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2 Controls on the spatial and temporal variability of
3 ^{222}Rn in riparian groundwater in a lowland Chalk
4 catchment

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1 **Abstract**

2 Radon is a powerful tracer of stream-aquifer interactions. However, it is important
3 to consider the source and behaviour of radon in groundwater when interpreting
4 observations of river radon in relation to groundwater discharge. Here we characterise
5 the variability in groundwater radon concentrations in the riparian zone of a Chalk
6 catchment. Groundwater ^{222}Rn (radon) concentrations were determined in riparian
7 zone boreholes at two sites in the Lambourn catchment, Berkshire, UK, over a two
8 year period. In addition, borehole core material was analysed for ^{226}Ra (radium) and
9 to determine radon emanation. Radon and radium concentrations and radon emanation
10 were found to change with depth and temporal variations in groundwater radon
11 concentrations were found at different scales. The abundance of radium and
12 emanation of radon increased nearer the surface leading to greater groundwater radon
13 concentrations. It is shown that seasonal changes in water table elevation can lead
14 to variable radon concentrations in groundwater as zones of radon production become
15 hydraulically active. Groundwater radon concentrations in shallow piezometers were
16 found to respond to both seasonal changes in the water table and individual rainfall
17 events. Riparian sources of radon can be variable and are therefore potentially
18 influential in the radon signals observed in rivers and should be properly characterised
19 when interpreting river radon inputs.
20

1 **1. Introduction**

2 Groundwater-river water interactions are of great importance in groundwater
3 dominated catchments such as those found in Chalk areas. The conditions under
4 which groundwater will maintain river flow and the interactions between these bodies
5 of water must be understood to allow effective catchment management. Groundwater
6 makes up one third of public water supplies in England and Wales, with
7 approximately half of this coming from Chalk aquifers (Downing, 1993). The
8 importance of Chalk catchments for water supply, as well as their ecological and
9 amenity value, means that competing pressures on groundwater abstraction and river
10 flows must be balanced.

11 Tracers are an important tool in the study of interactions between ground and river
12 waters and enable the understanding of transport and mixing processes between water
13 bodies. Tracers allow the identification and quantification of flow paths and
14 estimation of the mixing ratios of water bodies, if sufficiently different chemical
15 signatures can be identified for each end member.

16 Radon is a radioactive noble gas produced by the decay of radium that has been
17 widely used as a tracer in groundwater studies. There are three naturally occurring
18 isotopes of radon: ^{219}Rn , ^{220}Rn and ^{222}Rn . Here we are concerned only with the ^{222}Rn
19 isotope, as the others have short half lives ($t_{1/2} < 1$ minute) which preclude them from
20 the methods of analysis used here. ^{222}Rn ($t_{1/2} = 3.82$ days) is the daughter of ^{226}Ra and
21 both are members of the ^{238}U decay series. From here on the term 'radon' refers solely
22 to the ^{222}Rn isotope. The terms 'parent' and 'daughter' are used to describe the
23 decaying and the resulting nuclides respectively.

24 Uranium is present in different mineral phases of all rock types at varying
25 concentrations (Ball et al., 1991). Differences in the abundance and distribution of

1 minerals, and therefore uranium and radium, lead to differences in radon production
2 and emanation between geological units. Emanation describes amount of radon
3 produced by decay of radium released from a material, in this case that which escapes
4 the rock matrix into solution in the saturated zone of an aquifer. Emanation may be
5 referred to as a rate if measured as the activity of radon released from a material per
6 unit time or as a coefficient, which reflects the proportion of radon produced by
7 radium that is released from a material. Radon emanation and the processes involved
8 are discussed comprehensively in Osmond and Ivanovich (1992) and Porcelli and
9 Swarzenski (2003). Radon is chemically and biologically inert and so in the saturated
10 zone of an aquifer there are no sources other than the decay of ^{226}Ra and no sinks
11 other than its own radioactive decay. The chemical and physical characteristics of
12 radon make it a potentially powerful tracer in the study of groundwater-river water
13 interactions.

14 Radon has several advantages over other natural and anthropogenic tracers. As a
15 gas, radon is readily lost from river water to the atmosphere, where concentrations are
16 negligible by comparison. The enrichment of radon in groundwater with respect to
17 surface waters means that it is easily detectable in zones of groundwater discharge
18 and subsequent degassing to the atmosphere allows the detection of successive
19 groundwater inputs to a river. Sample collection and analysis requires relatively
20 simple field and laboratory techniques and analysis by liquid scintillation
21 spectrometry can be automated allowing for high sample throughput (Pates and
22 Mullinger, 2007).

23 In a closed system, ^{222}Rn will reach radioactive equilibrium with its parent ^{226}Ra .
24 Radioactive equilibrium occurs when the activity of the daughter nuclide is equal to
25 that of its parent, which is reached after approximately five daughter half-lives. The

1 3.82 day half life of radon means that equilibrium with a radium source will be
2 achieved in approximately 20 days. Previous studies of radon in groundwaters have
3 shown that its presence in solution is usually in excess of any dissolved radium
4 (summarised in Osmond and Cowart, 1992). Therefore, the majority of dissolved
5 radon must have been produced by decay of solid-phase radium and then released into
6 groundwater via emanation processes. Due to radon's short half-life and the tendency
7 for concentrations to evolve towards equilibrium with its parent, we can assume that
8 radon in groundwater is mostly derived from the recent flow path and not solution
9 phase radium from historic flow paths. Radon is, therefore, indicative of the
10 immediate geological environment unlike other solutes which may be transported
11 over greater distances.

12 Radon has been applied to the tracing of groundwater inputs into rivers and oceans
13 (e.g. Burnett et al., 2006; Cook et al., 2003; Genereux et al., 1993; Hamada, 1999; Lee
14 and Kim, 2006; Swarzenski et al., 2007) and in investigations of groundwater-river
15 water interactions (e.g. Bertin and Bourg, 1994; Hoehn and von Gunten, 1989;
16 Macheleidt et al., 2002; Schubert et al., 2004). These studies have usually sampled a
17 number of groundwater monitoring wells in a catchment or aquifer and utilised either
18 the mean or most reasonable single values as representative of catchment waters, i.e. a
19 constant source term to the river is assumed (Cook et al., 2003; Ellins et al., 1990;
20 Genereux and Hemond, 1990). Cook et al. (2006) took account of spatial variability
21 of radon production within a river reach due to changes in geology while Genereux
22 and Hemond (1990) distinguished between vadose zone water and saturated zone
23 water from the soil and bedrock horizons.

24 Recent work (Mullinger et al., 2007) has shown that temporal as well as spatial
25 variation of radon in groundwater inputs can occur. Mullinger et al. used radon to

1 develop an understanding of some of the controls on groundwater inputs to the Pang
2 and Lambourn Chalk catchments in South-East England. In the Pang catchment
3 temporally variable radon concentrations in spring discharges exerted a strong
4 influence over river radon concentrations. In the Lambourn, the modelled radon
5 concentration in groundwater entering the river varied over time and appeared to
6 reflect local flow accretion. Grapes et al. (2006) observed that river stage in the
7 Lambourn was closely related to local groundwater levels and the Lambourn's
8 alluvial aquifer. The water table immediately adjacent to the river was generally 0.2-
9 0.4 m higher than the river stage, with no flow in the river when the water table falls
10 below the level of the river bed (Grapes et al., 2005). Changes in radon inputs are
11 thought to be indicative of connectivity with the alluvial aquifer located in the river
12 valley. Therefore, it is hypothesised that changes in the level of the local water table
13 have an impact on the source of radon being supplied to the river in the Lambourn.
14 This hypothesis is the focus of the present study.

15 Groundwater studies of radon in the Chalk of the UK have previously focused on
16 deep groundwaters. Sampling has typically been from public supply boreholes for the
17 purpose of investigating bulk aquifer properties (e.g. Low, 1996; Younger and Elliot,
18 1995). Observations by Low at public supply boreholes in the Chalk of East Anglia,
19 UK showed temporal variations in groundwater radon concentrations of up to 3 Bq l^{-1}
20 in individual boreholes and a range of 3.5 to 9 Bq l^{-1} across the different sites. A large
21 recharge event was shown to significantly lower groundwater radon concentrations
22 across several boreholes. Low suggests that lower radon concentrations occur during
23 times of recharge.

24 Another example of temporal changes in groundwater radon concentrations is
25 found in a study of spring water derived from the Mendip Hills near Bristol (Andrews

1 and Wood, 1972). Andrews and Wood (1972) observed generally higher radon
2 concentrations during periods of higher rainfall in water from two springs discharging
3 from the Carboniferous Limestone of the Mendips. The studies by Low (1996) and
4 Andrews and Wood (1972) show that, despite differences in the systems being
5 observed, temporal changes in groundwater radon can exist under different
6 hydrological conditions.

7 The source and behaviour of radon in groundwater are important factors in
8 interpreting observations of river radon in relation to stream-aquifer interactions. In
9 this paper we concentrate on the spatial and temporal variations that exist in the
10 groundwater system only. The aims of this work are to characterise spatial variability
11 in the sources of radon relevant to groundwater-river interactions, i.e. the groundwater
12 and aquifer immediately adjacent to the river, to understand temporal changes in
13 groundwater radon in this zone and to add to the relatively sparse data that exists on
14 radon in Chalk catchments.

15

16 **2. Site description**

17 The Lambourn is a groundwater dominated Cretaceous Chalk catchment
18 (Bradford, 2002) located in West Berkshire, UK (Fig. 1). The outcropping solid
19 geology is almost entirely Chalk with minor Palaeogene deposits overlying the lower
20 catchment and significant drift deposits in the river valley (Allen et al., 1997).

