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## Variability of dissolved CO<sub>2</sub> in the Pang and Lambourn Chalk rivers

J. Griffiths<sup>1</sup>, J. Nutter<sup>2</sup>, A. Binley<sup>3</sup>, N. Crook<sup>4</sup>, A. Young<sup>1</sup> and J. Pates<sup>3</sup>

<sup>1</sup>Centre for Ecology and Hydrology, Wallingford, UK

<sup>2</sup>Wallingford Hydrological Solutions, Wallingford, UK

<sup>3</sup>Department of Environmental Science, Lancaster University, UK

<sup>4</sup>Department of Geophysics, Stanford University, California, USA

Email for corresponding author: [jimg@ceh.ac.uk](mailto:jimg@ceh.ac.uk)

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### Abstract

This paper presents the results of a two-year field campaign to determine the spatial and temporal variability of groundwater interaction with surface waters in two Cretaceous Chalk catchments (the Pang and Lambourn) in the Upper Thames in Berkshire, UK, based on measurement of dissolved carbon dioxide (CO<sub>2</sub>). Average stream water concentrations of dissolved CO<sub>2</sub> were up to 35 times the concentration at atmospheric equilibrium. Mean groundwater concentrations of 85 and 70 times the atmospheric equilibrium were determined from borehole water sampled in the Pang and Lambourn respectively. Diurnal and seasonal variation of in-stream concentration of dissolved CO<sub>2</sub> is not significant enough to mask the signal from groundwater inputs.

**Keywords:** chalk, river, groundwater, alkalinity, pH, carbon dioxide, Pang, Lambourn, LOCAR

### Introduction

Analysis of stream and groundwater chemistry has been used to assess the extent of groundwater interaction with surface waters (Neal *et al.*, 1990; Hill and Neal, 1997; James *et al.*, 2000; Cook *et al.*, 2003; Malcolm *et al.*, 2004; Rodgers *et al.*, 2004). Such methods provide relatively quick and inexpensive descriptions of the spatial and temporal distribution of surface-groundwater interactions. For a naturally occurring substance to be used as an indicator of groundwater, its concentration in groundwater must be relatively consistent over both space and time, as well as significantly different from that of stream water. Initially, dissolved CO<sub>2</sub> is captured from the atmosphere by rainfall. Processes of organic material decomposition in the soil column further increase the CO<sub>2</sub> concentration of this water as it percolates through the soil. Resulting levels of dissolved CO<sub>2</sub> in groundwater are, therefore, higher than those found in surface waters (Neal *et al.*, 2000), making it a good candidate for use as a groundwater tracer.

When groundwater emerges at an interface with a surface-water body, dissolved CO<sub>2</sub> in the groundwater starts to degas

at a rate determined by the dimensional characteristics of the water-body, the amount of disturbance or turbulence in the water and external interferences such as wind-speed (Genereux and Hemond, 1992; Raymond and Cole, 2001). Once at the surface, the concentration of CO<sub>2</sub> in the water may be affected by photosynthetic and respirative processes of biological organisms in surface sediments and in the water column. Such processes make the interpretation of surface-water CO<sub>2</sub> concentrations for calculation of the rate and extent of groundwater inputs more difficult (Schurr and Ruchti, 1977; Simonsen and Harremoes, 1978). For measurements of dissolved CO<sub>2</sub> to be useful as reliable indicators of surface-groundwater interaction therefore, the potential magnitude of extraneous sources and sinks of CO<sub>2</sub> must first be quantified.

Worrall and Lancaster (2005), observed significant intra-annual variation in groundwater-dissolved CO<sub>2</sub>, and between different aquifers. While physically-based models for simulation of conservative natural tracers may be used as a starting point in the context of CO<sub>2</sub> (e.g. Choi *et al.*, 1998), parameterisation of such models is difficult (Genereux and

Hemond, 1992) and extraneous processes of CO<sub>2</sub> production, CO<sub>2</sub> degassing and carbonate precipitation are still not addressed. Indeed, Finlay (2003), suggests that even the presence of canopy cover above streams can affect the temporal dynamics of dissolved CO<sub>2</sub> significantly.

This paper investigates the potential of using simple surface/groundwater ratios of dissolved CO<sub>2</sub> to describe the spatial and temporal distribution of surface–groundwater interaction in groundwater catchments. The influence of streamflow and in-stream vegetation on the seasonal and diurnal variability of in-stream dissolved CO<sub>2</sub> has been assessed using water sampled at nine surface water and five groundwater locations, over a three-year period in the Pang and Lambourn Chalk catchments in Berkshire, UK.

The Pang and Lambourn catchments are key sites of the Lowland Catchment Research project (LOCAR) which aims to develop a better understanding of hydrological, geochemical and ecological processes in permeable lowland catchments. In this research new interdisciplinary science and improved modelling tools were developed to meet the challenges of integrated catchment management as defined by the Water Framework Directive (Wheater and Peach, 2004).

## Site description

Covering areas of 170.9 km<sup>2</sup> and 234.1 km<sup>2</sup> respectively, the Pang and Lambourn catchments are located on the northern side of the Thames basin (Fig. 1) and each catchment consists of predominantly Upper and Middle Cretaceous Chalk. The Upper Chalk is approximately 75 m thick and outcrops extensively on the dip slopes of both catchments. The Middle Chalk is up to 60 m thick and is slightly more argillaceous than the Upper Chalk, (Allen *et al.*, 1997; Aldiss *et al.*, 2002). Due to the highly permeable nature of Chalk aquifers, rivers in both catchments are groundwater fed. The Lambourn, for example, has an average stream gauge baseflow index (BFI) of 0.93, whilst the Pang has average BFI of 0.867 (Gustard *et al.*, 1992). In addition to groundwater springs, there are several sink holes in both catchments, the most significant one being in the lower Pang catchment (Banks *et al.*, 1995; Maurice *et al.*, 2006). Significant impermeable Tertiary (Eocene) formations are also found in the lower Pang, including Reading Beds and London Clay. Geological variation between the two catchments is reflected in contrasting landscape features and topography. The river valley of the

