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Hydrogeological investigations at Morestead, Twyford, 2009-2010

Groundwater Resources Programme

Open Report OR/10/038

BRITISH GEOLOGICAL SURVEY

GROUNDWATER RESOURCES PROGRAMME

OPEN REPORT OR/10/038

Hydrogeological investigations at Morestead, Twyford, 2009-2010

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Keywords

Chalk, groundwater, nitrate, sampling, borehole geophysics

Front cover

Drilling of Borehole B

Bibliographical reference

SORENSEN, J P R, BUTCHER A S AND STUART M E . 2010. Hydrogeological investigations at Morestead, Twyford, 2009-2010. *British Geological Survey Open Report*, OR/10/038. 41pp.

Keyworth, Nottingham British Geological Survey 2010

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on the seasonal fluctuations of nitrate in groundwater at a research site at Morestead, Twyford, Hampshire. It forms the fourth output from the BGS project “Nitrate fluctuations in groundwater” and records details of activities and results obtained during the 2009/10 campaign.

Acknowledgements

The authors are extremely grateful to Barry Townsend (BGS) who undertook the majority of the project fieldwork. Additionally, we would particularly like to thank the following: Chris Chapman, owner of the Hazeley Estate, for access to the site; Alex Gallagher (ex-BGS), Ian Woods (BGS) and Mike Davies (UCL) for their assistance with the geophysical work. Ian Woods also kindly provided Appendix B.

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Summary

This report describes work undertaken at Morestead, Twyford during the 2009/10 recharge season as part of a BGS research project “Nitrate Fluctuations in Groundwater”. The previous year’s work had been reported earlier in Sorensen *et al*. (2010). The project uses the same site as that described in Stuart *et al*. (2008a) for the project “Nitrate Mass Balance in the Saturated Zone”.

During the 2009/10 recharge season a second year’s set of data were obtained from the multi-level sampler. The sampler was modified to allow sample collection at a greater resolution of 0.05 m over the first 2.05 m and at 0.1 m resolution up to 3.9 m. This was deployed in association with a GPRS telemetry system. This allowed the visualisation of water levels in the office which facilitated targeted, more efficient site visits. The telemetered Druck PDCR 1830 also provided superior quality water level data in comparison with the CTD Diver.

During the recharge season water levels varied between 26 m below datum (m bd) in November 2009 and 12.3 m bd in February 2010. The groundwater hydrograph was characterised by an initial rapid rise in water level to 17 m bd, which was followed by four successive peaks. All water level peaks could be correlated to specific rainfall events.

A total of 252 groundwater samples were collected between 25.73 and 12.34 m bd at a typical depth resolution of 0.05 m. These indicated concentrations of chloride, sulphate and nitrate (as NO_3) range between 14.6 and 39.5 mg/l, 9.9 and 37.3 mg/l, and 21.8 and 62.2 mg/l, respectively. Additionally a discoloured sample was retrieved from above the water table which contained a chloride concentration of 85.3 mg/l, sulphate of 104 mg/l and nitrate of 123.7 mg/l. The high levels of $H_2PO_4^{2-}$ indicated that this sample was derived from the near surface suggesting that pollution of the borehole from the surface is possible at the site.

Analysis of the groundwater samples indicated:

- A general rising trend in groundwater nitrate concentration with water level towards a maximum around 14.3 m bd, although concentrations decreased between 17.5 and 16.5 m bd and also 19.5 and 18 m bd.
- Sudden increases in concentration at several depths, notably at around 20 m bd and 15.5 m bd corresponding to site visits and/or open fractures.
- Fractures could be delivering high levels (e.g. 20 m bd) or low levels (16.8 m bd) of nitrate to the water table.
- A potential correlation with an estimated current nitrate porewater profile with concurrent peaks at 14.5-15.0, 19.5 and 24.0 m bd.
- Concentrations below the adjacent porewater concentration.