21 Groundwater dominated catchments are often, but not exclusively, characterised
22 by stable flow conditions with a high base flow index as well as stable temperature
23 and chemistry signals (Sear et al., 1999). The base flow index in the Lambourn is 0.96
24 (Grapes et al., 2005) and Neal et al. (2004) observed stable Ca, Mg and Sr profiles
25 along the length of the perennial river channel. Stable physical and chemical

1 parameters in catchments of this type mean that many natural tracers are of limited
2 use due to the homogeneity of water in the aquifer and river. As well as its importance
3 as a water source, the River Lambourn is of high ecological value as recognised by its
4 designation as a Site of Special Scientific Interest. The Lambourn catchment itself has
5 a topographical catchment area of 234 km² (Griffiths et al., 2006) and is a tributary of
6 the River Kennet, which in turn flows into the River Thames.

7 This paper focuses on the results of investigations carried out at two borehole
8 installations in the Lambourn valley at Maidencourt Farm (MCT) and East Shefford
9 (ESF) (Fig. 1). The study sites are located approximately halfway down the length of
10 the catchment, where boreholes with nested piezometer arrays have been drilled in the
11 riparian zone. Drilling took place in June 2004 and at each site five boreholes were
12 installed, each with two piezometers screened at different depths. Inset diagrams in
13 Fig. 1 show the layout of each site with respect to the river channel. The nomenclature
14 of the boreholes is described by the site initials (MCT or ESF) followed by a number
15 (1-5), which relates to the individual boreholes shown in Fig. 1 and Fig. 2, and a
16 second number (1 or 2), which defines the piezometer, piezometer 1 being the deeper
17 and piezometer 2 the shallower. E.g. MCT4-2 describes the shallow piezometer in
18 borehole 4 at Maidencourt Farm. The piezometers at these sites range in depth from
19 1.6 to 12.5 m bgl, with screened sections 0.8 m in length. At each site, four of the
20 boreholes are located in the alluvial plain close to the river and an additional deeper
21 borehole at each site (MCT1 and ESF1) is located further from the river on an
22 adjacent hill slope with both piezometers in these boreholes being located in the
23 Chalk rather than the alluvium (Fig. 2). A common lithology is found at these
24 borehole sites. From 0 to 0.5 m there is a layer of stony / gravelly soil below which
25 alluvial material is found mixed with marl and flint gravels to approximately 4 m.

1 This alluvial layer is very heterogeneous between boreholes, with some sandy and
2 clayey layers found amongst chalky soils, and tends to be 0.5-1 m thicker at East
3 Shefford. From 4 to 10 m is predominantly weathered Chalk and below 10 m the
4 Chalk becomes more consolidated. The hill slope boreholes (MCT1 and ESF1) have a
5 soil layer (~ 0.5 m) overlying weathered Chalk.

6

7 **3. Methods**

8 Routine borehole sampling was carried out between January 2005 and May 2006.
9 This involved collecting triplicate samples from each piezometer on an approximately
10 monthly basis. Additional sampling was also carried out at the end of 2006 to monitor
11 the response of groundwater radon concentrations to rainfall events.

12 Groundwater samples were taken from piezometers using a submersible pump
13 fitted with a suitable length of hose and the pump inlet positioned in the middle of the
14 screened section. First the piezometer was purged of three times the volume of the
15 screened section to remove any water that may have been residing there for some
16 time. Then 5 litres water were carefully pumped to a bucket from which a standard
17 600 ml bottle was filled and sealed under the water surface to exclude any air. A
18 further three screened section volumes were removed between samples, with triplicate
19 sampling used to ensure that the radon concentrations measured were representative
20 and had stabilised after purging.

21 Dissolved radon concentrations were determined by liquid scintillation
22 spectrometry (LSS) according to Pates and Mullinger (2007). Samples were extracted
23 using 20 ml of toluene, with a 10 ml aliquot being combined with the scintillation
24 cocktail Ultima Gold LLT (PerkinElmer) in a low-potassium glass vial before
25 counting for 60 minutes on a Packard Tri-Carb 3170 liquid scintillation counter.

1 Borehole radon concentrations are means of triplicate samples and errors are standard
2 deviations of the triplicate results. This method is hereafter referred to as the
3 “Toluene” method.

4 To verify the results of the Toluene analyses an additional method (ASTM, 1998)
5 was used. Ten millilitre samples of borehole water were taken from an overflowing
6 funnel attached to the pump outlet using a disposable syringe. These samples were
7 injected into pre-weighed glass scintillation vials containing the water-immiscible
8 scintillation cocktail Ultima Gold F (PerkinElmer), which were then counted (as
9 above) with no further processing. This method of analysis was the only one
10 employed in event sampling due to the logistics of collecting and analysing samples
11 over the observation period. Results for these analyses are for single samples; the
12 errors quoted are the result of propagated counting and analytical errors. In all cases
13 the relative errors of radon analysis by both methods are less than 10 %. Field trials of
14 these radon analysis methods found highly reproducible results between replicate
15 sample analyses. Relative standard deviations of 5.2 % (n = 25) and 2.3 % (n = 19)
16 were obtained for the ASTM and Toluene methods respectively (see Pates and
17 Mullinger (2007) for a detailed discussion on the analytical errors and reproducibility
18 of both radon analysis methods used).

19 Cores retained from the borehole drilling were analysed for radium content. Sub-
20 samples of 200-500 g were taken from the borehole core material at approximately
21 one metre intervals from two boreholes at each site to a depth of 5 m. MCT2, MCT5,
22 ESF3 and ESF5 were selected as providing the most continuous profiles of recovered
23 core material. Samples were dried in an oven at 60 °C to constant mass, ground and
24 homogenised using a tungsten carbide Tema mill and then passed through a 250 µm
25 mesh sieve. Radium was analysed by gamma spectrometry; 20 grams of sample was

1 pressed into a pellet and sealed in polycarbonate petri dishes using an epoxy resin.
2 These were then left for at least 30 days to allow ^{214}Pb to reach secular equilibrium
3 with ^{226}Ra before counting by gamma spectrometry. Radium concentrations (Bq kg^{-1}
4 of dry sample) were calculated from the ^{214}Pb 352 keV photopeak with errors derived
5 from counting statistics (Currie, 1968) and errors in sample size.

6 Estimates of radon emanation from borehole core material were made by slurring
7 approximately 60 g of sample material, prepared as for radium analysis, in a 60 ml
8 glass bottle with deionised water. The bottle was then filled to the brim with deionised
9 water and sealed to exclude any air by a plastic screw cap with a PTFE faced sealing
10 disc. The mass of rock sample and volume of water added was measured by weighing
11 the sample bottle at each step. At least 30 days were allowed for radon to reach
12 equilibrium concentrations in the water. Ten millilitres of water was then extracted
13 from the bottle and analysed for radon content via the ASTM (1998) method giving
14 results as Bq l^{-1} . This concentration was then used to calculate the radon emanation
15 (E_{Rn}) from each rock sample in Bq kg^{-1} using equation (1).

$$E_{Rn} = \frac{[Rn] \cdot V_w}{M}, \quad (1)$$

16 where $[Rn]$ is the concentration of dissolved radon in the sample bottle (Bq l^{-1}), V_w is
17 the volume of water (litres) and M is the mass of the rock sample (kg). Results of
18 emanation measurements are presented as Bq kg^{-1} of dry sample material and are
19 means of triplicate analyses, errors are standard deviation of triplicate analyses.

20 Emanation coefficients were then calculated using equation (2).

$$E_{coeff} = \frac{E_{Rn}}{[Ra]}, \quad (2)$$

21

1 where E_{coeff} is the emanation coefficient and $[Ra]$ the concentration of radium in the
2 rock sample ($Bq\ kg^{-1}$).

3 To estimate the density and porosity at these borehole sites, retained complete
4 core samples (10 cm in diameter) from each piezometer depth were sectioned into 5
5 cm sub-samples. These sections were then hydrated at 20 °C under pressure (max. 4
6 bar) to ensure maximum saturation before weighing. The cores were then oven dried
7 at 60 °C until constant mass was reached. The porosity was calculated by mass
8 difference from the volume of water lost after drying and the density was calculated
9 from the dry sample mass and sample volume. Errors in porosity and density
10 estimates are calculated by the propagation of errors in the measurement of sample
11 size and mass.

12 From the results of radon emanation, porosity and density measurements the
13 following equation was used to calculate the theoretical radon concentration of
14 groundwater ($[Rn]_{gw}$ in $Bq\ l^{-1}$) that would be in equilibrium with the local rock.

$$[Rn]_{gw} = E_{Rn} \rho \phi, \quad (3)$$

15 where E_{Rn} is the emanation of radon from a sample ($Bq\ kg^{-1}$), ρ is density ($kg\ dm^{-3}$)
16 and ϕ is porosity.

17 Slug tests were carried out to measure the hydraulic conductivity of each
18 piezometer and a number of the deeper piezometers at each site were equipped with
19 pressure sensors (PS2100, Greenspan; HOBO U-20-001-01 series, Onset Computer
20 Corp. and miniTROLL, In-Situ Inc.). These sensors were set to log at 15 minute
21 intervals in order to monitor the changes in local hydraulic head. At least three repeat
22 measurements were made of hydraulic conductivity and results presented are the
23 mean and standard deviation of these measurements.