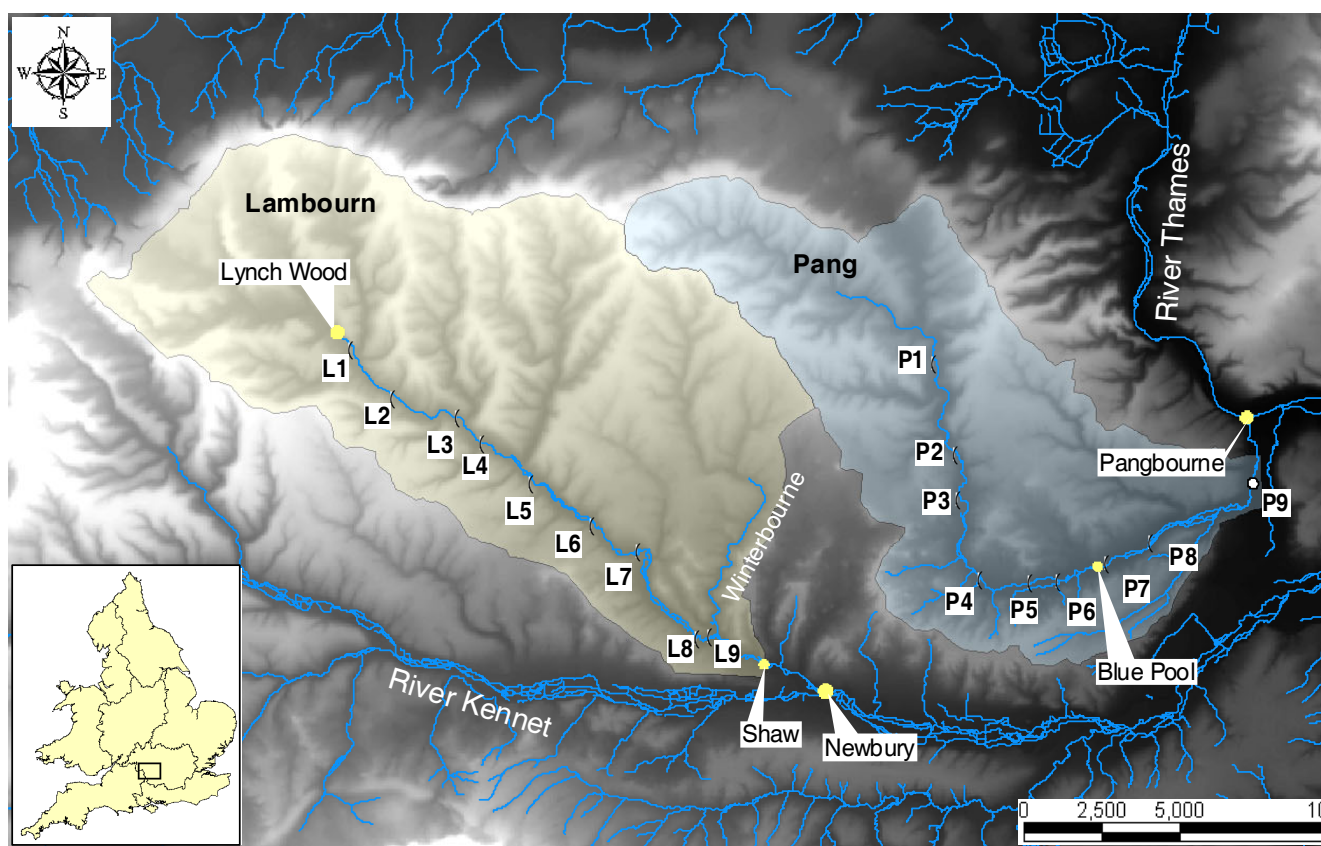


Fig. 1. Location of water sampling sites within the Pang and Lambourn catchments. Position of Thames, Kennet and Winterbourne Rivers also shown.

Lambourn, for example, is relatively narrow (typically 250–500 m) with sharp gradient sides. The Pang, by comparison, is characterised by wide river valleys (up to 2 km width) with less-defined sides of lower topographic gradient. Consequently, dry-valley landscape-features that intersect the main river-valley, and which are thought to promote convergence of subsurface flow (Grapes *et al.*, 2005), are more prevalent in the Lambourn catchment. Grapes *et al.* (2006) also identified a localised alluvial gravel aquifer in the Lambourn valley which is probably associated with a number of small wetland areas in the main river valley. Larger regional-scale controls on groundwater movement in the two catchments include major hydrological sinks (the Thames and Kennet valleys), geological boundaries (Pewsey Anticline) and the stratigraphic position relative to sea level (Bradford, 2002). Hard-grounds and harder bands in the Chalk, associated with more cleanly fractured areas of deeper Chalk, may also promote the formation of preferential flow pathways (Brettal, 1971).

The River Lambourn flows in a predominantly south-easterly direction throughout its course and covers a distance of 20 km from its source at Lynch Wood to its confluence with the larger River Kennet at Newbury. The River Lambourn has a mean annual flow of  $1.76 \text{ m}^3 \text{ s}^{-1}$  (1962–2003), at the Shaw gauging station, situated 2 km upstream of Newbury (NRFA, 2004a). From spring to summer, the seasonal head of the river rises from outcrops of Middle Chalk in Lynch Wood at the top of the catchment. Stream levels generally peak and begin to recede from the end of May. Summer streamflow recession is then followed by a period, usually between August and January depending on rainfall, in which the stream becomes ephemeral in its upper reaches between Lynch Wood and L4 (Fig. 1). At such times, the head of the river may occur as far as 6 km downstream of its winter location.

The Pang flows north-south for its first 10 km and then turns east for 7 km, before turning north to meet the Thames at Pangbourne 22 km downstream from its winter head (Fig. 1). The river has a mean annual flow of  $0.65 \text{ m}^3 \text{ s}^{-1}$  (1962–2003) at Pangbourne (NRFA, 2004b). In late winter, the river rises from the Upper Chalk in the northern half of the catchment, flow is then supported by springs at a number of downstream locations (Maurice *et al.*, 2006). The largest of these occurs at an area known locally as the Blue Pool (between P6 and P7). In average rainfall years, the river channel becomes ephemeral between P1 and P2 and between P3 and P6, whence perennial springs are insufficient to support flow. Such conditions may prevail from September/November to as late as the following April.

## Dissolved $\text{CO}_2$ in Chalk streams

In Chalk catchments,  $\text{CO}_2$  in groundwater is the result of calcium carbonate (calcite) acid dissolution due to microbiological activity; this generates carbonic acid and nitrogen transformations. The rates of these reactions are determined by  $\text{CO}_2$  concentrations and the degree of mineral unsaturation in the water, and the availability of individual minerals, especially those that dissolve rapidly, such as calcite and other carbonate-based minerals. Upper and middle Chalk consists of relatively pure calcium carbonate such as the mineral calcite but may still contain impurities, including Mg, Sr, Mn and Fe.

The chemistry of percolating rainwater in Chalk catchments will change gradually as it passes through different subsurface layers. Chalk soils are typically less than one metre in depth and, whilst well drained, have relatively slow infiltration times of about a metre per year. The production of  $\text{CO}_2$  by biological activity in such soils results in the  $\text{CO}_2$  concentration of percolating rainfall increasing from 340 ppm in the open-air to up to 6000 ppm (Edmunds *et al.*, 1992). The rate of  $\text{CO}_2$  production through biological activity in the soil is linearly related to temperature, but the relationship is also dependent on the type of vegetation and will be greater for natural vegetation than for wheat crops, for example.

Beneath the soil layer, in the unsaturated zone of the Chalk, moisture moves in what is essentially a dual-porosity medium comprising the saturated micro-pores of the Chalk rock matrix, and a largely unsaturated fissure network that runs through the Chalk. Due to processes of  $\text{CO}_2$  dissolution in the upper soil layers, infiltrating water is already close to equilibrium with the groundwater held in the Chalk matrix in this zone. Water is gradually displaced downwards under gravity according to the piston-flow model, allowing the liberation and transfer of bicarbonate and calcium ions from the Chalk. Variation in calcium and bicarbonate concentrations and, hence, in dissolution and precipitation rates will be related to the variation in dissolved  $\text{CO}_2$  in percolating water.

Under normal diffuse recharge conditions in the saturated zone, calcite saturation is rapidly established near bedrock outcrops (Edmunds *et al.*, 1992). As a marine limestone however, Chalk will continue to undergo diagenetic changes, especially where younger influent water comes into contact with older water stored in the Chalk matrix. Groundwater chemistry may thus be modified slowly as it flows through the Chalk, resulting in increases in Mg/Ca and Sr/Ca ratios (Elliot *et al.*, 1999). These ratios are useful in determining water to rock contact times, but because of the heterogeneity of groundwater movement and mixing in the subsurface

(Younger and Elliot, 1995), may be difficult to use in estimating groundwater residence times. Deeper groundwater in the Chalk may undergo mineral dissolution, precipitation and cation exchange at a slower rate than groundwater nearer the surface. The salinity of deep groundwater may also be higher, depending on the extent of system flushing with freshwater that has occurred since formation. Both of the above factors will produce a distinct geochemical zonation of groundwater with depth. In general, groundwaters are approximately calcite saturated in the Chalk, at least in the present study area (Neal *et al.*, 2002b).

Elevated concentrations of dissolved CO<sub>2</sub> in groundwater entering surface-water drainage systems will result in accelerated rates of CO<sub>2</sub> degassing which can significantly affect stream water-chemistry (Jacobson and Usdowski, 1975). Degassing of CO<sub>2</sub> will take place at a rate determined by stream dimensions, turbulence and wind-speed, but will invariably be susceptible to modification through biogeochemical processes (Wilcock *et al.*, 1999). For example, processes of photosynthesis and respiration by benthic algae, phytoplankton and macrophytes, will generate or remove CO<sub>2</sub> from the water column depending on temperature and daylight available. Biological photosynthesis and respiration processes described by Neal *et al.* (1998a, 2002a) in long-term studies in the Kennet Valley, suggest a diurnal variation in dissolved CO<sub>2</sub> of up to 150% in summer but just 50% in winter (maximum CO<sub>2</sub> occurs at night). The breakdown of dissolved or particulate organic carbon will occur in the surface and near-subsurface environment and will, thus, also promote increased levels of dissolved CO<sub>2</sub> in the aquifer in summer.