Several recommendations regarding the improvement of the sampling procedure and future work have also been made.

1 Introduction

1.1 BACKGROUND AND OBJECTIVES

Concentrations of groundwater nitrate observed in abstraction boreholes have increased significantly during the past 30-40 years in response to the intensification of farming. Many of these show within-year fluctuations of various amplitudes and forms. Where suitable continuous groundwater level records are available nearby, a close relationship between groundwater levels and nitrate concentrations can often be observed – higher concentrations being associated with higher groundwater levels. It is often the resulting transient winter peaks of nitrate that can be problematic for compliance by water companies, perhaps many years before the “average” concentration reaches a level requiring action.

The objective of this project is to determine which of the following mechanisms is resulting in rising nitrate concentrations near a public supply borehole: rapid vertical recharge and enhanced winter leaching, flushing out of “stored” unsaturated zone nitrate by the rising groundwater levels, or inactivation of shallow high transmissivity flow paths during periods of low water levels. This report summarises the activities and data collected during the 2009/10 recharge season.

1.2 SUMMARY OF PREVIOUS WORKS

This project builds upon the infrastructure and information from a previous project aimed at evaluating the role of diffusive exchange of nitrate between fracture water and porewater in the saturated zone of the aquifer. As part of this project a cored borehole (Borehole A) was drilled during May 2006 to a depth of 75 m in the Chalk at Morestead, Twyford, Hampshire. The final installation comprised separate shallow and deep, 50 mm diameter piezometers in an area of set-aside land adjacent to arable farmland.

The core obtained was fractured but most of these fractures appeared to be to be parallel to the bedding (e.g. along marl seams) and were probably drilling-induced. Some high-angle fractures with mineralised fracture faces were found in the uppermost 10 m and mineralised fractures with slickensides (possibly associated with a minor fault) were observed at 31 m depth, a few metres below the water table at the time of drilling.

The results of packer testing of the borehole confirmed that the highest permeabilities were in the zone close to the water table, with low values at depth, consistent with results from boreholes in the nearby Candover catchment. Marl seams appeared to be much more important than fractures in controlling groundwater movement to this borehole. Groundwater samples obtained during packer testing were all of similar composition and were interpreted as being drilling water which had not been fully flushed from the borehole before the test.

A detailed profile of porewater quality was obtained by centrifugation of core samples. Nitrate concentrations were mainly at and above the current drinking water standard of 50 mg/l nitrate (11.3 mg N/l) and there did not appear to be any zones of unfractured chalk where porewater had retained pre-1960s concentrations of nitrate. Zones close to major fractures did not show steep nitrate concentration gradients, suggesting that there were not large differences in quality between the fracture water and porewater. Porewater concentrations followed a typical nitrate profile for chalk overlain by arable land, with elevated concentrations (up to 78 mg/l as NO_3) in the unsaturated zone and declining concentrations in the saturated zone (up to 39 mg/l as NO_3), except in a 15 m thick zone of the Lewes Nodular Chalk at about 25 m below the water table at that time. Here a number of marl bands appear to result in a zone of slow-moving water with low nitrate concentration.

It was concluded that, if the results were representative of local conditions, and given the significant proportion of similar arable land in the immediate catchment of the Twyford Pumping Station, then groundwater nitrate concentrations are likely to continue rising under the present landuse and agricultural regime. Moreover, much of the cultivated land is located in the upper part of the catchment and nitrate is likely to be still present in the unsaturated zone and saturated groundwater flow paths. The site lies within a Nitrate Vulnerable Zone but even ‘improved grassland’ may have significant applications of inorganic fertiliser and organic manure, within the limits set by the Nitrate Directive. Present conditions do not therefore suggest any immediate reduction in the upward trend in groundwater nitrate concentration. For further details the reader is referred to Stuart *et al*. (2008a).