1 River flow at each borehole site was measured using a handheld acoustic Doppler
2 flow meter (SonTek FlowTracker). Surveys were carried out following the guidance
3 of the relevant British Standard (ISO748:2000, 2000) and Environment Agency R&D
4 Technical Report W4 (Ramsbottom et al., 1997) to provide discharge data with an
5 accuracy of $\pm 10\%$. Rainfall was measured by means of a tipping bucket rain gauge
6 located at East Shefford.

7

8 **4. Results**

9 The results of groundwater radon sampling at Maidencourt Farm and East
10 Shefford in Table 1 and Table 2 respectively. Mean radon concentrations and the
11 maximum and minimum observed concentrations are given for each piezometer. The
12 results of hydraulic conductivity measurements, as well as porosity and density
13 estimates made from borehole core material recovered from each screened section, are
14 also given. Table 3 shows the results of radium and radon emanation measurements
15 for borehole core material.

16

17 *4.1 Spatial variability*

18 The water table is usually deeper at Maidencourt Farm than at East Shefford
19 during the study period (Fig. 3a). There is also greater variation observed in the water
20 table at Maidencourt Farm compared to East Shefford. Over the monitoring period the
21 water table varied by 0.8 m at Maidencourt Farm and by 0.2 m at East Shefford.
22 Maidencourt Farm is the perennial head of the River Lambourn during late summer,
23 low flow conditions (Grapes et al., 2006).

24 As a result of the deeper water table and its variation during the sampling period
25 samples were not obtained from MCT2-2. It was also not possible to obtain samples

1 from MCT4-2 due to the low hydraulic conductivity (Table 1) at this piezometer
2 preventing purging and sampling on a reasonable time scale. The results from each
3 sampled borehole show consistently low radon concentrations in water samples from
4 the deeper piezometers, located in weathered Chalk, with means of between 1.1 and
5 1.8 Bq l⁻¹ and a maximum range of 0.6 Bq l⁻¹ in MCT4-1 (Table 1).

6 There are differences between the observed radon concentrations in the shallower
7 piezometers MCT3-2 and 5-2. MCT3-2 has elevated radon concentrations relative to
8 all other sampled piezometers at Maidencourt Farm including MCT5-2, which is at a
9 similar depth and located on the opposite river bank. Radon in MCT3-2 switches
10 between two relatively stable concentrations of approximately 5 and 7 Bq l⁻¹ (Fig. 4a)
11 during the sampling period while MCT5-2 remains stable at between 1.2 and 1.8 Bq
12 l⁻¹ (Table 1). Geological logs indicate that the cores from these piezometers consisted
13 of sandy gravel material, which at MCT5-2 is mixed with some Chalk.

14 At East Shefford a similar vertical distribution of groundwater radon
15 concentrations (Table 2) is observed as at Maidencourt Farm. The piezometers deeper
16 than 4 m bgl have low and stable mean groundwater radon concentrations from 1.1 to
17 2.2 Bq l⁻¹ with ranges of 0.7 Bq l⁻¹ in ESF3-1 and 5-1. ESF4-1 is the shallowest of the
18 'deep' piezometers (3.9 m bgl) and has a mean radon concentration of 3.3 Bq l⁻¹.
19 ESF3-2, 4-2 and 5-2 all have relatively high mean groundwater radon concentrations
20 (> 10 Bq l⁻¹), comparable to MCT3-2 (Fig. 4). ESF2-2 has low groundwater radon
21 concentrations compared with piezometers of similar depths and locations at ESF and
22 may be considered analogous in this respect to MCT5-2. As with MCT5-2 it is the
23 only piezometer in the flood plain on its respective side of the river (Fig. 1). Overall it
24 is found that the shallower piezometers at East Shefford have higher groundwater

1 radon concentrations than those found in the shallower piezometers at Maidencourt
2 Farm.

3 Radium concentrations in core samples retained from drilling at Maidencourt
4 Farm reflect the trend seen in groundwater radon concentrations, with greater values
5 being observed nearer the surface (Fig. 5a). Radium concentrations in borehole core
6 material are generally within the range 4.4-14.1 Bq kg⁻¹ with a notable exception in
7 the upper most sample from MCT2 of 39.4 ± 1.3 Bq kg⁻¹. Core material from MCT2-
8 2 has a very high radium concentration, which is associated with a clayey region
9 identified in the geological log of this borehole. There is a general increase in radium
10 concentration with decreasing depth of sample. There is clear heterogeneity in radium
11 across both sites in the top few meters of each alluvial aquifer borehole. The mixture
12 of clay, gravel, flint material mixed to varying degrees with Chalk leads to differences
13 in radium concentration between the borehole core samples.

14 Emanation coefficients from borehole core material ranges from 0.05-0.23 with a
15 single high value at 0.37 corresponding to the upper most sample from MCT2, where
16 a high radium concentration was also found (Fig. 5b). There is a general increase in
17 emanation with decreasing depth, similar to that observed in the core radium and
18 groundwater radon data. These emanation results broadly reflect the range found in
19 other emanation studies. The emanation from a wide range of rock and soil types has
20 been investigated by Baretto et al. (1972) with other studies looking at limited rock
21 and soil types (Andrews and Wood, 1972; Bonotto and Andrews, 1997; Misdaq and
22 Amghar, 2005; Przylibski, 2000; Rama, 1991). No studies have been found in the
23 literature for Chalk and soils of the type investigated here. Soils and heavily
24 weathered material have high and variable emanation coefficients, typically between

1 0.1 and 0.6. Consolidated rocks usually have much lower emanation, between 0.01
2 and 0.2, with higher values for less consolidated materials.

3 The mean porosity and density measured in recovered core sections from the two
4 borehole sites are 39 % (range 24-47 %, standard deviation 8 %) and 1.7 g cm^{-3} (range
5 $1.5\text{-}2.2 \text{ g cm}^{-3}$, standard deviation 0.2) respectively. From these data and the radon
6 emanation results, estimates of equilibrium groundwater radon concentrations were
7 made as described in equation (3) (Fig. 5c, errors calculated from propagation of
8 errors in emanation, porosity and density measurements). For comparison the mean
9 observed radon concentrations in each piezometer to a depth of 6 m bgl are shown in
10 Fig. 5d (error bars show standard deviation of observations from each piezometer).
11 These results are comparable with the observed data, with the exception of the high
12 radon value obtained for the upper most sample of MCT2 associated with the high
13 radium and emanation values. No groundwater radon samples were available from
14 MCT2-2 for comparison with the high estimated value, due to the low water table at
15 this site during the study period (Fig. 2a).

16 Hydraulic conductivities of the measured piezometers at both sites range from 0.4
17 to 156.2 m d^{-1} . The lowest hydraulic conductivity occurs at MCT4-2 where its low
18 conductivity and close proximity to the water table led to slow recovery from
19 pumping and prevented radon sampling. There is no observed relationship between
20 the depth and the hydraulic conductivity at each of the piezometers, although there are
21 a limited number of samples to compare below seven metres.

22

23 *4.2 Temporal variability*

24 Deep piezometers (below 4 m bgl) at both borehole sites exhibit relatively low
25 radon concentrations, which are stable over time (Table 1 and Table 2). There is some

1 temporal variation in radon concentrations in the piezometers located in the alluvial
2 plain. The consistency in replicate samples and the common patterns of variation in
3 boreholes ESF3 to ESF5 indicates that this variation is not simply a result of sample
4 scatter (Fig. 4). MCT3-2 switches between approximately 5 and 7 Bq l⁻¹, increasing
5 between 21 July 2005 and 29 September 2005 and decreasing between 16 March
6 2006 and 4 May 2006. During both periods when switching occurs the riparian zone
7 water table is falling or rising between the limits of 0.8 and 1.1 m bgl, c.f. study
8 period range of 0.6-1.4 m bgl (Fig. 3a). The fall in the water table also results in the
9 source of the Lambourn migrating downstream of Maidencourt Farm, which is why
10 no river flow is recorded at this site between August 2005 and June 2006 (Fig. 3b).
11 The shaded areas in Fig. 3b and Fig. 4a show that the change in radon concentration
12 in MCT3-2 coincides with the no-flow period in the river at Maidencourt Farm.

13 At East Shefford, piezometers ESF3-2, 4-2 and 5-2 show changes in radon
14 concentrations (Fig. 4b-d), but without the distinct periods of stability observed in
15 MCT3-2. During this period there is little movement in the depth of the riparian zone
16 water table at East Shefford, which varies between 0.6 and 0.8 m bgl, and the changes
17 in radon concentrations do not indicate a relationship with seasonal groundwater
18 movements. Additional higher resolution sampling was undertaken to help understand
19 the observed temporal variations in groundwater radon at East Shefford.

20 From higher resolution sampling of groundwater radon during rainfall events it
21 can be seen that short term responses occur at East Shefford. Two sampling periods
22 took place in October and November 2006, during which rainfall events were
23 captured (Fig. 6). The October event is early in the recharge period and the water
24 table at ESF3 is 0.78 m bgl, while in November groundwater has recovered to 0.68 m
25 bgl.

1 A total of 17.2 mm of rain fell on 11 October (Fig. 6a) contributing to a 7 cm head
2 response in ESF3-1 between 07:00 and 18:00 (Fig. 6b), followed by a steady
3 recession period. There is a subtle response in groundwater radon concentrations to
4 this input of water with decreases of 1.5 Bq l^{-1} in ESF3-2 and 2 Bq l^{-1} in ESF4-2 (Fig.
5 6c). The radon concentration in the shallow piezometers then increases during the
6 recession in groundwater level. The magnitude of variation in deeper piezometers
7 makes the responses to rainfall more difficult to discern.