## Methods and analysis

The variability of pH and dissolved CO<sub>2</sub> have often been used as an indicator of groundwater interaction with surface waters to characterise water quality in lowland rivers (Neal *et al.*, 1998a,b,c, 2000). Similarly, variation of in-stream alkalinity and silica have been used as groundwater tracers in upland rivers (Neal *et al.*, 1990; Rodgers *et al.*, 2004). In the present study, pH and Gran alkalinity were used to calculate dissolved CO<sub>2</sub> from water samples of 200 ml from up to ten locations in each catchment (Fig. 1 and Table 1), at weekly intervals from Dec 2002 to June 2005. Unfiltered samples were retrieved in sealed glass bottles for measurement of pH and of Gran alkalinity determined using a method derived from Neal (1988, 2001a).

The partial pressure of dissolved CO<sub>2</sub> (EpCO<sub>2</sub>) was determined from Gran alkalinity and pH using a method described by Neal *et al.* (1998b). The method assumes that the effect of other ions on Gran alkalinity will be negligible

Table 1. Sample sites location and downstream distances in the Lambourn and Pang catchments.

| Location            | Site Name | National Grid ref. | Distance (km) |
|---------------------|-----------|--------------------|---------------|
| Riverside Cottage   | L1        | SU 328 792         | 0.1           |
| Eastbury            | L2        | SU 343 775         | 2.75          |
| East Garston        | L3        | SU 366 768         | 4.95          |
| Maidencourt Farm    | L4        | SU 373 759         | 6.45          |
| East Shefford House | L5        | SU 389 747         | 7.8           |
| Welford Park        | L6        | SU 410 732         | 10.45         |
| Westbrook Farm      | L7        | SU 426 722         | 12.75         |
| Woodspen            | L8        | SU 446 693         | 16.2          |
| Bagnor              | L9        | SU 451 693         | 17            |
| Compton             | P1        | SU 528 787         | 0             |
| St Abb's            | P2        | SU 534 756         | 4             |
| Frilsham Meadow     | P3        | SU 536 740         | 6.45          |
| River Barn          | P4        | SU 543 713         | 8.9           |
| Bucklebury          | P5        | SU 560 711         | 10.8          |
| Jewell's Farm       | P6        | SU 570 711         | 11.8          |
| Frogmore Farm       | P7        | SU 587 719         | 13.68         |
| Bradfield           | P8        | SU 602 725         | 15.43         |
| Tidmarsh            | P9        | SU636 747          | 21.13         |

and that EpCO<sub>2</sub> does not vary under different meteorological conditions. EpCO<sub>2</sub> represents the number of times that the sampled water is oversaturated with CO<sub>2</sub>, with respect to a similar sample that has reached equilibrium with the atmosphere. Thus, for example, the CO<sub>2</sub> concentration of a sample with an EpCO<sub>2</sub> equal to ten, will be ten times that of a sample that has been given time to equilibrate with atmospheric conditions.

River water chemistry of the Pang and Lambourn is characteristic of most Chalk streams in the UK; it is both calcium-rich and of high alkalinity (Neal *et al.*, 2000, 2002b, 2004a). As precipitation of carbonate material in the river is minimal (Neal, 2002), CO<sub>2</sub> gas exchange to the atmosphere will cause an increase in pH, but a negligible change in alkalinity. Variation in pH therefore, can also be used as a surrogate measure of changes in dissolved CO<sub>2</sub> when linked to average alkalinity values (Neal *et al.*, 2002a). Previous studies illustrate a strong inverse relationship between pH and EpCO<sub>2</sub> (Neal *et al.*, 1998b,c; Howland *et al.*, 2000). To assess the degree of diurnal variation in dissolved CO<sub>2</sub>, in-stream EpCO<sub>2</sub> was also calculated from pH data sampled at 15 minute intervals from October 2002 to June 2004. Measurements of pH were obtained at sites P3, P5, P7 and P9 in the Pang catchment and at site L5 and the streamflow gauge at Shaw in the Lambourn catchment. The method of calculation used (Neal *et al.*, 1998b), also required alkalinity/Gran alkalinity and, preferably,

temperature data. For this purpose, in-stream alkalinity was assumed to be constant and calculated for each site from samples analysed previously. Daily temperature data were obtained from the LOCAR weather station at site P3 in the Pang.

## Results and discussion

### VARIATION IN STREAM $\text{EpCO}_2$

Figure 2 illustrates long-term variation of calculated  $\text{EpCO}_2$  for site P9 in the lower Pang. Data between July 1997 and October 2002, taken from Neal *et al.* (2000), have been added to measurements from the present study for October 2002 to June 2004. In addition to a marked diurnal variation identified by Neal *et al.* (2004b), levels of dissolved  $\text{CO}_2$  dip in the summer months and peak in the winter months. Significant inter-month variation also occurs, perhaps because under wetter conditions the less permeable geology of the site in the lower reaches of the Pang catchment promotes rainfall runoff. If the long term variation in dissolved  $\text{CO}_2$  at this site is representative of the variation in the catchments studied, then the period of study was one of increased variability. Catchment averaged  $\text{EpCO}_2$  over the studied period was 19.8 in the Pang, compared to 16.8 in the Lambourn.

Variation of catchment-averaged monthly  $\text{EpCO}_2$  for the Pang and Lambourn is shown in Figs. 3 and 4. These figures represent the mean dissolved  $\text{CO}_2$  in samples collected at all sites in a catchment, in a given month. The standard deviation boundaries represent both in-month variability (temporal) and variability between sites (spatial). The higher standard deviation observed for the Pang catchment represents greater spatial variability (mean monthly s.d. between sites = 10.3), as opposed to temporal variability

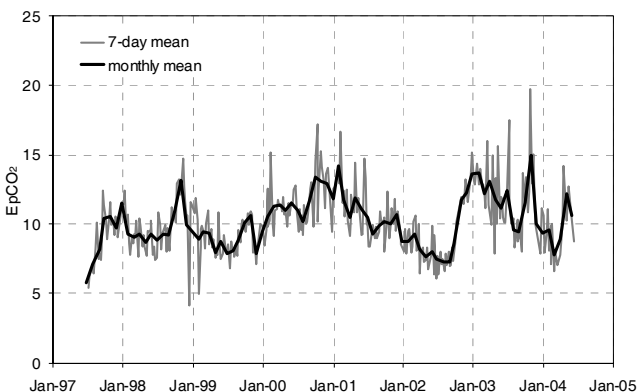


Fig. 2. Monthly and 7-day mean  $\text{EpCO}_2$  at site P9 in the Pang catchment.

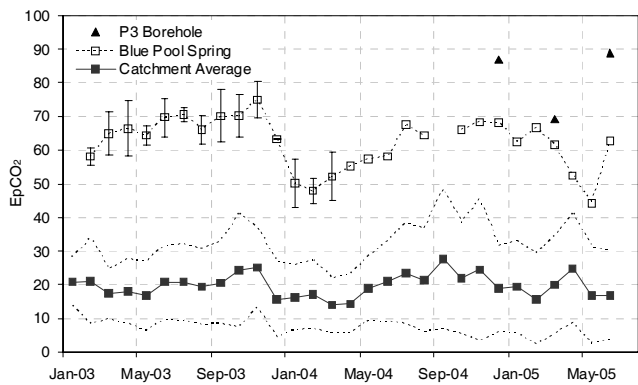


Fig. 3. Variation in averaged stream-water dissolved  $\text{CO}_2$  (s.d. boundaries indicated), compared to dissolved  $\text{CO}_2$  in spring and borehole sampled waters in the Pang catchment.

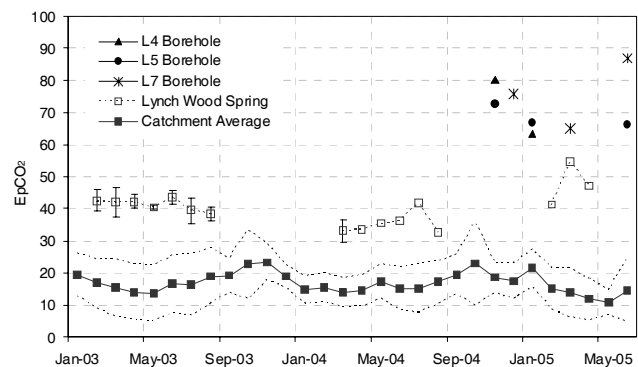


Fig. 4. Variation in averaged stream-water dissolved  $\text{CO}_2$  (s.d. boundaries indicated), compared to dissolved  $\text{CO}_2$  in spring and borehole sampled waters in the Lambourn catchment.