A preliminary review of the nitrate concentration fluctuation data available from Twyford PS did not lead to any firm conclusions from this site (Stuart *et al*. 2008b). Unlike the other examples reviewed, piston flow from the overlying unsaturated zone cannot be ruled out. The good correspondence between nitrate concentration and water levels throughout the time series does not suggest that the rising of the water table to a particular level triggers an increase of nitrate into the borehole.

1.3 APPROACH

The project objective is to be achieved by the following activities:

1. Drilling of a second borehole (Borehole B) at the Morestead site close to the existing piezometers. This would enable the use of existing information obtained at the site, e.g. geological information, and also allow future use of cross-borehole techniques. The hole was to be of adequate diameter to facilitate the use of geophysical techniques. Moreover, it was to remain unlined against the Chalk to allow water to enter from every fracture horizon, thus allowing an assessment of flow and nitrate contributions from individual fractures.
2. Instrumentation of Borehole B to obtain frequent nitrate samples from the water table, and continue groundwater level monitoring in Borehole A. This would determine the concentration of nitrate arriving at, and also define the location of, the water table.
3. Employing a range of borehole geophysical logging techniques to identify and characterise significant fracture horizons, including an assessment of nitrate concentrations at selected fractures.
4. Comparing the relationship between nitrate concentrations and groundwater levels, with local recharge events examined in detail, in order to improve the understanding in relation to mechanisms and processes.

Subsequently, existing models would be adapted to represent the seasonal processes identified by the study and to use these to model the magnitude and duration of future peak concentrations in different scenarios.

Objective 1 has now been completed and the project is now entering the 3rd recharge season.

1.4 LINKS

This project falls within the Sustainable Use of Natural Resources Theme in the NERC Strategy “Next Generation Science for Planet Earth”. This project was originally linked to the project “Nitrate mass balance in the saturated zone” in the use of common infrastructure. It follows on from co-funded work for UKWIR and commissioned work for Defra.