8 On the morning of 28 November 16 mm of rain fell (Fig. 6d) and this event
9 resulted in a 10 cm head response in ESF3-1 (Fig. 6e). Here the radon concentrations,
10 monitored only in ESF3 on this occasion, show a response of 2 Bq l^{-1} . Less of the
11 recession curve was captured by post event sampling and so it is not clear whether
12 radon concentrations in ESF3-2 recovered fully after this event.

13 Although only small differences in radon concentrations are found in the first
14 event the simultaneous response of piezometers ESF3-2 and ESF4-2 indicates that the
15 observations are a response to rainfall. This hypothesis is then further supported by
16 the observations during the second event, which show significant differences in pre-
17 and post-event radon concentrations. The greater radon response in the November
18 event is likely to be due to the shallower depth of the water table providing more rapid
19 connection of the infiltrating water to the aquifer and also to the greater intensity of
20 rainfall, which can be seen in the hydraulic head response.

21

22 **5. Discussion**

23 *5.1 Spatial Variability*

24 From the analysis of groundwater and borehole core samples it can be seen that
25 groundwater radon concentrations are related to the abundance of radium and

1 differences in emanation with depth. The increased abundance of radium and
2 emanation of radon near the surface results in a distinctive vertical groundwater
3 profile in the riparian zone. It is also shown that measurements of radium
4 concentration and radon emanation can give good indicative estimates of the
5 distribution of groundwater radon concentrations that may be found at a site. The
6 results reflect the types of deposit found in the vertical profile and the degree of
7 weathering in the near surface. The alluvial gravels and sediments in the river valley
8 are materials remaining after the erosion of the overlying Palaeogene deposits and the
9 insoluble fraction of sediments co-deposited when the Chalk was formed. These
10 insoluble sediments, containing clays and other fine material, tend to be higher in
11 radium than the carbonate matrix of the Chalk due to their mineral composition and
12 also their adsorption properties, which allows for accumulation of parent nuclides on
13 surfaces (Bonotto and Andrews, 1993; Osmond and Cowart, 1992).

14 The higher radon concentrations in groundwaters from the shallow riparian
15 piezometers at East Shefford compared with Maidencourt Farm may be due to the
16 thicker alluvial deposits found at East Shefford, providing a larger radon source, and
17 the elevated water table allowing dissolution of radon from nearer the surface.

18 The heterogeneity of groundwater radon concentrations found in the shallow
19 piezometers of riparian zone boreholes indicates that spatial variation can occur in
20 near-surface groundwater inputs to surface waters. Therefore, contributions to stream
21 radon from this type of system may vary along the course of a river. In river reaches
22 where there is significant interaction of groundwater with alluvial deposits in the river
23 corridor, such as in the Lambourn Valley, the variation in groundwater radon could be
24 used to identify contributions to stream flow from the near-surface and deeper
25 groundwaters depending upon the concentration of radon in the input water. It is also

1 shown that measurements of radium concentration and radon emanation can give
2 good indicative estimates of the distribution of groundwater radon concentrations that
3 may be found at a site.

4

5 *5.2 Temporal Variability*

6 At Maidencourt Farm the temporal trend of radon in MCT3-2 is to switch between
7 two relatively stable concentrations (Fig. 4a), suggesting that the changes occurring at
8 this site are due to the seasonal changes in the water table (Fig. 3). When flow in the
9 river at Maidencourt Farm stops, the radon concentration in groundwater of MCT3-2
10 increases. This shows that there is a dynamic equilibrium between the radium source
11 and groundwater radon in the vicinity of MCT3-2. The controls on this relationship
12 are not known but may come from changes in water table elevation activating
13 different radon sources.

14 There is relatively little variation in the water table at East Shefford compared to
15 Maidencourt Farm (Fig. 3a) and no seasonal changes in groundwater radon are
16 observed in the shallower piezometers at East Shefford. However, shorter time scale
17 changes in groundwater radon concentrations of the order of weeks were observed at
18 East Shefford during the routine sampling period (January 2005 to May 2006, Fig. 4b-
19 d).

20 From greater temporal resolution event sampling (October and November 2006) it
21 can be seen that rainfall events have a rapid impact on the concentration of radon in
22 the shallowest groundwaters (Fig. 6). The precise time of response is not captured in
23 the samples taken and so estimates of the groundwater radon concentrations between
24 samples are indicated by the interpreted response lines. The effect of infiltration of
25 low radon event water is observed as deep as 3 metres below ground level and

1 approximately 2.5 m below the water table, demonstrating relatively rapid subsurface
2 mixing. The effects of greater rainfall intensity and the shallower water table at East
3 Shefford in November lead to a greater event response in the groundwater radon
4 concentration than in October.

5 Following the October event, reductions in radon concentrations of 18 and 12 %
6 are observed in ESF3-2 and 4-2, respectively. In November, radon concentrations
7 decrease by 19 % in ESF3-2 following rain. Assuming that infiltrating water has a
8 zero radon concentration, mixing of between 12 and 19 % event water with existing
9 groundwater is implied at these sites for the events observed. These values could be
10 considered a minimum degree of mixing as it assumes that the event water contains
11 no radon when it reaches the saturated zone. In reality it is likely to have accumulated
12 some dissolved radon as a result of dissolution of radon in soil gas during transit
13 through the unsaturated zone. The accumulation of radon by recharge water will
14 depend partially upon the mechanism of recharge and water movement through the
15 unsaturated zone at these sites (e.g. direct recharge by new rain water via fracture
16 flow vs. displacement of existing unsaturated zone water via a piston flow
17 mechanism, see Ireson et al., 2006).

18 Estimates of the time it would take for groundwater radon to recover to pre-event
19 concentrations were made. The recovery time was estimated as the time taken to reach
20 95 % of the pre-event radon concentration, assuming a quasi-steady state system,
21 where the pre-event groundwater is in equilibrium with its source and the
22 accumulation of radon post event is governed by radioactive ingrowth (Andrews and
23 Wood, 1972; Hoehn et al., 1992). Ingrowth of radon is calculated by the equation,

$$A_t = A_0(1 - e^{-\lambda t}), \quad (4)$$

1 where A_t is the groundwater radon concentration (Bq l^{-1}) at time t , A_0 is the pre-event
2 groundwater radon concentration (Bq l^{-1}) and λ is the radioactive decay constant (t^{-1}).
3 Recovery of radon concentrations from these rainfall events is calculated to take
4 between 5 and 7 days, depending on the piezometer and event. This is a theoretical
5 maximum time for recovery to occur. Rapid recovery of pre-event radon
6 concentration is observed in the October event where groundwater radon regains pre-
7 event concentrations less than 30 hours from the time of first rainfall. If radon
8 recovery continues at the rate seen during recession of the second rainfall event then
9 the groundwater will return to pre-event radon concentration within 48 hours.
10 Groundwater radon concentrations recover more quickly than is predicted by
11 radioactive ingrowth, emphasising that this is not a closed system. Speculation on the
12 driving mechanism for this rapid recovery is not possible from this data set.

13 Unlike at East Shefford short time scale variations in groundwater radon
14 concentrations are not seen in the routine monitoring data from Maidencourt Farm. It
15 may be that the greater depth of unsaturated zone at Maidencourt protects the
16 groundwater from such rapid and significant responses to rainfall events.

17 Mullinger et al. (2007) proposed that the variations in modelled radon inputs to the
18 Lambourn could be caused by changes in the radon concentration of groundwater
19 feeding the river. The data presented here shows that consistently higher radon
20 concentrations are found in groundwater nearer the surface of the alluvial aquifer. It is
21 hypothesised that the fluctuations in the water table provide a changing source of
22 radon in groundwater that may be discharged to a river. To examine the impact of
23 changing water table elevation on radon concentrations in groundwater discharges, a
24 trendline was fitted to the observed groundwater radon data using a linear regression
25 method to provide a relationship with depth (equation (5)).

$$[Rn] = 14.191d^{-1.234}, \quad (5)$$

1 where $[Rn]$ is groundwater radon concentration (Bq l^{-1}) and d is depth (m). Fig. 5d
2 shows the groundwater radon concentrations estimated by equation (5) against mean
3 observed radon concentrations ($R^2 = 0.65$). By integrating over a given depth range
4 the net radon concentration of groundwater discharges can be estimated. This has
5 been done for three example depth ranges, assuming an aquifer base of 3, 5 and 10 m
6 bgl and an equal contribution of groundwater from each depth. One metre has been
7 used as the upper limit of integration in all cases, as extrapolation of the relationship
8 beyond this to shallower depths could not be justified given the rate of increase in
9 radon concentration increase that would result from the derived relationship. Results
10 of this exercise are shown in Fig. 7a, which shows the estimated radon concentration
11 of discharging groundwater for a given water table depth.

12 By combining the above approach with observed water table data from Fig. 3a, the
13 variation in groundwater radon concentration over time has been estimated for an
14 aquifer depth of 5m (Fig. 7b). Result ranges are 4-6 Bq l^{-1} for MCT3 and 5.3-6.2 Bq
15 l^{-1} for ESF3, the greater variation in water table at Maidencourt Farm being reflected
16 in the estimated radon concentration. These results could be viewed as a lower limit
17 for variation in discharge radon concentrations due to the assumption of equal
18 contribution from each depth. Exponential mixing of groundwaters in shallow
19 unconfined systems leads to shorter residence times of shallower groundwaters (Cook
20 and Böhlke, 2000). Therefore, groundwater discharges may be made up by a greater
21 proportion of shallower groundwater, which will increase the mean concentration of
22 discharge water. The conceptual model in Fig. 7c illustrates how movement of the
23 water table could result in changes in radon concentrations of groundwater entering a
24 river. As the water table rises it interacts more with the near-surface zone where radon

1 production is highest, leading to a higher mean groundwater radon concentration. This
2 may also result in greater contributions of shallower groundwater to the river at times
3 when the water table is elevated, which will be of higher radon concentration.