(mean monthly s.d. of all sites = 3.4). Both temporal and spatial variability is lower in the Lambourn catchment: variability between sites (mean monthly s.d. = 6.9) is still greater than variability in sites (mean monthly s.d. = 2.7), but to a lesser degree than samples taken from the Pang.  $\text{EpCO}_2$  data for bore-hole and spring water sampled in each catchment are also shown in Figs. 3 and 4. The  $\text{EpCO}_2$  calculated for spring-water samples was at least twice that calculated for river water samples (mean  $\text{EpCO}_2$  of 62.2 at the Blue Pool spring in the Pang, and 40.3 at Lynch Wood springs in the Lambourn). Groundwater samples retrieved from boreholes at P3 and L7 exhibited mean  $\text{EpCO}_2$  values of 81.8 and 76.2, respectively.

For both rivers, catchment averaged in-stream  $\text{EpCO}_2$  was minimal in May of 2003, 2004 and 2005, when streamflow in the rivers was near its maximum. Conversely, catchment averaged in-stream  $\text{EpCO}_2$  was at a maximum between September and November in 2003 and 2004, when streamflow in both rivers was low. This seasonal variability

may also be amplified by increased plant, macrophyte and algal activity in the river-bed in summer months (Neal *et al.*, 2002a), which promotes the breakdown of dissolved or particulate organic carbon (Neal *et al.*, 1998a). This seasonal variation is also observed in water samples taken from springs in each catchment, indicating that water being delivered to rivers via springs is also influenced by microbial activity that is more intense in summer.

The temporal variation in EpCO<sub>2</sub> at selected sites in the Lambourn and Pang catchments (Figs. 5 and 6) confirms that the trend of increasing stream EpCO<sub>2</sub> through the summer occurs at most sampled sites. This is particularly obvious for the sites in the Lambourn catchment (Fig. 5) which exhibit a relatively small range of variation between sites throughout the period of study. However, the relative ranking of EpCO<sub>2</sub> at sampling sites in each catchment may change with time relative to the location of the nearest active source of groundwater input. For example, low flow conditions in the upper Lambourn between September 2004

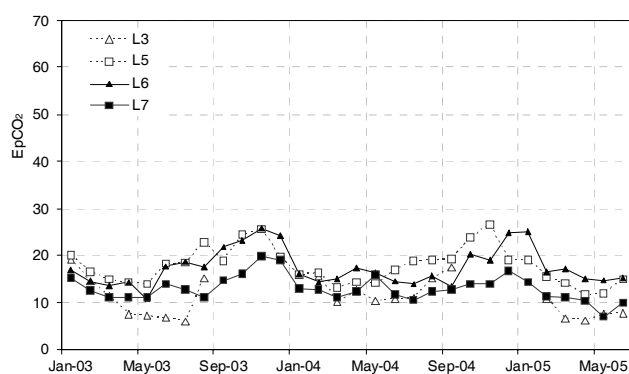


Fig. 5. Monthly average measured EpCO<sub>2</sub> for the sites at East Garston (L3), East Shefford House (L5), Welford Park (L6), and Westbrook Farm (L7) in the Lambourn catchment.

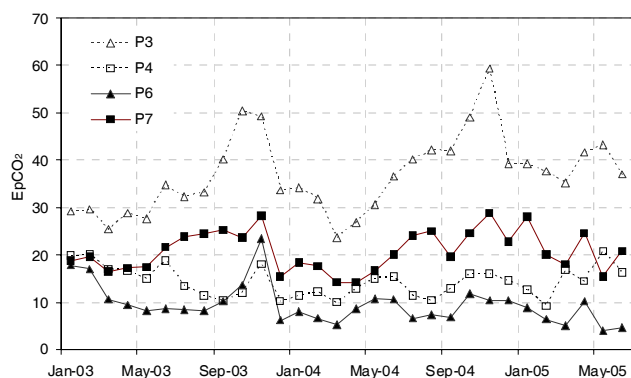


Fig. 6. Monthly average measured EpCO<sub>2</sub> for the in-stream sites at Firilsham Meadow (P3), River Barn (P4), Jewell's Farm (P6) and Frogmore Farm (P7) in the Pang catchment.

and January 2005 (as indicated by the cessation of flow at L3), led to increased EpCO<sub>2</sub> at L5 and L6, as springs in that area became the dominant source of streamflow. When streamflow in the upper catchment recommenced, EpCO<sub>2</sub> at these sites fell again as a higher proportion of streamflow consisted of groundwater from the upper catchment that was closer to atmospheric equilibrium.

In the Pang catchment, larger differences in EpCO<sub>2</sub> between sample sites are due to a greater number of groundwater springs contributing to streamflow. Where springs join the stream under low flow conditions, in-stream dissolved CO<sub>2</sub> is more significantly affected. For example, the mean monthly EpCO<sub>2</sub> calculated for P3 is ten times the atmospheric equilibrium than that of P7 (Fig. 6), even though a greater volume of groundwater actually enters the river channel just upstream of P7 (at Blue Pool). In-stream EpCO<sub>2</sub> at each site will, therefore, be a function of the distance of the site from the nearest upstream input of groundwater; the volume and CO<sub>2</sub> concentration of groundwater entering the stream; the volume and CO<sub>2</sub> concentration of water already in the stream; and the rate at which CO<sub>2</sub> will degas from the stream into the atmosphere.

A summary of downstream variation in mean EpCO<sub>2</sub> for the period studied is shown for the Pang and Lambourn in Figs. 7 and 8, respectively. Also shown is the mean flow accretion (m<sup>3</sup> s<sup>-1</sup> km<sup>-1</sup>) between the sites in each catchment. EpCO<sub>2</sub> was generally high at upstream sites in both rivers (P2 and P3 in the Pang and L1 in the Lambourn). Increases in stream EpCO<sub>2</sub> between each site correlate well with streamflow accretion. The increase in EpCO<sub>2</sub> between sites P6 and P7, representing the input from the Blue Pool springs, for example, corresponds to a streamflow accretion of approximately 0.15 m<sup>3</sup> s<sup>-1</sup> km<sup>-1</sup>. Similarly, Fig. 8 shows an increase in EpCO<sub>2</sub> between L3 and L4 in the Lambourn. This level of dissolved CO<sub>2</sub> is conserved through sites L5 and L6, representing a more diffused input of groundwater to the river, which is characteristic of this catchment. This is reflected by mean flow accretion of between 0.07 and 0.18 m<sup>3</sup> s<sup>-1</sup> km<sup>-1</sup>, between L3 and L7. These findings are consistent with previous studies in this area (Bradford, 2002; Grapes *et al.*, 2005; Grapes *et al.*, 2006; Griffiths *et al.*, 2006).

For both rivers, EpCO<sub>2</sub> reaches its maximum in November and its minimum in May. The summer rise in EpCO<sub>2</sub> coincides with the fall in streamflow, which reduces the dilution of the CO<sub>2</sub>-rich groundwater as it enters the stream. This result is similar to that of Pinol and Avila (1992) who found an inverse relationship between dissolved CO<sub>2</sub> and discharge in Mediterranean catchments, though lowest flows tended to exhibit greater variation in EpCO<sub>2</sub> and degassing of EpCO<sub>2</sub> tended to precipitate calcite. They also found, as

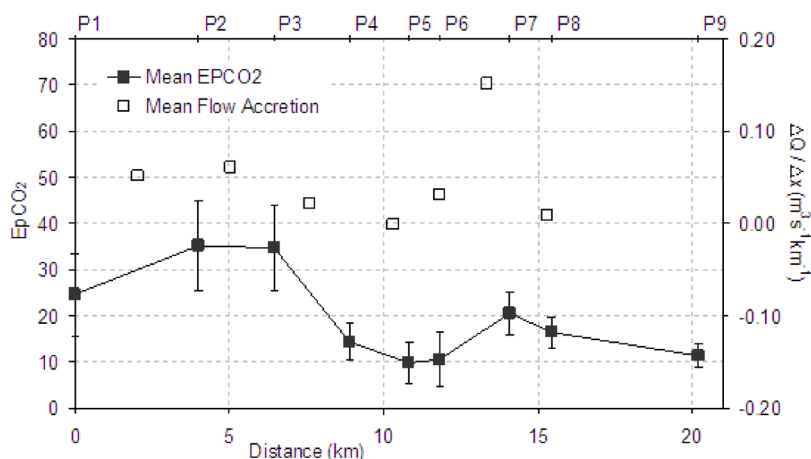


Fig. 7. Average calculated  $EpCO_2$  and mean flow accretion between sample points on the River Pang in the period Jan 2003 to Feb 2005.

