Chalk groundwater as provided by H1 over the period 2003–2008. The plot suggests that the composition of the deepest river-bed piezometer T is 2:1 mixture of river water with N4-type water, while the higher piezometers S and R, and the bank-side piezometer P, each show increasing amounts of a Chalk baseline component. Thus, it appears that river water does enter the gravels, but this occurs upstream of the river-bed piezometer array.

Discussion

The combination of geological, hydraulic and hydro-chemical approaches has enabled a conceptual model of the study site to be formulated which is clear in certain respects but more ambiguous in others. In broad terms, it is apparent that groundwater in the Chalk aquifer underlying the valley flows in a southerly or south-easterly direction, and thus transversely to the river at the site. The overlying gravel aquifer is generally hydraulically disconnected from the Chalk along the river bank at the site, causing it to be locally confined, possibly due to reworked Chalk incorporated in the lower 1–2 m of the gravels. The gravels are in broad hydraulic continuity with the river, with groundwater flowing generally in a southerly or easterly direction, both to and under the river.

In detail, however, the picture is more complex. One example of this is the relationship between the Chalk and the gravel aquifers. While there is good evidence of a hydraulic separation between the aquifers along the river banks, with the Chalk at a higher head, this seems to be contradicted by the presence in the Chalk of elevated concentrations of some of the chemical species found in the N4 gravel borehole, suggesting downward movement of water from gravel to Chalk. This apparent inconsistency may be resolved when the extent of the gravel outcrop is considered. The edge of this lies across the farm and therefore the farming activities resulting in the anomalous chemistry of the N4 gravel borehole may also have caused elevated chemical concentrations in waters recharging the Chalk to the north of the N boreholes. In addition, it has been found that at a time when the Chalk/gravel head difference in piezometers near to the river was around 0.3 m, further from the river (in boreholes X and Y), the difference was only 0.03 m. Thus, the Chalk and gravels may well be in hydraulic continuity near the edge of the gravel outcrop, allowing movement of water between the aquifers.

Groundwater flows within the gravels and the hydraulic relationship between the gravels and the river

appear to be particularly complex. The generally southerly and easterly flow in the gravels is supported by the chemical evidence of water movement from the N4 borehole area eastwards and southwards under the river. Also, chemical evidence supports the contention of Chalk water rising into the overlying sediments around borehole A, causing the local anomaly in hydraulic head. The hydraulic data suggest flow towards the river from the north bank, upward flow within the river bed gravels and a more variable relationship between river and gravels on the southern bank. However, the chemistry data indicate that a component of river water exists in the gravels both by and under the river, which conflicts with the hydraulic interpretation. The most likely reason for this is that interpretations based on the hydraulic head data can strictly only apply to the site itself (and the river bed piezometers are emplaced at only one location). It is therefore possible that river water enters the gravel aquifer upstream of the site where the hydraulic relationship between the river and gravels may be different. In addition, short-term events such as flood peaks may alter the hydraulic relationship between the surface and groundwaters, allowing the river to temporarily recharge the aquifer; however, this is considered to be a less viable mechanism as recharged waters would subsequently be subject to flushing once the normal hydraulic regime was re-established.

Another issue is the chemical evidence from the river bed piezometers of a higher component of Chalk-derived water at shallow depths than in the deeper piezometer which appears anomalous given the upward head gradient in the gravels. The similarity between the shallow piezometer chemistry and bank-side piezometer P (Fig. 15c) might argue for a source in this area, but piezometer P is somewhat downstream of the river piezometers so this seems unlikely and the anomaly is unresolved. The increasing component of N4-type water with depth below the river bed does, however, reinforce the concept of groundwater flow under the river within the gravels in a south-easterly direction from the northern bank.

Given the geometry of the gravels, their likely high permeabilities and the head gradients encountered, it is pertinent to examine the question of the importance of groundwater flow in the aquifer within the catchment. Flow in the gravels will be dominated by the highly permeable coarse layers. If these parts of the gravel sequence are assumed to be around 2 m thick, to extend over an average width of 150 m and to have an average hydraulic conductivity of 5,000 m/day then, assuming a hydraulic gradient along the valley bottom of 0.003 m/m, the rate of flow through the gravels along the valley bottom is calculated to be 4,500 m³/day or 5.2×10^{-2} m³/s. This is only 3% of the mean river flow (of 1.73 m³/s) or 7% of the Q95 flow (of 0.76 m³/s) at the flow gauging station at Shaw [SU 470 682] (Marsh and Hannaford 2008), downstream of the site. While the calculation is based on estimates, it is considered unlikely that the groundwater flow in the gravels would significantly exceed these amounts (in particular the value of hydraulic

conductivity used is likely to be a maximum as it assumes connectivity of the coarse gravels along the length of the river), suggesting that gravel flow is a noticeable, but not significant proportion of river flow.