4

5 **6. Conclusions**

6 Consistently higher groundwater radon and borehole core radium concentrations
7 are found near the surface (0-4 m bgl) at both East Shefford and Maidencourt Farm
8 borehole sites, with low and stable radon concentrations at greater depths in the
9 weathered Chalk. The groundwater radon concentrations are consistent with
10 observations at other comparable sites in Pang and Lambourn catchments (Mullinger
11 et al., 2007).

12 A combination of radium abundance and radon emanation control the
13 concentration of radon in groundwater. The enrichment of radium and greater rates of
14 emanation in the near-surface alluvial materials influence the spatial variation of
15 radon at these sites. High spatial variability in the hydraulic conductivities found at
16 these sites mean that local controls will influence groundwater movement and radon
17 concentrations in the riparian zone.

18 Variations in radon concentrations in near-surface groundwater at East Shefford
19 can be affected by short time scale hydrological events, whereas those at Maidencourt
20 Farm can be influenced by seasonal variations in water table elevation. Perturbations
21 to groundwater radon concentrations following rainfall events are relatively short-
22 lived and of the order of a few days at most in areas where the water table is very
23 close to the surface.

24 Observations of groundwater radon concentrations over time and the distribution
25 of radium at the Lambourn borehole sites show that there are variable sources of

1 radon for groundwater that is discharged to the river. Seasonal changes in the water
2 table can lead to a greater source of river water from near the surface of the alluvial
3 aquifer, which is higher in radon. This may account for the observations of changing
4 radon inputs to the river in Mullinger et al. (2007) and is illustrated by the conceptual
5 model in Fig. 7c.

6 These results show that there can be significant spatial and temporal variability in
7 groundwater radon in the riparian zone. The riparian zone, due to the proximity of the
8 river channel, has a potentially important influence on groundwater radon
9 concentrations before discharge occurs to rivers. Therefore, it is essential that this part
10 of the groundwater system is studied in order to properly characterise the sources of
11 radon being discharged to rivers.

12

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- 13
14

1 **Figure captions**

2
3 Fig. 1 Location of the Lambourn catchment. Cross-sections locations (Fig. 2) and
4 local topography are indicated. Insets show layout of borehole sampling sites.

5
6 Fig. 2 Cross sections of (a) Maidencourt Farm and (b) East Shefford borehole sites,
7 showing ground level, relative distance of boreholes from river, piezometer depths
8 and water table minima and maxima during the sampling period. Insets show the full
9 length of cross sections in Fig. 1 and indicate the extent of the enlarged sections.

10
11 Fig. 3 (a) Water table in riparian boreholes in MCT3-1 and ESF3-1 (the gap in data
12 from ESF3 is due to logger failure). (b) River flow at East Shefford and Maidencourt
13 Farm. Shaded area indicates period of no flow at Maidencourt Farm.

14
15 Fig. 4 Temporal variability of groundwater radon in the most variable boreholes
16 (error bars show standard deviation of triplicate samples). Shaded area indicates
17 period of no flow at Maidencourt Farm.

18
19 Fig. 5 (a) Radium concentration of borehole core material (errors derived from
20 counting statistics and errors in sample size). (b) Emanation coefficients from
21 borehole core material (error bars show standard deviation of triplicate samples). (c)
22 Estimated groundwater radon concentrations as calculated by equation (3) (errors
23 calculated from propagation of errors in emanation, porosity and density
24 measurements). (d) Observed mean groundwater radon concentrations in piezometers
25 above 6 m bgl and trendline (equation (5)) fitted by linear regression (error bars show
26 standard deviation of all observations from each piezometer). Hollow symbols in (a-c)
27 represent samples associated with piezometer screened sections. Hollow symbols in
28 (d) represent piezometer screened sections from which core material was analysed for
29 radium and radon emanation.

30
31 Fig. 6 Borehole responses to rainfall events in October and November 2006. (a) & (d)
32 Hourly precipitation. (b) & (e) ESF3-1 water table. (c) & (f) Groundwater radon
33 concentrations (ASTM method, errors based on counting statistics and errors in
34 sample size).

35
36 Fig. 7 (a) Estimated discharge groundwater radon concentration for a given water
37 table depth assuming equal contributions from each depth, calculated using equation
38 (5) with examples of contributions assuming different aquifer depths. (b) Estimated
39 impact of water table fluctuation on groundwater radon concentration, calculated by
40 the integration of radon over the saturated depth of aquifer down to 5 m bgl using
41 equation (5). (c) Conceptual model of variations in radon input to streams from an
42 alluvial aquifer. A rise in the water table leads to groundwater occupying the zone of
43 higher radon production in the near-surface of the riparian zone. This provides a
44 greater source of high radon water feeding the river, resulting in seasonal changes in
45 the input of radon to rivers.

46

1 **Tables**

2

3 Table 1 Parameters observed for Maidencourt Farm boreholes. All boreholes are
 4 screened for 0.8 m, with the pump depth located at the centre of screened section.
 5 Errors in porosity and density estimates are calculated by the propagation of errors in
 6 the measurement of sample size and mass. Hydraulic conductivity results are mean
 7 and standard deviation of repeat measurements.

Piezometer	Pump depth (m bgl)	²²² Rn (Bq l ⁻¹)			Porosity (%)	Density (g cm ⁻³)	Hydraulic conductivity (m d ⁻¹)
		Mean	Min	Max			
MCT1-2	5.6	1.7	1.5	1.8	45 ± 2	1.7 ± 0.1	7.7 ± 0.5
MCT1-1	9.6	1.3	1.1	1.4	47 ± 2	1.6 ± 0.1	32.3 ± 2.6
MCT2-2	1.6	Not sampled			34 ± 2	1.8 ± 0.1	9.9 ± 0.6
MCT2-1	4.6	1.4	1.2	1.5	45 ± 2	1.5 ± 0.1	49.0 ± 3.3
MCT3-2	3.0	6.1	4.7	7.2	No sample		83.2 ± 20.2
MCT3-1	5.6	1.2	1.0	1.4	43 ± 2	1.6 ± 0.1	12.6 ± 1.4
MCT4-2	2.4	Not sampled			29 ± 2	2.0 ± 0.1	0.4 ± 0.1
MCT4-1	4.6	1.8	1.5	2.1	43 ± 2	1.6 ± 0.1	46.3 ± 3.8
MCT5-2	3.5	1.5	1.2	1.8	42 ± 2	1.6 ± 0.1	5.5 ± 2.1
MCT5-1	6.4	1.1	0.9	1.3	29 ± 2	1.9 ± 0.1	68.0 ± 4.0

8

9 Table 2 Parameters observed for East Shefford boreholes. All boreholes are screened
 10 for 0.8 m, with the pump depth located at the centre of screened section. Errors in
 11 porosity and density estimates are calculated by the propagation of errors in the
 12 measurement of sample size and mass. Hydraulic conductivity results are mean and
 13 standard deviation of repeat measurements.

Piezometer	Pump depth (m bgl)	²²² Rn (Bq l ⁻¹)			Porosity (%)	Density (g cm ⁻³)	Hydraulic conductivity (m d ⁻¹)
		Mean	Min	Max			
ESF1-2	9.6	1.6	1.4	2.1	45 ± 2	1.6 ± 0.1	No measurement
ESF1-1	12.5	1.2	1.1	1.2	43 ± 2	1.6 ± 0.1	No measurement
ESF2-2	2.6	3.1	2.3	3.6	No sample		156.2 ± 46.5
ESF2-1	5.5	1.1	0.9	1.2	42 ± 2	1.6 ± 0.1	No measurement
ESF3-2	2.1	10.6	9.1	11.7	26 ± 2	1.8 ± 0.1	16.8 ± 1.9
ESF3-1	4.6	2.2	1.7	2.4	44 ± 2	1.6 ± 0.1	13.2 ± 6.2
ESF4-2	1.6	11.0	8.5	14.2	24 ± 2	2.2 ± 0.1	15.4 ± 0.4
ESF4-1	3.9	3.3	2.6	4.6	43 ± 2	1.6 ± 0.1	5.3 ± 0.8
ESF5-2	2.6	11.1	9.2	11.8	No sample		1.5 ± 0.4
ESF5-1	4.5	1.5	1.2	1.9	39 ± 2	1.7 ± 0.1	32.1 ± 3.6

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1 Table 3 Results of borehole core radium and emanation measurements. * indicates
 2 samples which are located within 0.8 m deep piezometer screened sections.
 3