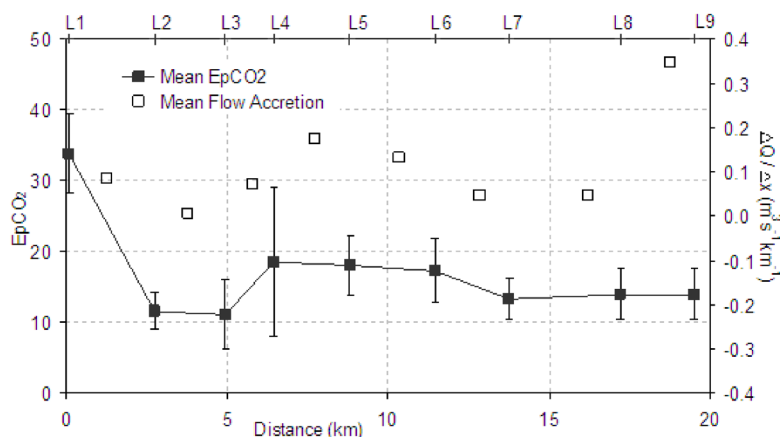


Fig. 8. Average calculated  $EpCO_2$  and mean flow accretion between sample points on the River Lambourn in the period Jan 2003 to Feb 2005.

in this study, that this pattern is disrupted during large storm events when  $EpCO_2$  increased with the storm hydrograph, in response to greater shallow groundwater delivery to the main channel system.

Standard deviation of  $EpCO_2$  was higher at sites of significant but intermittent surface-groundwater interactions. This occurred, for example, at L4 in the Lambourn catchment and at P2 and P3 in the Pang catchment, where the groundwater to surface water ratio varies throughout the year in response to seasonal groundwater recharge of streams. In addition to annual variation, Fig. 9 illustrates the monthly standard deviation ( $n=4$ ) of calculated  $EpCO_2$  at each site for 2003 to 2004. The higher variability when streamflow is at its annual minimum and stream  $EpCO_2$  is at its annual maximum, indicates that stream water-chemistry is extremely sensitive to even small increases in groundwater delivery (the variation is certainly above that expected in relation to

analytical chemistry errors). The standard deviation at the sampling site just downstream of the Blue Pool springs (P7) is small, underlining the consistency of its contribution to streamflow of the Pang as identified by Neal *et al.* (2000).

#### DIURNAL VARIATION

Average Gran alkalinity values determined for the Pang and Lambourn (4986 and 4532  $\mu Eq l^{-1}$ , respectively), were used with 15-minute resolution pH data collected from L5 and Shaw in the Lambourn catchment, and at P3, P5, P7 and P9 in the Pang catchment, to examine diurnal variation in  $EpCO_2$ . The method used follows one akin to that described by Neal *et al.* (2002a). At all of the sites, diurnal variation in  $EpCO_2$  was a maximum between 03:00 and 10:00, and a minimum between 14:00 and 15:00. Though both catchments had the same annual average pH (6.7), temporal variability in pH (and thus  $EpCO_2$ ) tended to differ between



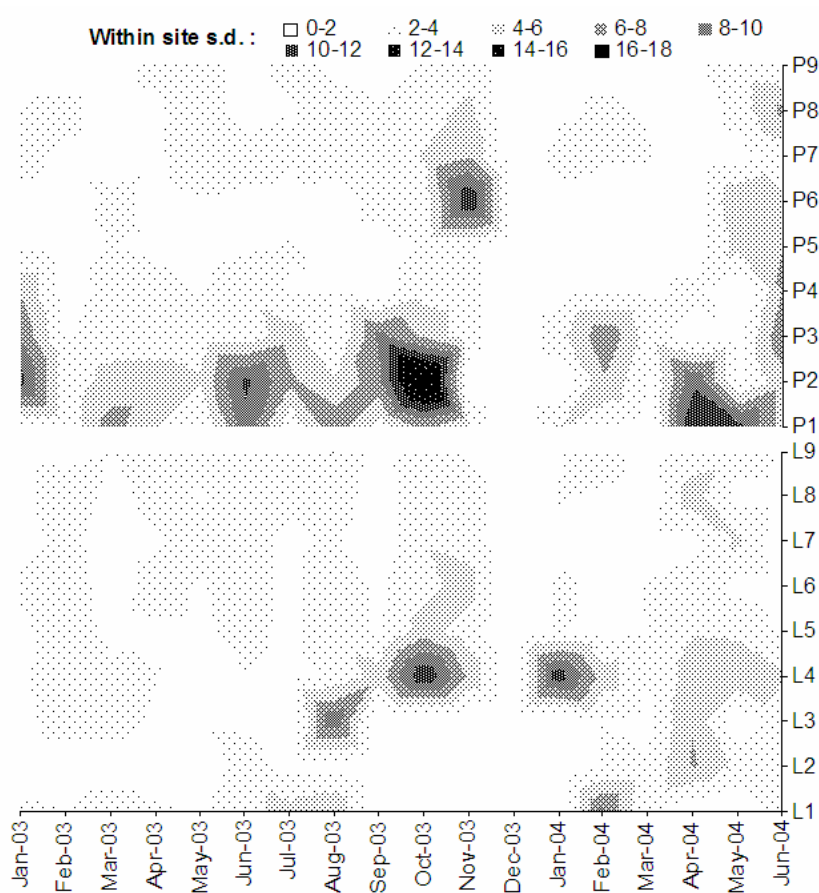


Fig. 9. Spatial variation in standard deviation of monthly calculated  $EpCO_2$  at sampling sites within the Pang and Lambourn catchment (2003–2004).

the catchments. For example, the maximum amplitude of diurnal variation occurred in the summer at sites in the Lambourn, but in spring at sites in the Pang. Catchment-averaged changes in stream  $EpCO_2$  are shown in Fig. 10 and Fig. 11. The flatter shape of the profile between evening and morning represents the duration of lower light levels and thus lower photosynthetic activity. Whilst the size of the diurnal variation is related to the amount of biological activity in the stream channel, the maximum percentage change in  $EpCO_2$  (relative to the catchment average) was lower in the Lambourn, reflecting not only lower concentrations of groundwater  $EpCO_2$  at many sites, but also higher volumes and velocity of streamflow, which tended to keep sites more free of vegetation.

In addition to the effect of increased biological activity, variations in stream  $EpCO_2$  may be related to river flow. Seasonal trends in streamflow were similar in both catchments. In the Lambourn, high flows ( $>3 \text{ m}^3 \text{ s}^{-1}$ ) occurred in January 2003, then decreased throughout the year to an autumn minimum of  $0.38 \text{ m}^3 \text{ s}^{-1}$ . Flow then increased into the spring of 2004. In the Pang, flows

$>1.21 \text{ m}^3 \text{ s}^{-1}$  in January decreased to a minimum of  $0.06 \text{ m}^3 \text{ s}^{-1}$  in October and, following this minima, flows began to increase into spring of 2004. These trends of low flows in the spring/summer due to decreased precipitation, coincide with values of high  $EpCO_2$ . This suggests that high summer in-stream  $EpCO_2$  is due both to increased biological activity and lower flows. The lower volume of 'degassed' water in the channel results in higher values of in-stream  $EpCO_2$  if inputs from local groundwater sources remain constant throughout the year (such as at Blue Pool). Under such conditions, biological activity will result in higher diurnal variation than is seen at sites with lower mean in-stream concentrations of  $EpCO_2$ . Tables 2 and 3 show the mean, minimum and maximum seasonal (monthly) values for streamflow, pH,  $EpCO_2$  and water temperature values for the Lambourn and Pang catchments during 2003. Whilst streamflow,  $EpCO_2$  and pH reach their seasonal maximum and minimum turning points around May and November, maximum water temperatures (representative of photosynthetic and respirative activity) occur mid-way between these months, in August. Seasonal variability in

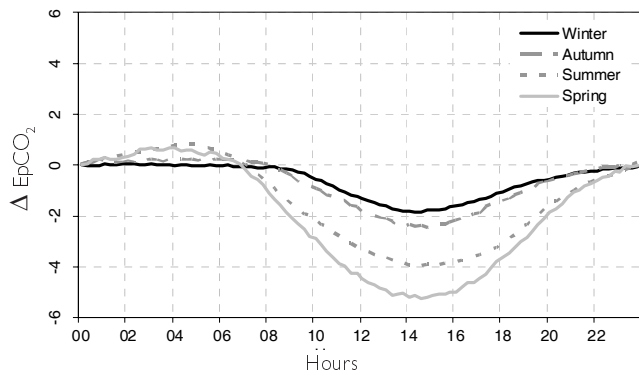


Fig 10. Seasonally averaged diurnal change in  $EpCO_2$  as calculated from 15 minute resolution pH data measured at P3, P5, P7 and P9 in the Pang.