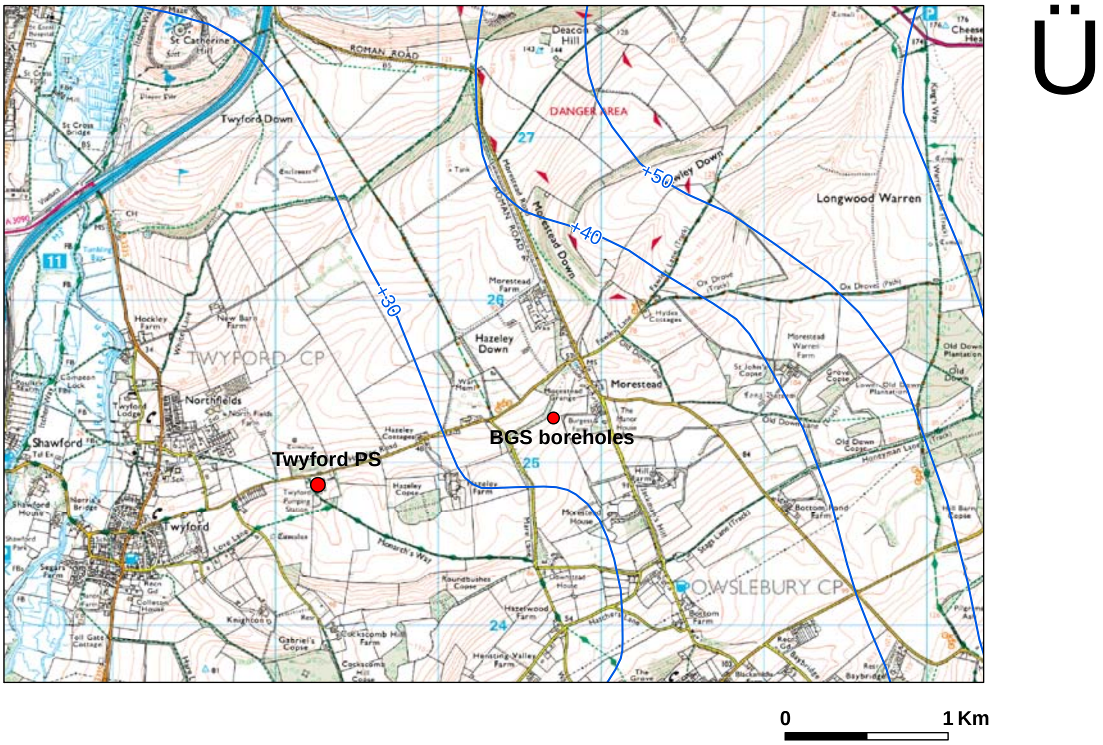
2 Research site

2.1 LOCATION

The site is located at SU 5073 2528 (© Crown Copyright. All rights reserved. NERC 100017897/2010.

Groundwater levels from the Hampshire and Isle of Wight hydrogeological map (IGS, 1979).

Figure 2.1). It lies 1.5 km east of the public supply borehole at Twyford, Hampshire on the Chalk of the South Downs. Further details of the location and hydrogeological setting are outlined in Stuart *et al*. (2008a).



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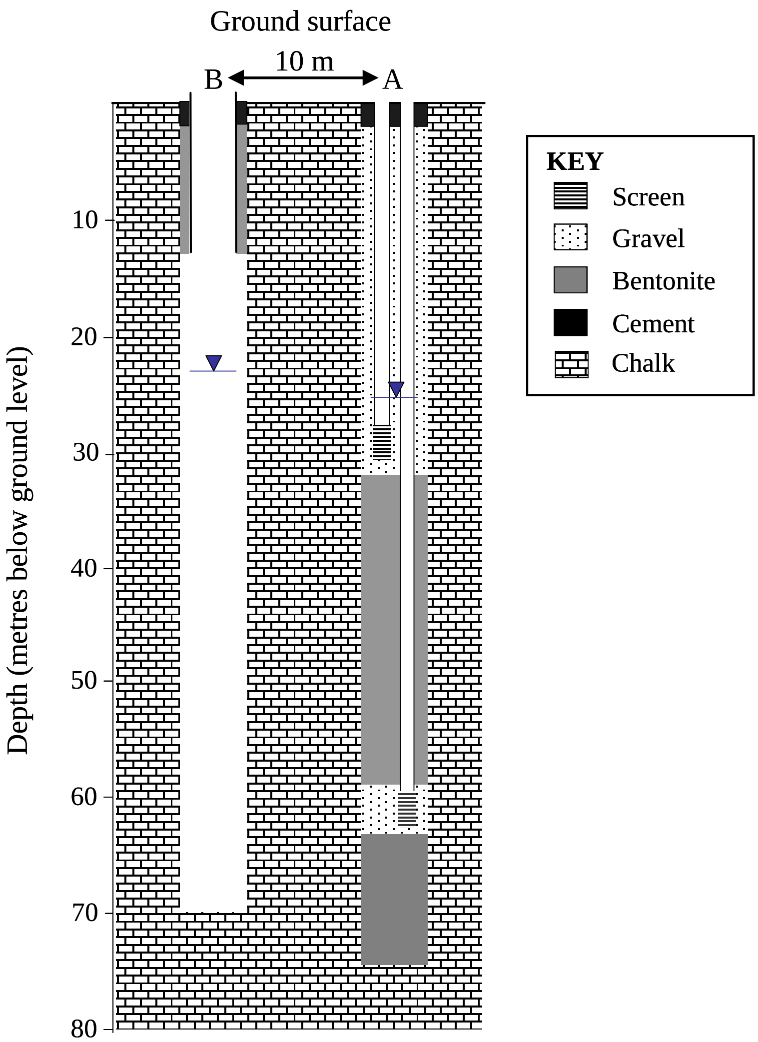
Groundwater levels from the Hampshire and Isle of Wight hydrogeological map (IGS, 1979).