Borehole	Depth (m)	Ra activity (Bq kg ⁻¹)	Rn emanation (Bq kg ⁻¹)	Emanation coefficient
ESF3	1.0	13.4 ± 0.5	2.8 ± 0.2	0.21 ± 0.02
ESF3	2.3	7.9 ± 0.4	1.2 ± 0.2	0.15 ± 0.02
ESF3	3.1	12.0 ± 0.6	1.2 ± 0.2	0.10 ± 0.01
ESF3	4.4*	4.9 ± 0.5	0.4 ± 0.2	0.08 ± 0.01
ESF3	5.0	5.8 ± 0.3	0.4 ± 0.2	0.06 ± 0.01
ESF5	1.1	13.1 ± 0.5	3.0 ± 0.2	0.23 ± 0.02
ESF5	2.4*	13.0 ± 0.5	1.6 ± 0.1	0.13 ± 0.01
ESF5	3.0	10.4 ± 0.5	1.2 ± 0.1	0.12 ± 0.01
ESF5	4.3*	6.4 ± 0.5	0.3 ± 0.1	0.05 ± 0.02
ESF5	4.8	7.5 ± 0.4	0.5 ± 0.1	0.07 ± 0.01
MCT2	1.2*	39.4 ± 1.3	14.5 ± 1.2	0.37 ± 0.03
MCT2	2.1	14.1 ± 0.7	3.3 ± 0.1	0.23 ± 0.01
MCT2	2.8	6.1 ± 0.4	0.6 ± 0.1	0.10 ± 0.02
MCT2	4.2	4.9 ± 0.5	0.4 ± 0.1	0.07 ± 0.01
MCT2	4.9*	4.4 ± 0.4	0.6 ± 0.1	0.14 ± 0.01
MCT5	1.1	8.4 ± 0.3	1.0 ± 0.1	0.12 ± 0.01
MCT5	1.9	10.8 ± 0.6	1.3 ± 0.1	0.12 ± 0.01
MCT5	3.2*	11.2 ± 0.4	1.2 ± 0.1	0.11 ± 0.01
MCT5	4.0	6.4 ± 0.4	1.0 ± 0.1	0.16 ± 0.02
MCT5	5.4	7.4 ± 0.5	0.4 ± 0.1	0.05 ± 0.01

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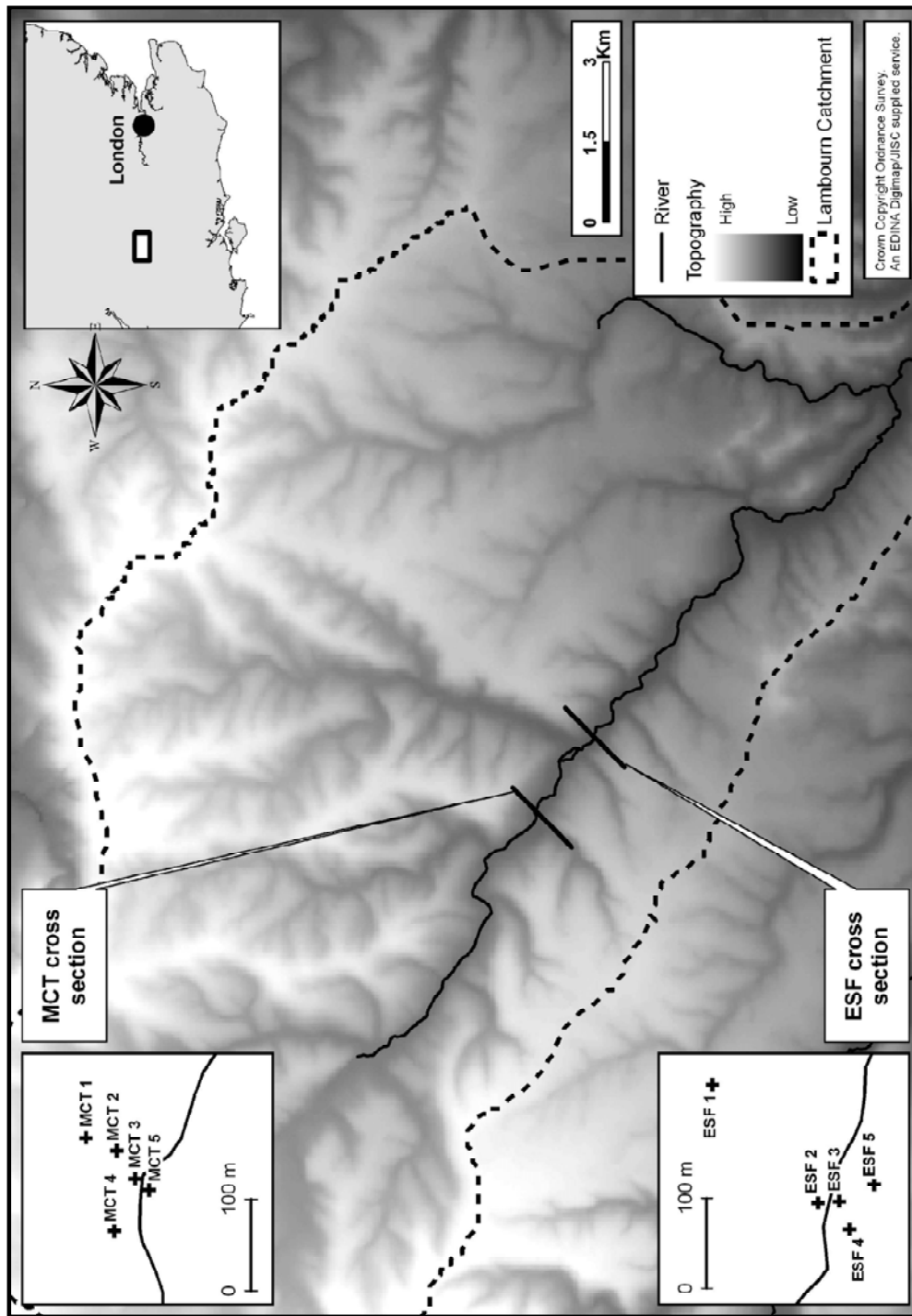


Fig. 1 Location of the Lambourn catchment. Cross-sections locations (Fig. 2) and local topography are indicated. Insets show layout of borehole sampling sites.

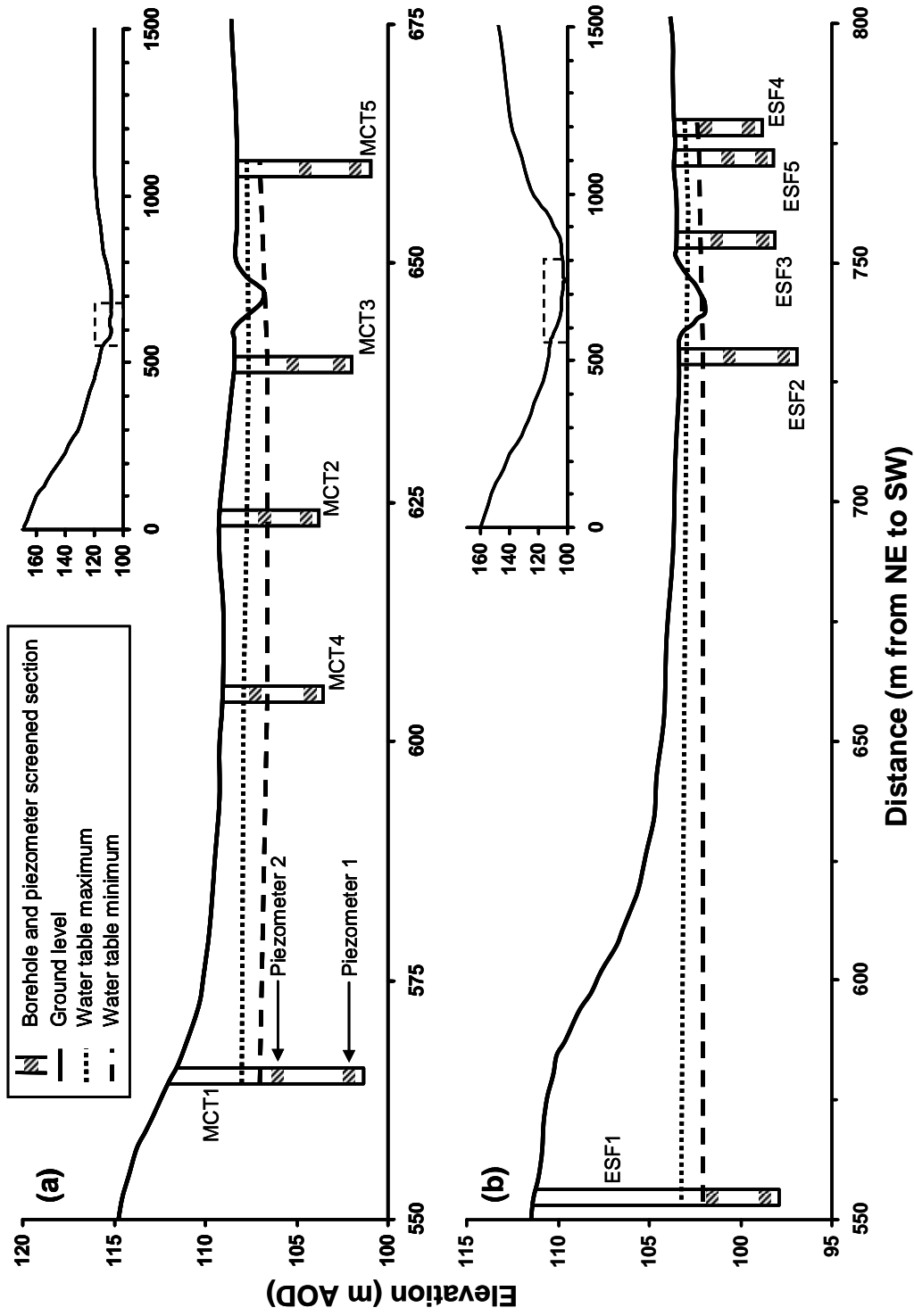


Fig. 2. Cross sections of (a) Maidencourt Farm and (b) East Sheffield borehole sites, showing ground level, relative distance of boreholes from river, piezometer depths and water table minima and maxima during the sampling period. Insets show the full length of cross sections in Fig. 1 and indicate the extent of the enlarged sections.