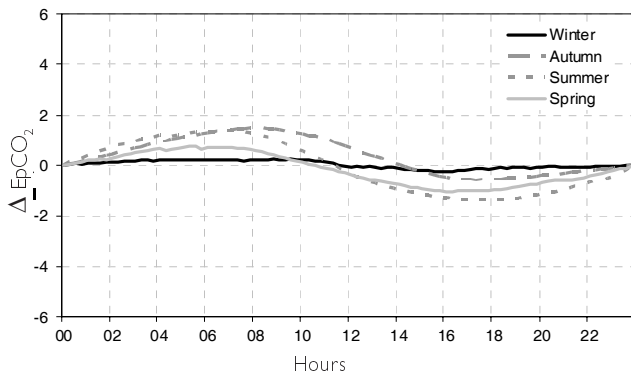


Fig 11. Seasonally averaged diurnal change in  $EpCO_2$  as calculated from 15 minute resolution pH data measured at L5 and Shaw gauging station in the Lambourn.

the standard deviation of the monthly averaged pH (and thus  $EpCO_2$ ) are greater in the Lambourn than in the Pang, with the standard deviation increasing during low flow spring/summer conditions.

GROUNDWATER  $EpCO_2$

Values of the  $EpCO_2$  of groundwater, sampled from boreholes adjacent to the rivers studied, are similar in both catchments, ranging between 65 and 90 times the concentration at atmospheric equilibrium (Figs. 3 and 4). In contrast, a mean magnitude of  $EpCO_2$  in water sampled from the Lynch Wood spring in the upper Lambourn (c. 100 m upstream of L1) of 40.3 (s.d.= 5.7), suggests that these springs are derived from a groundwater environment different from that of the groundwater sampled from boreholes. Mean  $EpCO_2$  of Blue Pool spring water in the lower Pang (c. 100 m upstream of P7) was 62.6 (s.d.= 7.6).

A more detailed description of the variability of shallow groundwater was obtained by sampling groundwater from a set of boreholes at L4 and at L5 (Fig. 12). Variability in  $EpCO_2$  decreased with depth at both sites and the highest levels of  $EpCO_2$  occurred at depths between 2 and 6 m below ground level in surveys conducted in November. This result agrees with the pattern seen in the streams and suggests that there may be some connectivity between the surface water and shallow groundwater at this site.

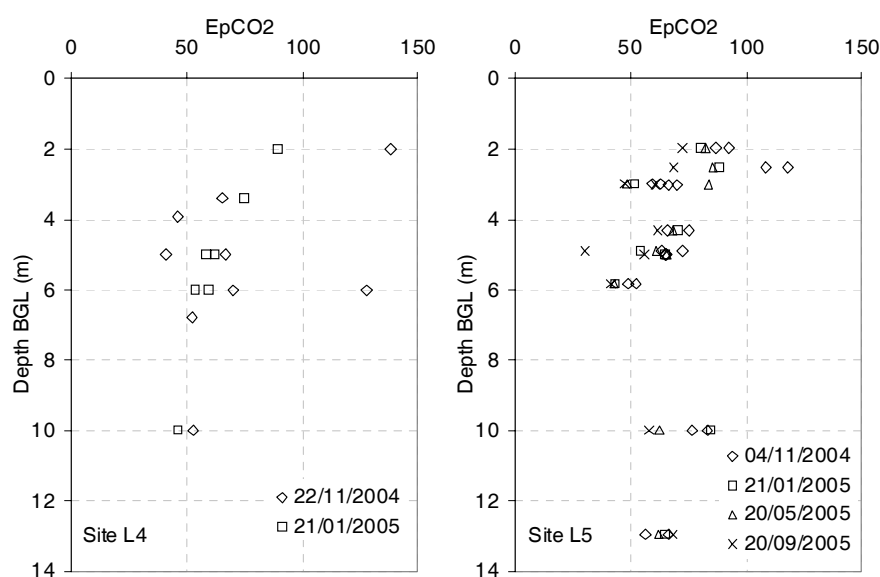
Catchment-averaged increases of in-stream  $EpCO_2$  correspond with increases in shallow groundwater  $EpCO_2$ , as indicated by samples obtained from spring water and

Table 2. The monthly physio-chemical variables for the Lambourn catchment (January-December 2003)

| Variable                                          | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
|---------------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>DISCHARGE (<math>m^3 s^{-1}</math>)</b>        |      |      |      |      |      |      |      |      |      |      |      |      |
| Minimum                                           | 0.21 | 0.17 | 0.33 | 0.20 | 0.14 | 0.12 | 0.02 | 0.00 | 0.00 | 0.13 | 0.00 | 0.12 |
| Maximum                                           | 5.53 | 3.49 | 3.11 | 1.86 | 1.78 | 1.22 | 0.94 | 1.02 | 0.86 | 0.55 | 0.73 | 0.97 |
| Mean                                              | 3.08 | 2.03 | 1.78 | 1.15 | 0.83 | 0.62 | 0.41 | 0.39 | 0.41 | 0.40 | 0.38 | 0.55 |
| <b>pH</b>                                         |      |      |      |      |      |      |      |      |      |      |      |      |
| Minimum                                           | 7.31 | 7.20 | 7.20 | 7.23 | 7.22 | 7.22 | 7.24 | 7.24 | 7.42 | 7.23 | 7.36 | 7.45 |
| Maximum                                           | 7.83 | 7.91 | 8.05 | 8.27 | 8.10 | 8.15 | 8.19 | 8.27 | 7.89 | 7.77 | 7.72 | 7.68 |
| Mean                                              | 7.63 | 7.66 | 7.71 | 7.77 | 7.76 | 7.68 | 7.70 | 7.64 | 7.63 | 7.60 | 7.56 | 7.61 |
| <b><math>EpCO_2</math></b>                        |      |      |      |      |      |      |      |      |      |      |      |      |
| Minimum                                           | 12.2 | 8.2  | 7.3  | 5.8  | 6.1  | 5.2  | 5.6  | 4.5  | 13.7 | 9.1  | 15.4 | 15.1 |
| Maximum                                           | 39.2 | 45.7 | 49.0 | 45.2 | 41.5 | 45.9 | 47.6 | 42.2 | 33.3 | 55.3 | 39.9 | 25.1 |
| Mean                                              | 19.2 | 19.0 | 17.7 | 16.5 | 16.1 | 19.5 | 18.8 | 20.2 | 20.6 | 23.9 | 24.6 | 20.5 |
| <b>WATER TEMPERATURE (<math>^{\circ}C</math>)</b> |      |      |      |      |      |      |      |      |      |      |      |      |
| Minimum                                           |      | 8.3  | 9.8  | 9.0  | 9.6  | 10.1 | 10.7 | 12.2 | 8.7  | 6.7  | 6.2  | 9.1  |
| Maximum                                           |      | 10.1 | 11.6 | 11.8 | 13.4 | 13.4 | 15.3 | 22.5 | 15.7 | 12.4 | 13.5 | 9.8  |
| Mean                                              |      | 9.6  | 10.6 | 10.7 | 11.5 | 12.0 | 13.2 | 15.6 | 10.8 | 9.2  | 9.6  | 9.3  |