Conclusions

The present study of GW–SW interactions in a Chalk catchment has illustrated some of the problems in investigating a system which is hydraulically complex at the site scale, and where chemically similar groundwaters exist in the different components of the system. Despite the number of boreholes at the site, the heterogeneity of the river gravels is such that the Chalk/gravel/river hydraulic relationship is still only partially understood from the available physical and geological data. The hydrochemical data were very valuable in identifying the subsurface flow patterns, but this was mainly as a result of fortuitous local hydrochemical ‘tracers’ resulting from agricultural practice.

Nevertheless, while there are unresolved issues within the conceptual hydrogeological model of the site, an interpretation has emerged of a heterogeneous groundwater system involving complex flows within the alluvial aquifer, between that aquifer and the underlying Chalk, and in particular between the gravels and the river. It is likely that interchange of water between the gravel aquifer and the river occurs at a range of scales, with most active mixing occurring within a few tens of centimetres of the river bed, but with some river-aquifer interaction likely down to a depth of several metres. This conceptualization has ramifications both for understanding GW–SW interaction in the Lambourn catchment and in other comparable locations.

The effect of the layer of high-permeability gravels overlying the Chalk in the Lambourn is likely to be twofold. Firstly, it will tend to disperse the impact of the potentially more discrete inputs of water from the underlying fractured Chalk, giving rise to more-elongated gaining sections of the river. Secondly, the gravels will provide a route for some groundwater flow down the catchment, although most valley-bottom flow will occur via the river, as discussed previously.

It is commonly accepted that hydrological understanding is essential to elucidating the hydrochemical and ecological functioning of a GW–SW system (Lewandowski et al. 2009; Vidon and Hill 2004; Bencala 1993). This study has shown that even an apparently straightforward aquifer/stream system can be hydrologically complex at the site scale. While examples of site-specific investigations of lowland GW–SW interaction are not common in the literature, recent examples suggest that hydrological (Lewandowski et al. 2009) and hydrochemical complexity (Krause et al. 2009) are not unusual at such scales. This has implications both for the way in which such systems are investigated and for their management. If GW–SW interaction is commonly complex at the scale of metres or tens of metres, then careful consideration needs to be given to the nature of the

investigation—for example, the appropriate density of monitoring and sampling points. For management purposes, for instance the setting of environmental objectives for the Water Framework Directive, methodologies need to be developed to encapsulate such detailed knowledge at the site scale into decisions about appropriate standards to be applied at the larger water-body scale.