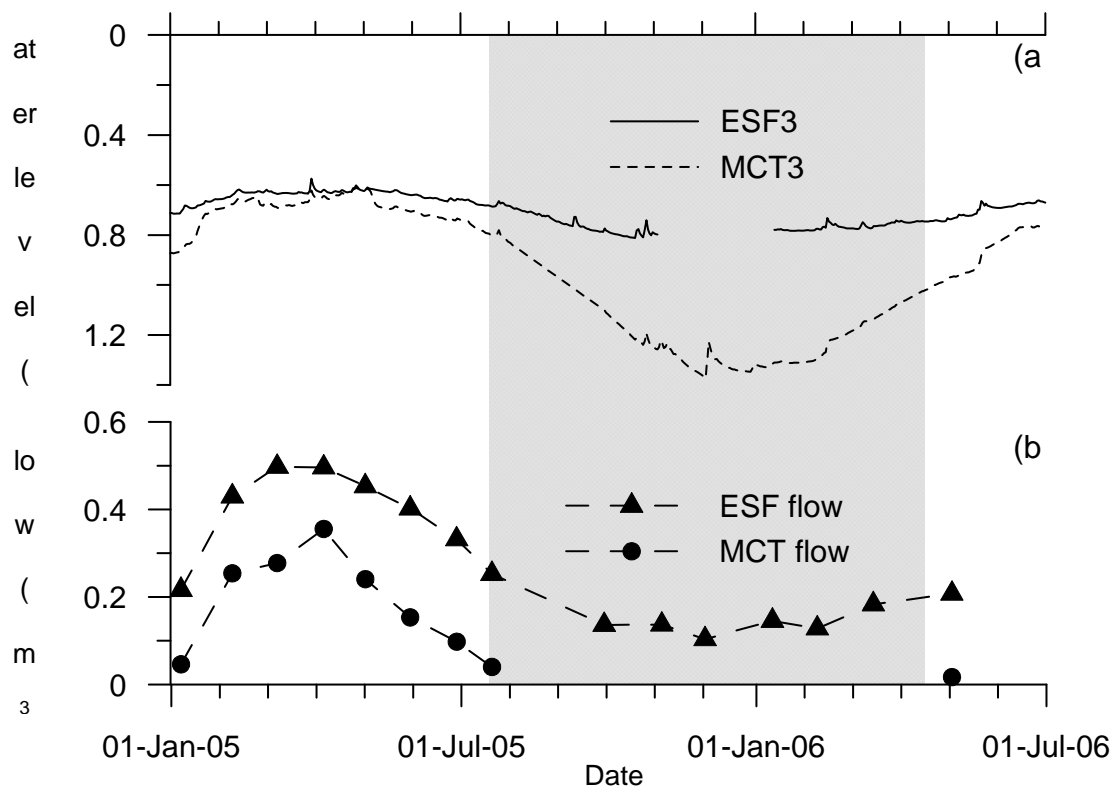


Fig. 3 (a) Water table in riparian boreholes in MCT3-1 and ESF3-1 (the gap in data from ESF3 is due to logger failure). (b) River flow at East Shefford and Maidencourt Farm. Shaded area indicates period of no flow at Maidencourt Farm.

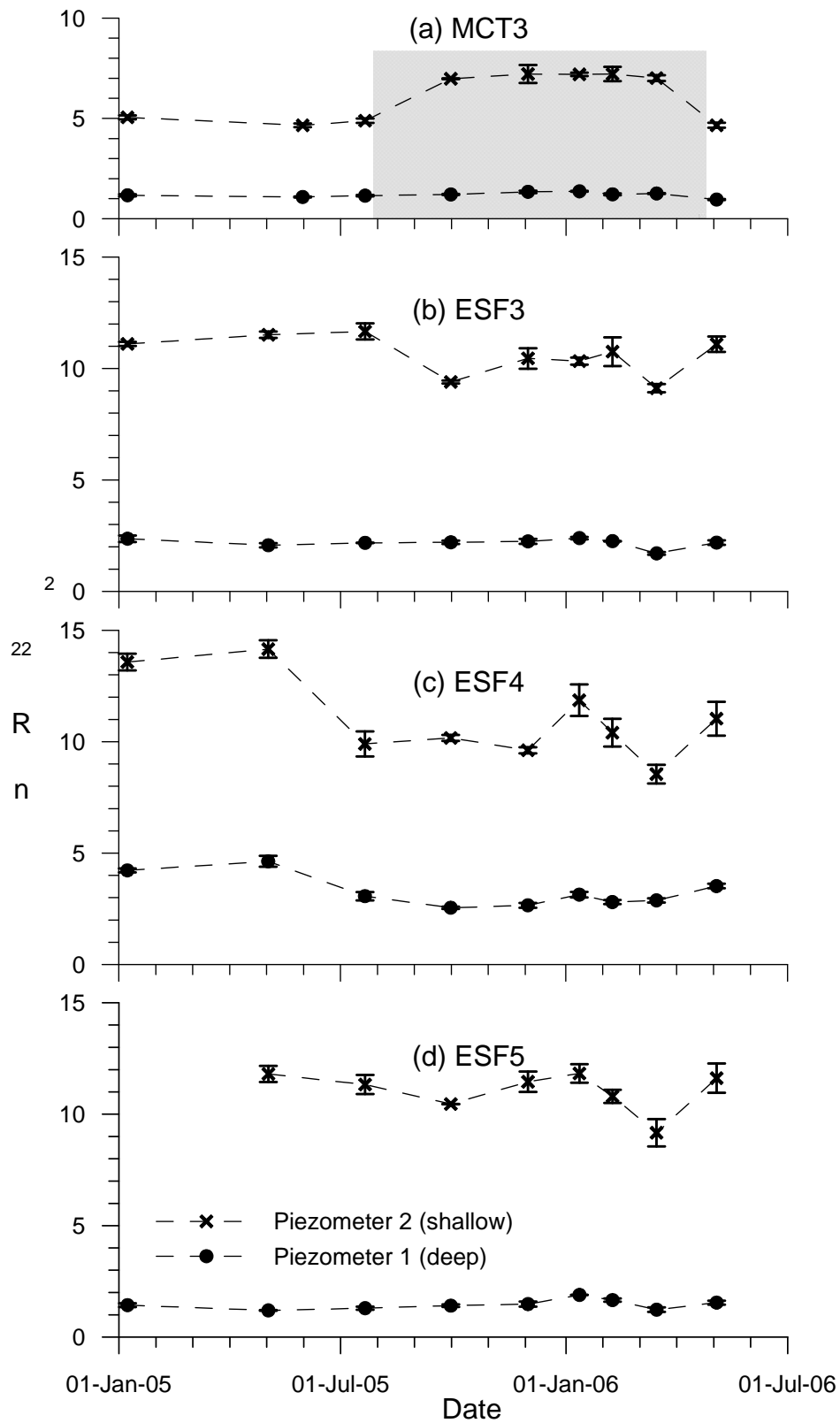


Fig. 4 Temporal variability of groundwater radon in the most variable boreholes (error bars show standard deviation of triplicate samples). Shaded area indicates period of no flow at Maidencourt Farm.

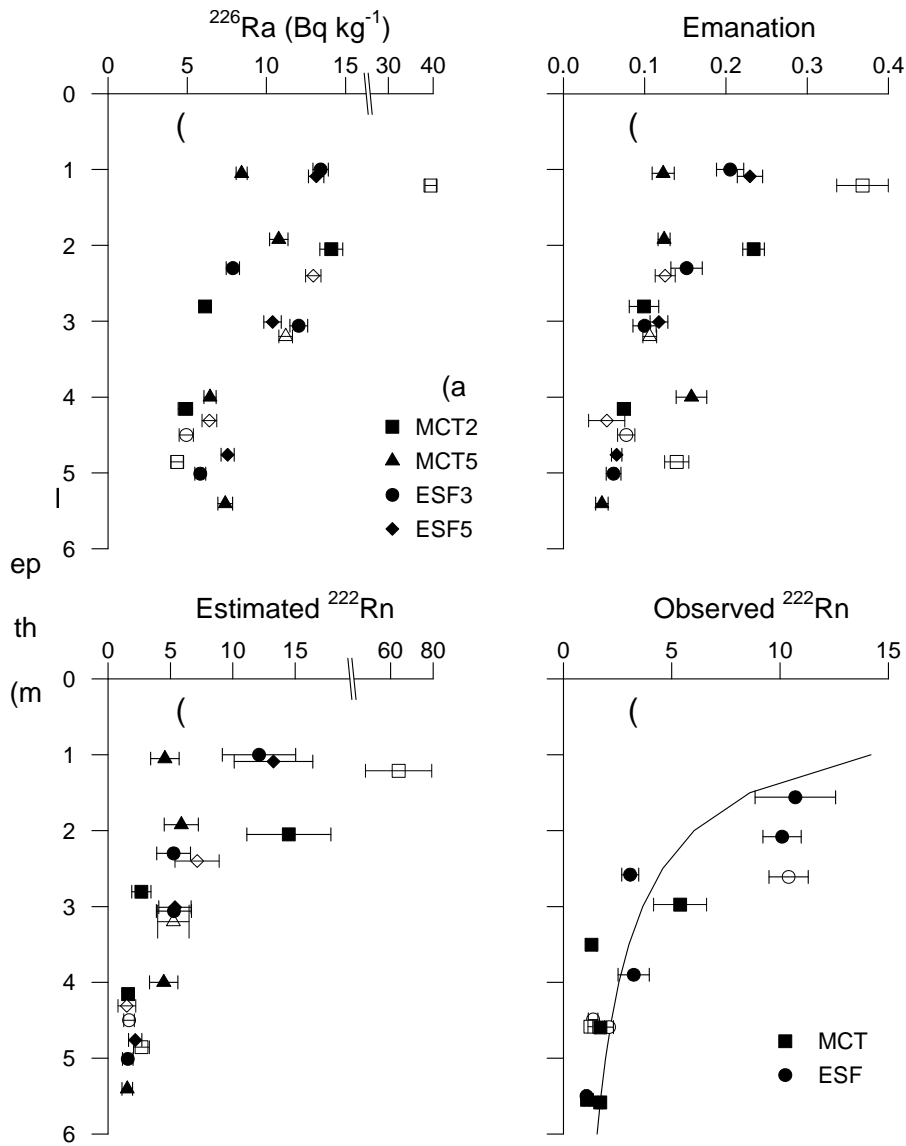


Fig. 5 (a) Radium concentration of borehole core material (errors derived from counting statistics and errors in sample size). (b) Emanation coefficients from borehole core material (error bars show standard deviation of triplicate samples). (c) Estimated groundwater radon concentrations as calculated by equation (3) (errors calculated from propagation of errors in emanation, porosity and density measurements). (d) Observed mean groundwater radon concentrations in piezometers above 6 m bgl and trendline (equation (5)) fitted by linear regression (error bars show standard deviation of all observations from each piezometer). Hollow symbols in (a-c) represent samples associated with piezometer screened sections. Hollow symbols in (d) represent piezometer screened sections from which core material was analysed for radium and radon emanation.