Table 3. The monthly physio-chemical variables for the Pang catchment (January-December 2003)

| Variable                                    | Jan-03 | Feb-03 | Mar-03 | Apr-03 | May-03 | Jun-03 | Jul-03 | Aug-03 | Sep-03 | Oct-03 | Nov-03 | Dec-03 |
|---------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| DISCHARGE (m <sup>3</sup> s <sup>-1</sup> ) |        |        |        |        |        |        |        |        |        |        |        |        |
| Minimum                                     | 0.19   | 0.50   | 0.11   | 0.05   | 0.08   | 0.10   | 0.06   | 0.03   | 0.01   | 0.00   | 0.00   | 0.01   |
| Maximum                                     | 1.82   | 1.88   | 1.26   | 0.99   | 0.81   | 0.58   | 0.47   | 0.32   | 0.33   | 0.20   | 0.21   | 0.58   |
| Mean                                        | 1.21   | 1.19   | 0.73   | 0.56   | 0.44   | 0.29   | 0.21   | 0.13   | 0.09   | 0.06   | 0.07   | 0.18   |
| pH                                          |        |        |        |        |        |        |        |        |        |        |        |        |
| Minimum                                     | 7.37   | 7.11   | 7.10   | 7.10   | 7.10   | 7.10   | 7.10   | 7.10   | 7.06   | 7.00   | 7.04   | 7.21   |
| Maximum                                     | 7.84   | 7.85   | 8.12   | 8.08   | 8.35   | 8.12   | 8.24   | 8.16   | 8.15   | 8.22   | 7.98   | 8.12   |
| Mean                                        | 7.62   | 7.60   | 7.71   | 7.72   | 7.77   | 7.67   | 7.67   | 7.70   | 7.66   | 7.60   | 7.51   | 7.73   |
| EpCO <sub>2</sub>                           |        |        |        |        |        |        |        |        |        |        |        |        |
| Minimum                                     | 11.3   | 12.9   | 7.5    | 6.3    | 2.3    | 7.2    | 6.3    | 6.9    | 7.2    | 6.4    | 8.7    | 5.5    |
| Maximum                                     | 40.2   | 60.7   | 74.5   | 78.8   | 67.9   | 75.6   | 72.8   | 71.2   | 78.3   | 81.0   | 81.7   | 63.3   |
| Mean                                        | 20.8   | 24.2   | 21.6   | 22.3   | 20.5   | 24.2   | 25.2   | 23.7   | 25.7   | 29.8   | 31.1   | 20.2   |
| WATER TEMPERATURE (°C)                      |        |        |        |        |        |        |        |        |        |        |        |        |
| Minimum                                     |        | 6.1    | 7.4    | 9.5    | 10.5   | 10.2   | 10.5   | 10.5   | 8.1    | 5.2    | 6.9    | 4.2    |
| Maximum                                     |        | 9.6    | 10.7   | 13.4   | 16.9   | 18.8   | 18.9   | 23.6   | 19.2   | 13.4   | 12.1   | 10.6   |
| Mean                                        |        | 8.2    | 9.1    | 10.4   | 12.6   | 13.6   | 13.8   | 15.0   | 11.9   | 9.8    | 9.7    | 7.1    |


 Fig. 12. EpCO<sub>2</sub> sampled from borehole at site L4 and L5 in the Lambourn between winter 2004 and autumn 2005.

shallow boreholes in both catchments. The Blue Pool spring, for example, shows an increase in EpCO<sub>2</sub> of approximately ten times the atmospheric equilibrium between May and September in 2004, a period in which mean river EpCO<sub>2</sub> saw a comparable increase. This pattern is repeated in the Lambourn, where stream EpCO<sub>2</sub> between L1 and L5 shows good correlation with EpCO<sub>2</sub> at Lynch Wood spring. This

effect may be due to mixing of surface and groundwater, and microbial activity within the hyporheic zone. The groundwater samples obtained from shallow boreholes at sites L4 and L5 in November 2004 (Fig. 10), indicate greater variability at depths of between 2 and 6 m at this time of year.

## Conclusion

A better understanding of surface-groundwater interactions is crucial for the effective management of groundwater-fed rivers. To date, the description of such interactions has been limited by a lack of readily available data regarding the extent and nature of such interactions. In this study, it is suggested that a simple sampling strategy, together with a laboratory analysis method for calculation of  $\text{EpCO}_2$ , could improve understanding of surface-groundwater interaction in riparian areas of permeable lowland catchments.

Using measurements of river flow, pH, and average Gran alkalinity, semi-quantitative analysis to characterise the extent of surface-groundwater interaction in a catchment was achieved. The spatial variation in surface-water  $\text{EpCO}_2$  was related predominantly to flow accretion due to the inflow of  $\text{CO}_2$  rich groundwater.  $\text{CO}_2$  production and consumption due to biological photosynthetic activity was not significant enough to mask the net difference in dissolved  $\text{CO}_2$  between most sites (max. diurnal variation in  $\text{EpCO}_2 = -5.25$ ). Changes in  $\text{EpCO}_2$  between sample sites could therefore be related directly to the delivery of groundwater from diffuse or point-source locations in both the Lambourn and the Pang. The results indicate that the source of groundwater in these two catchments is of different origin. The Pang for example, exhibits higher levels of  $\text{EpCO}_2$  in groundwater, spring water and stream water.

Seasonal variation of in-stream  $\text{EpCO}_2$  due to biotic photosynthetic activity was greater in the Pang, but followed groundwater  $\text{EpCO}_2$  closely in both the Lambourn and Pang — again confirming a high level of surface-groundwater interaction in these catchments. The assessment of the diurnal  $\text{EpCO}_2$  variation using high-resolution pH data showed an early morning maximum and a mid-afternoon minimum. This is consistent with maximum respiration (release of  $\text{CO}_2$  into the water column) during darkness, and photosynthesis (removal of  $\text{CO}_2$  from the water column) during the daytime. Diurnal variation is at its highest in the spring/summer; which is consistent with the study by Neal *et al.* (2002a) which shows that large diurnal patterns of change in dissolved  $\text{CO}_2$  were maximal during the summer months.

This paper assesses the dynamics of surface-groundwater interactions, and thus, the extent of processes related to changes in dissolved  $\text{CO}_2$  in the Pang and Lambourn. This new information on the spatial and temporal variability of  $\text{EpCO}_2$  in the Pang and Lambourn catchments at a number of different scales may help in assessing the variability in calcite saturation of the rivers studied, which in turn may be used to describe the potential for phosphorous co-precipitation and the so-called 'self-cleansing' potential of

Chalk rivers (Neal, 2001b, 2002). Similarly, as  $\text{CO}_2$  degassing affects the pH of water bodies, the estimates of dissolved  $\text{CO}_2$  may be a measure of the propensity of a stream to carry metal contaminants relative to processes of dissolution and precipitation (Runkel *et al.*, 1996).

This paper confirms the appropriateness of using a simple water sampling strategy to identify areas of increased surface-groundwater interaction in Chalk catchments. Such a method may well be a simple but effective tool in improving scientific understanding of catchment-scale processes of major aquifers in the UK, a need identified in the main objectives of the LOCAR project. This is particularly relevant for the study and management of water resources in lowland permeable catchments where competition in socio-economic demands can lead to increased stress on water-dependent ecology.

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## References

- Aldiss, D.T., Marks, R.J., Newell, A.J., Royse, K.A., Hopson, P.M., Farrant, A.R., Aspden, J.A., Napier, B., Wilkinson, I.P. and Woods, M.A., 2002. *The geology of the Pang-Lambourn Catchment, Berkshire*. British Geological Survey Commissioned Report, CR/02/298N. 38pp.
- Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., MacDonald, A.M., Wagstaff, S.J. and Williams, A.T., 1997. *The physical properties of major aquifers in England and Wales*. British Geological Survey Technical Report WD/97/34, p 312, EA R&D Publication 8.
- Banks, D., Davies, C. and Davies, W., 1995. The Chalk as a karstic aquifer: evidence from a tracer test at Stanford Dingley, Berkshire, UK. *Quart. J. Eng. Geol.*, **28**, S31–S38.
- Bradford, R.B., 2002. Controls on the discharge of Chalk streams of the Berkshire Downs, UK. *Sci. Total Envir.*, **282/283**, 65–80.
- Brettal, E.J., 1971. *Report on the Lambourn Valley Pilot Scheme 1967-1969*. Thames Conservancy, Reading, UK.
- Choi, J., Hulseapple, S.M., Conklin, M.H. and Harvey, J.W., 1998. Modeling  $\text{CO}_2$  degassing and pH in a stream-aquifer system. *J. Hydrol.*, **209**, 297–310.
- Cook, P.G., Favreau, G., Dighton, J.C. and Tickell, S., 2003. Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. *J. Hydrol.*, **277**, 74–88.
- Edmunds, E.M., Darling, W.G., Kinniburgh, D.G., Dever, L. and Vachier, P., 1992. *Chalk groundwater in England and France: hydro-geochemistry and water quality*. British Geological Survey Research Report SD/92/2.
- Elliot, T., Andrews, J.N. and Edmunds, W.M., 1999. Hydrochemical trends, palaeorecharge and groundwater ages in the fissured Chalk aquifer of the London and Berkshire Basins, UK. *Appl. Geochem.*, **14**, 333–363.