Figure 2.1 Site location and contours of autumn rest groundwater levels (1973).

2.2 INFRASTRUCTURE

Two boreholes have been drilled at the site since the commissioning of the project. Borehole A was completed with two separate 50 mm diameter piezometers in 2006 (Stuart *et al* 2008a). Borehole B was completed with steel casing to 12.7 metres below ground level (m bgl), with the hole remaining unsupported below this depth (Sorensen *et al*. 2010). Borehole B lies approximately 10 m west of Borehole A. The site datum is the top of the casing at Borehole B. This is 0.337 m below ground level (datum) at Borehole A. Further borehole completion details are provided in the respective reports above and Figure 2.2.



Note: water levels are shown from time of drilling; Borehole A datum (ground level) is 0.337 m above Borehole B datum (top of casing - which protrudes 0.16 m above ground level).

Figure 2.2 Borehole completions: A - as two 50 mm diameter piezometers; B - as 200 mm diameter and open hole below casing.

3 Testing methodology

3.1 RAINFALL

Daily rainfall data were retrieved from the Meteorological Office Database – MIDAS for selected currently operational stations near Morestead (UK Meteorological Office, 1853-current). These stations are shown in Table 3.1.

Otterbourne Water Works was the nearest MIDAS station to the field site and recorded two separate rainfall datasets: from an ordinary climatological station and also a rainfall station. These data were processed to remove duplicates. Data from the rainfall station were deemed the most suitable as there were no gaps in the record. It was noted that between 1st October 2006 and 1st April 2010 total precipitation differed by around 4% (over 100 mm) between the two time series.

Table 3.1 Nearby MIDAS stations with rainfall data

Station Name	National Grid Reference (NGR)	Elevation (m aOD)	Data start date
Lake End: Longwood View	SU 557257	128	01/10/2000
Merdon Manor	SU 411266	118	01/01/1938
Otterbourne Water Works	SU 467234	34	01/01/1892
Sparsholt: Woodman Close	SU 437309	102	01/11/2000

Note: metres above Ordnance Datum (m aOD)

3.2 WATER LEVEL RECORDING

A 5-m range pressure transducer (Diver) was installed in the shallow piezometer of Borehole A on 1st December 2006 to assess seasonal groundwater level changes prior to installation of water sampling equipment. Water level variations within the borehole were significant and the diver had to be frequently raised or lowered in the borehole. Additionally, on occasions, the water level exceeded the specified range of the diver. Consequently, a 30 m range CTD Diver was deployed, instead, at the base of the shallow piezometer (c. 30 metres below ground level) on 11th April 2008. Unfortunately the CTD Diver subsequently failed and water level data is only available until 16th December 2009. Therefore data from the Druck PDCR 1830 pressure transducer from Borehole B were used after this date (see 3.3).

On each site visit the diver data were downloaded, and the borehole was dipped manually to allow the later conversion of the diver pressure readings to actual groundwater level. Borehole B was also dipped manually. Pressure data from the Druck sensor was considered to be of superior quality to the CTD Diver and could be referenced against dip measurements with minimal uncertainty.

3.3 TELEMETRY SYSTEM

On 25th November 2009 a telemetry system was installed onsite. The system comprised a Druck 7-m range PDCR 1830 pressure transducer, a Cambell Scientific CR10X logger and an associated solar power supply. The Druck sensor was attached at a known depth below the base of the multi-level sampler (Figure 3.3) and logged at 3-hourly intervals. The system enabled water levels to be visualised in the office via the GPRS network, thus facilitating targeted sampling visits to site.

3.4 GEOPHYSICAL LOGGING

On completion of Borehole B, geophysical logging was carried out on 16th and 17th October 2008 to evaluate the suitability of the hole for further testing. Subsequently investigations were undertaken in 2009 to characterise the borehole flow regime and structural features. More detailed information and results are reported in Sorensen *et al*. (2010) and Woods (2010). Unfortunately, the water quality sonde could not be successfully calibrated following attempts to produce groundwater nitrate depth profiles. Moreover, the borehole has not been stressed sufficiently to allow satisfactory identification of all borehole flow horizons.