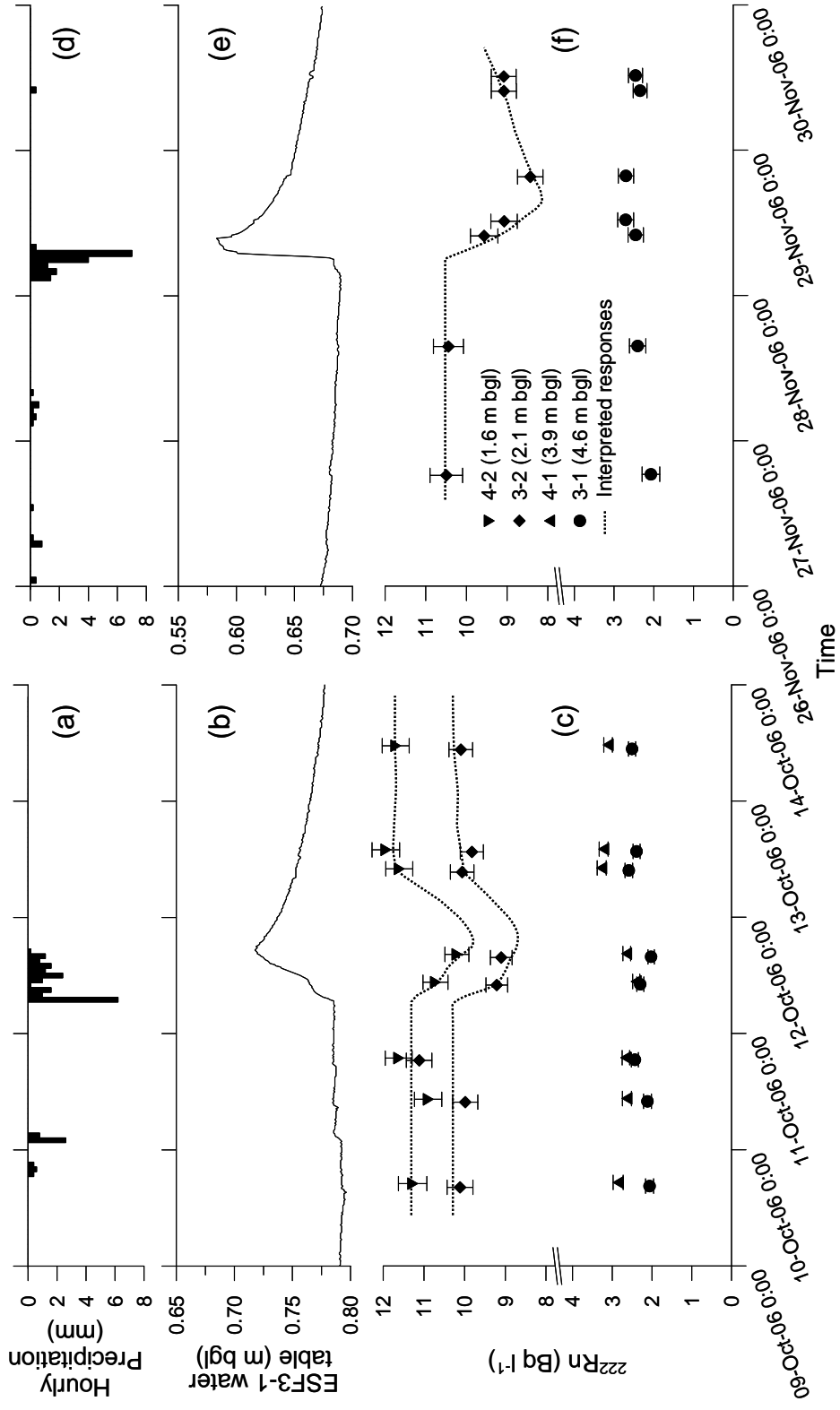


Fig. 6 Borehole responses to rainfall events in October and November 2006. (a) & (d) Hourly precipitation. (b) & (e) ESF3-1 water table. (c) & (f) Groundwater radon concentrations (ASTM method, errors based on counting statistics and errors in sample size).

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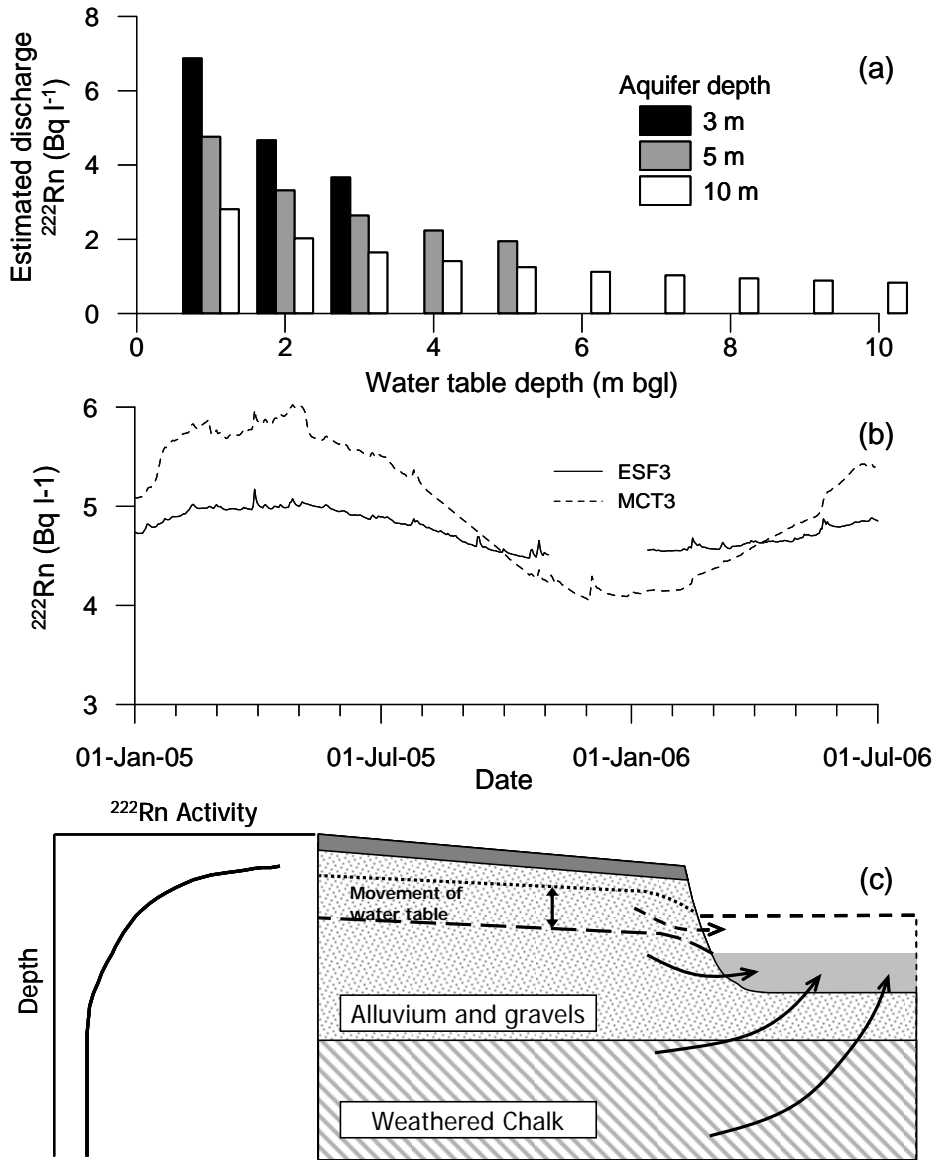


Fig. 7 (a) Estimated discharge groundwater radon concentration for a given water table depth assuming equal contributions from each depth, calculated using equation (5) with examples of contributions assuming different aquifer depths. (b) Estimated impact of water table fluctuation on groundwater radon concentration, calculated by the integration of radon over the saturated depth of aquifer down to 5 m bgl using equation (5). (c) Conceptual model of variations in radon input to streams from an alluvial aquifer. A rise in the water table leads to groundwater occupying the zone of higher radon production in the near-surface of the riparian zone. This provides a greater source of high radon water feeding the river, resulting in seasonal changes in the input of radon to rivers.