- Finlay, J.C., 2003. Controls of streamwater dissolved inorganic carbon dynamics in a forested watershed. *Biogeochemistry*, **62**, 231–252.
- Genereux, D.P. and Hemond, H.F., 1992. Determination of gas exchange rate constants for a small stream on Walker Branch Watershed, Tennessee. *Water Resour. Res.*, **28**, 2365–2374.
- Grapes, T.R., Bradley, C. and Petts, G.E., 2005. Dynamics of river-aquifer interactions along a chalk stream: the River Lambourn, UK. *Hydrol. Process.*, **19**, 2035–2053.
- Grapes, T.R., Bradley, C. and Petts, G.E., 2006. Hydrodynamics of floodplain wetlands in a chalk catchment: The River Lambourn, UK. *J. Hydrol.*, **320**, 324–341.
- Griffiths, J., Binley, A., Crook, N., Nutter, J., Young, A. and Fletcher, S., 2006. Streamflow generation in the Pang and Lambourn catchments, Berkshire, UK. *J. Hydrol.*, **330**, 71–83.
- Gustard, A., Bullock, A. and Dixon, J.M., 1992. Low flow estimation in the United Kingdom. *Institute of Hydrol. Report No. 108*, Wallingford, UK.
- Hill, T. and Neal, C., 1997. pH, alkalinity and conductivity in runoff and groundwater. *Hydrol. Earth Syst. Sci.*, **3**, 381–394.
- Howland, R.J.M., Tappin, A.D., Uncles, R.J., Plummer, D.H. and Bloomer, N.J., 2002. Distributions and seasonal variability of pH and alkalinity in the Tweed Estuary. UK. *Sci. Total Environ.*, **251/252**, 125–138.
- James, E.R., Manga, M., Rose, T.P. and Hudson, G.B., 2000. The use of temperature and the isotopes of O, H, C and noble gases to determine the pattern and spatial extent of groundwater flow. *J. Hydrol.*, **237**, 1–2.
- Jacobson, R.L. and Uzdowski, E., 1975. Geochemical controls on a calcite precipitating spring. *Cont. Min. Pet.*, **51**, 65–74.
- Malcolm, I.A., Soulsby, C., Youngson, A.F., Hannah, D.M., McLaren, I.S. and Thorne, A., 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival. *Hydrol. Process.*, **18**, 1543–1560.
- Maurice, L., Atkinson, T., Barker, J.A., Bloomfield, J., Farrant, A.R., and Williams, R.J. 2006. Karstic behaviour of groundwater in the English Chalk. *J. Hydrol.*, **330**, 63–70.
- Neal, C., 1988. Determination of dissolved CO<sub>2</sub> in upland stream water. *J. Hydrol. Sci.*, **99**, 127–142.
- Neal, C., 2001a. Alkalinity measurements within natural waters: towards a standardised approach. *Sci. Total Environ.*, **265**, 99–113.
- Neal, C., 2001b. The potential for phosphorous pollution remediation by calcite precipitation in UK freshwaters. *Hydrol. Earth Syst. Sci.*, **5**, 119–131.
- Neal, C., 2002. Calcite saturation in eastern UK rivers. *Sci. Total Environ.*, **282**, 311–26.
- Neal, C., Robson, A. and Smith, C.J., 1990. Acid neutralization capacity variations for the Hafren forest streams, Mid-Wales: inferences for hydrological processes. *J. Hydrol.*, **121**, 85–101.
- Neal, C., Harrow, M. and Williams, R.J., 1998a. Dissolved carbon dioxide and oxygen in the River Thames: Spring-summer 1997. *Sci. Total Environ.*, **210/211**, 205–211.
- Neal, C., House, W.A. and Down, K., 1998b. An assessment of excess carbon dioxide partial pressures in natural waters based on pH and alkalinity measurements. *Sci. Total Environ.*, **210/211**, 173–185.
- Neal, C., House, W.A., Jarvie, H.P. and Eatherall, A., 1998c. The significance of dissolved carbon dioxide in major lowland rivers entering the North Sea. *Sci. Total Environ.*, **210/211**, 187–203.
- Neal, C., Neal, M., Wickham, H. and Harrow, M., 2000. The water quality of a tributary of the Thames, the Pang, southern England. *Sci. Total Environ.*, **251/252**, 459–475.
- Neal, C., Watts, C., Williams R.J., Neal, M., Hill, L. and Wickham, H., 2002a. Diurnal and longer term patterns in carbon dioxide and calcite saturation for the River Kennet, south-eastern England. *Sci. Total Environ.*, **282/283**, 205–231.
- Neal, C., Jarvie, H.P., Williams, R.J., Neal, M., Wickham, H. and Hill, L., 2002b. Phosphorus-calcium carbonate saturation relationships in a lowland chalk river impacted by sewage inputs and phosphorus remediation: an assessment of phosphorus self-cleansing mechanisms in natural waters. *Sci. Total Environ.*, **282/283**, 295–310.
- Neal, C., Skeffington, R., Neal, M., Wyatt, R., Wickham, H., Hill, L. and Hewitt, N., 2004a. Rainfall and runoff water quality of the Pang and Lambourn, tributaries of the River Thames, south eastern England. *Hydrol. Earth Syst. Sci.*, **8**, 601–613.
- Neal, C., Jarvie, H.P., Wade, A.J., Neal, M., Wyatt, R., Wickham, H., Hill, L. and Hewitt, N., 2004b. The water quality of the LOCAR Pang and Lambourn catchments. *Hydrol. Earth Syst. Sci.*, **8**, 614–635.
- NRFA, 2004a. National Rivers Flow Archive; Summary sheet for station 39019 – Lambourn at Shaw [online]. Available from: [http://www.nerc-wallingford.ac.uk/ih/nrfa/station\\_summaries/039/019.html](http://www.nerc-wallingford.ac.uk/ih/nrfa/station_summaries/039/019.html) [accessed 02/12/04]
- NRFA, 2004b. National Rivers Flow Archive; Summary sheet for station 39027 – Pang at Pangbourne. [http://www.nerc-wallingford.ac.uk/ih/nrfa/station\\_summaries/039/027.html](http://www.nerc-wallingford.ac.uk/ih/nrfa/station_summaries/039/027.html) [accessed 02/12/04]
- Pinol, J. and Avila, A., 1992. Streamwater pH, alkalinity, pCO<sub>2</sub>, and discharge relationships in some forested Mediterranean catchments. *J. Hydrol.*, **131**, 205–225.
- Raymond, P.A. and Cole, J.J., 2001. Gas exchange in rivers and estuaries: Choosing a gas transfer velocity. *Estuaries*, **24**, 312–317.
- Rodgers, P., Soulsby, C., Petry, J., Malcolm, I., Gibbons, C. and Dunn, S., 2004. Groundwater-surface-water interactions in a braided river: a tracer-based assessment. *Hydrol. Process.*, **18**, 1315–1332.
- Runkel, R.L., McKnight, D.M., Bencala, K.E. and Chapra, S.C., 1996. Reactive solute transport in streams: simulation of a pH modification experiment. *Water Resour. Res.*, **32/2**, 419–430.
- Schurr, J.M. and Ruchti, J., 1977. Dynamics of O<sub>2</sub> and CO<sub>2</sub> exchange, photosynthesis and respiration in rivers from time-delayed correlations with ideal sunlight. *Limnol. Oceanogr.*, **22**, 208–225.
- Simonsen, J.F. and Harremoes, P., 1978. Oxygen and pH fluctuations in rivers. *Water Res.*, **12**, 477–489.
- Wheater, H.S. and Peach, D., 2004. Developing interdisciplinary science for integrated catchment management: the UK LOWland CAatchment Research (LOCAR) programme. *Int. J. Water. Res. Develop.*, **20**, 369–385.
- Wilcock, R.J., Champion, P.D., Nagels, J.W. and Croker, G.F., 1999. The influence of aquatic macrophytes on the hydraulic and physio-chemical properties of a New Zealand lowland stream. *Hydrobiologia*, **416**, 203–214.
- Worrall, F. and Lancaster, A., 2005. The release of CO<sub>2</sub> from river water – the contribution of excess CO<sub>2</sub> from groundwater. *Biogeochem.*, **76**, 299–317.
- Younger, P.L. and Elliot, T., 1995. Chalk fracture system characteristics: implications for flow and solute transport. *Quart. J. Eng. Geol.*, **28**, S39–S50.