3.5 WATER SAMPLING

3.5.1 Multi-level sampler

The multi-level sampler system comprised a series of Sterilin™ sample bottles. Each bottle contained a small ball which would rise to the top of the bottle as it was submerged, effectively sealing the sample from the surrounding groundwater (Figure 3.1). The sampler originally had 18 bottles fixed at regular intervals along two 1-m adjoined sections of slotted plastic tracking (Figure 3.2). Two additional bottles were later added in 2008 to increase the total to 20 sample bottles; the distance between sampling units was thus around 0.1 m.

In November 2009 a further two near-identical samplers were constructed. One sampler was coupled to the end of the original to increase the sampler length to 3.9 m. Additionally the third sampler was coupled to the rear of the original at a 0.05 m offset to allow sampling at 0.05 m resolution from 0.1-2.05 m (Figure 3.3).

The multi-level sampler was suspended just above the water table at the start of the 2009/10 recharge season with the aid of the Druck sensor, which was a known depth below the sampler. The water level could then be visualised in the office to assess whether samples had been captured or it was necessary to move the sampler in anticipation of a new rise in water level. After samples were retrieved the device would be re-suspended at the water table with fresh sample bottles in place.

During the 2009/2010 recharge season, samples were retrieved on 25th November; 2nd, 8th, 11th and 16th December 2009; 5th and 25th January; 2nd February, 16th March and 19th April.

All samples were scheduled for nitrate, chloride and sulphate analysis by ion chromatography. A full list of collected samples results is presented in Appendix A.

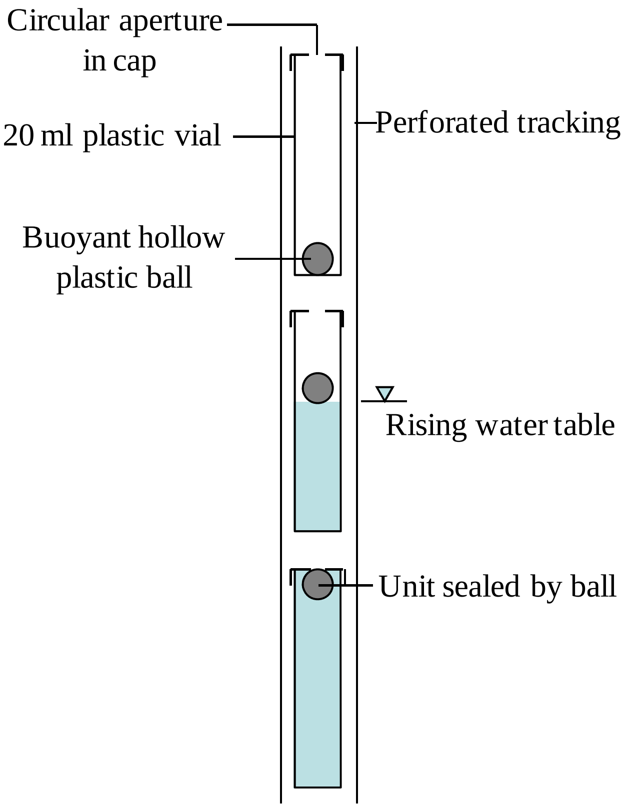


Figure 3.1 Schematic diagram of multi-level sampler bottle.