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References

- Abesser C, Shand P, Goody DC, Peach D (2008) The role of alluvial valley deposits in groundwater-surface water exchange in a Chalk river. *IAHS Publ* 321, IAHS, Wallingford, UK, pp 11–20
- Aldiss DT, Royle, KR (2002) The geology of the Pang-Lambourn catchment, Berkshire. British Geological Survey Commissioned Report, CR/20/289N, BGS, Keyworth, UK
- Allen D, Allen DJ (2008) Boxford research site infrastructure 2008. British Geol Surv Open Rep OR/08/67, BGS, Keyworth, UK
- Allen DJ, Brewerton LJ, Coleby LM, Gibbs BR, Lewis MA, MacDonald AM, Wagstaff SJ, Williams AT (1997) The physical properties of major aquifers in England and Wales. British Geol Surv Tech Rep WD/97/38, BGS, Keyworth, UK
- Bencala KE (1993) A perspective on stream-catchment connections. *J N Am Benthol Soc* 12(1):44–47
- Bloomfield JP, Brewerton LJ, Allen DJ (1995) Regional trends in matrix porosity and bulk density of the Chalk of England. *Q J Eng Geol* 28:131–142
- Cook PG, Favreau G, Dighton JC, Tickell S (2003) Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. *J Hydrol* 277:74–88
- Council of European Communities (2000) Establishing a framework for community action in the field of water policy (WFD; 2000/60/EC). Off J EC L327, December 2000
- Freeze RA, Cherry JA (1979) *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ, 604 pp
- Goody DC, Withers PJA, McDonald HG, Chilton PJ (1998) Behaviour and impact of cow slurry beneath a storage lagoon: II. Chemical composition of Chalk porewater after 18 years. *Water Air Soil Pollut* 107:51–72
- Goody DC, Darling WG, Abesser C, Lapworth DJ (2006) Using chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF₆) to characterise groundwater movement and residence times in a lowland Chalk catchment. *J Hydrol* 330:44–52
- Grapes TR, Bradley C, Petts GE (2005) Dynamics of river-aquifer interaction along a Chalk stream: the River Lambourn, UK. *Hydrol Process* 19:2035–2053
- Griffiths J, Binley A, Crook N, Nutter J, Young A, Fletcher S (2006) Streamflow generation in the Pang and Lambourn catchments, Berkshire, UK. *J Hydrol* 330:71–83
- Hill AR (1996) Nitrate removal in stream riparian zones. *J Env Qual* 25:743–755
- Keery J, Binley A, Crook N, Smith JWN (2007) Temporal and spatial variability of groundwater-surface water fluxes: development and application of an analytical method using temperature time series. *J Hydrol* 337:1–16
- Krause S, Bronstert A (2007) Water balance simulation and groundwater-surface water-interactions in a mesoscale lowland river catchment in northwestern Germany. *Hydrol Process* 21:169–184
- Krause S, Bronstert A, Zehe E (2007) Groundwater-surface water interactions in a north German lowland floodplain: implication for the river discharge dynamics and riparian water balance. *J Hydrol* 347:404–417
- Krause S, Heathwaite L, Binley A, Keenan P (2009) Nitrate concentration changes at the groundwater-surface water interface of a small Cumbrian river. *Hydrol Process* 23:2195–2211
- Lapworth DJ, Shand P, Abesser C, Darling WG, Haria AH, Evans CD, Reynolds B (2008) Groundwater nitrogen composition and transformation within a moorland catchment, mid-Wales. *Sci Tot Env* 390:241–254
- Lapworth DJ, Goody DC, Allen D, Old GH (2009) Understanding groundwater, surface water, and hyporheic zone biogeochemical processes in a Chalk catchment using fluorescence properties of dissolved and colloidal organic matter. *J Geophys Res* 114, G00F02, doi:10.1029/2009JG000921
- Lewandowski J, Lischeid G, Nutzmann G (2009) Drivers of water level fluctuations and hydrological exchange between groundwater and surface water at the lowland River Spree (Germany): field study and statistical analyses. *Hydrol Process* 23:2117–2128
- Mencio A, Mas-Pla J (2008) Assessment by multivariate analysis of groundwater-surface water interactions in urbanised Mediterranean streams. *J Hydrol* 352:355–366
- Marsh TJ, Hannaford J (eds) (2008) UK hydrometric register. Hydrological data UK Series, Centre for Ecology and Hydrology, Wallingford, UK, 210 pp
- McGlynn BL, McDonnell JJ, Shanley JB, Kendall C (1999) Riparian zone flowpath dynamics during snowmelt in a small headwater catchment. *J Hydrol* 222:75–92
- Pretty JL, Hildrew AG, Trimmer M (2006) Nutrient dynamics in relation to surface-subsurface hydrological exchange in a groundwater fed Chalk stream. *J Hydrol* 330:84–100
- Sear DA, Armitage PD, Dawson FH (1999) Groundwater dominated rivers. *Hydrol Process* 13:255–276
- Schmidt C, Conant B Jr, Bayer-Raich M, Schirmer M (2007) Evaluation and field-scale application of an analytical method to quantify groundwater discharge using mapped streambed temperatures. *J Hydrol* 347:292–307
- Soulsby C, Gibbins C, Wade AJ, Smart R, Helliwell R (2002) Water quality in the Scottish uplands: a hydrological perspective on catchment hydrochemistry. *Sci Tot Env* 294:73–94
- Tetzlaff D, Soulsby C (2008) Sources of baseflow in larger catchments: using tracers to develop a holistic understanding of runoff generation. *J Hydrol* 359:287–203
- Vidon GF, Hill AR (2004) Landscape controls on the hydrology of stream riparian zones. *J Hydrol* 292:210–228
- Wheater HS, Peach D (2004) Developing interdisciplinary science for integrated catchment management: the UK Lowland Catchment Research (LOCAR) programme. *Int J Water Resour Dev* 20(3):369–385
- Winter TC, Harvey JW, Franke OL, Alley WM (1998) Groundwater and surface water: a single resource. *US Geol Surv Circ* 1139