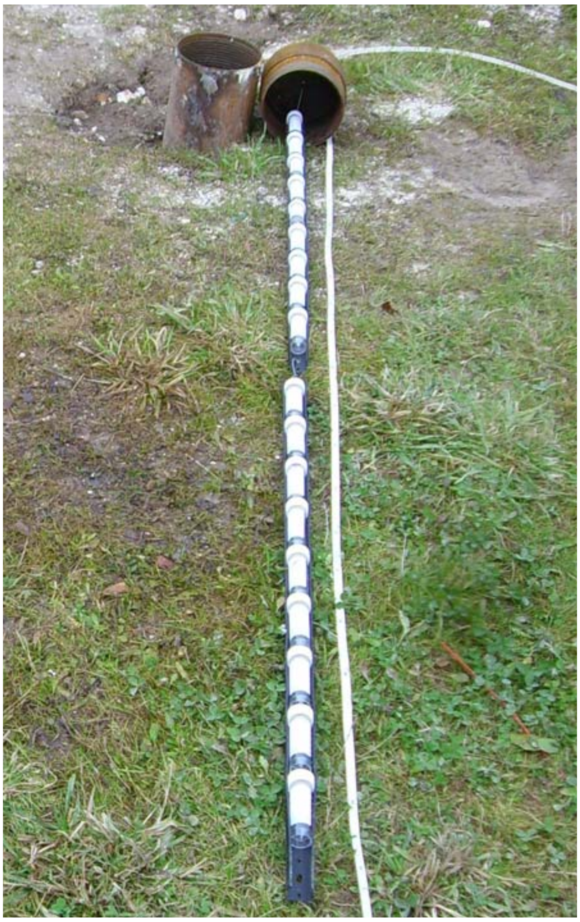


Figure 3.2 The original multilevel sampler hanging via a cable from the cap of Borehole B prior to lowering down the hole.

Figure 3.3 2009/10 multilevel sampler, attached Druck sensor and telemetry system.

4 Results and interpretation

4.1 WATER LEVEL RECORDING

Water level data were processed to remove spurious readings and combined with rainfall data from Otterbourne Water Works (Figure 4.1). Monthly totals of the rainfall data are shown for in Table 4.1.

The hydrograph shows annual water level maxima in March during 2007, and February in both 2009 and 2010. There are no data available prior to mid-March in 2008, when the maximum is likely to have been that year. Lowest recorded groundwater levels occurred between mid-September and mid-November in 2008, and October and mid-November in 2009. There is an absence of data where the lows of 2007 and 2008 are likely to have occurred.

Between December 2007 and August 2010, available water levels ranged between 26.1 and around 10.5 mbgl, although a manual dip undertaken in October 2006 recorded a level of 27.6 mbgl.

During the 2009/10 recharge season groundwater levels varied between 26 m below datum (m bd) in November 2009 and 12.3 m bd in February 2010. The groundwater hydrograph was characterised by an initial rapid rise in water level to 17 m bd, which was followed by four successive peaks. All peaks can be correlated to specific rainfall events (Figure 4.1).

Figure 4.2 compares the relationship between groundwater level and cumulative rainfall over the 2009/10 recharge period. The rapid rise and fall of water levels associated with precipitation events is similar to that observed at the North Heath Barn borehole north of Brighton. Here, fracture flow was regarded as significant if a certain threshold of rainfall was exceeded (Adams *et al*., 2008).

Table 4.1 Rainfall data from Otterbourne Water Works (mm/month).

					2007						
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
105.8	62.6	69.8	1.8	82.8	88.8	148.2	39.8	14.2	42.4	88.8	72.6
					2008						
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
106.2	28.8	92.8	56.8	119.8	66.4	77.2	76.8	61.6	71.4	83.0	48.0
					2009						
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
107.6	55.0	48.6	51.0	34.2	22.6	92.0	35.6	62.4	53.8	195.0	139.0
					2010						
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
81.0	79.6	82.6	24.4	-	-	-	-	-	-	-	-

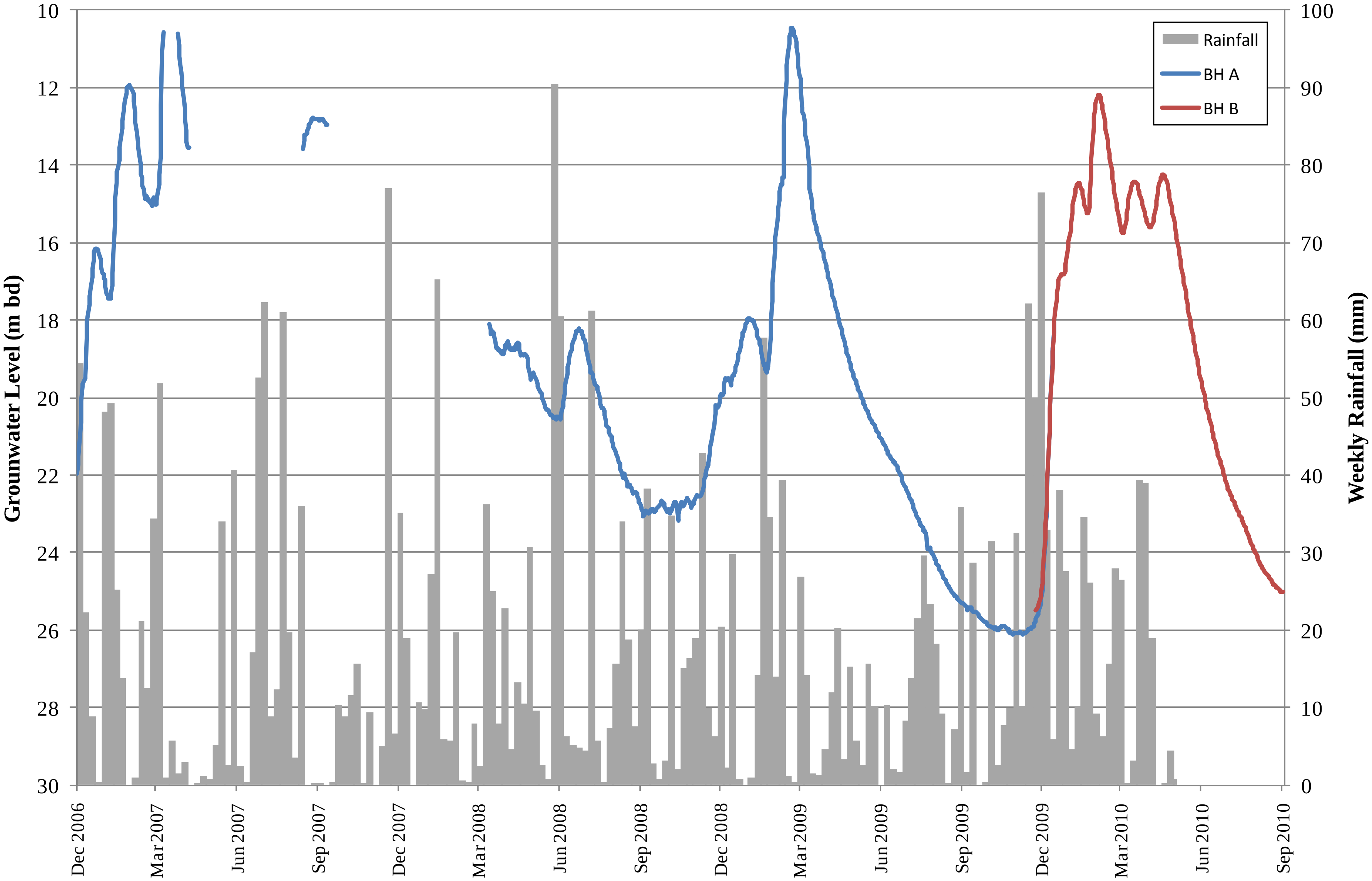


Figure 4.1 Daily groundwater hydrograph with rainfall from Otterbourne Water Works BADC station (rainfall data only until 1st May 2010).

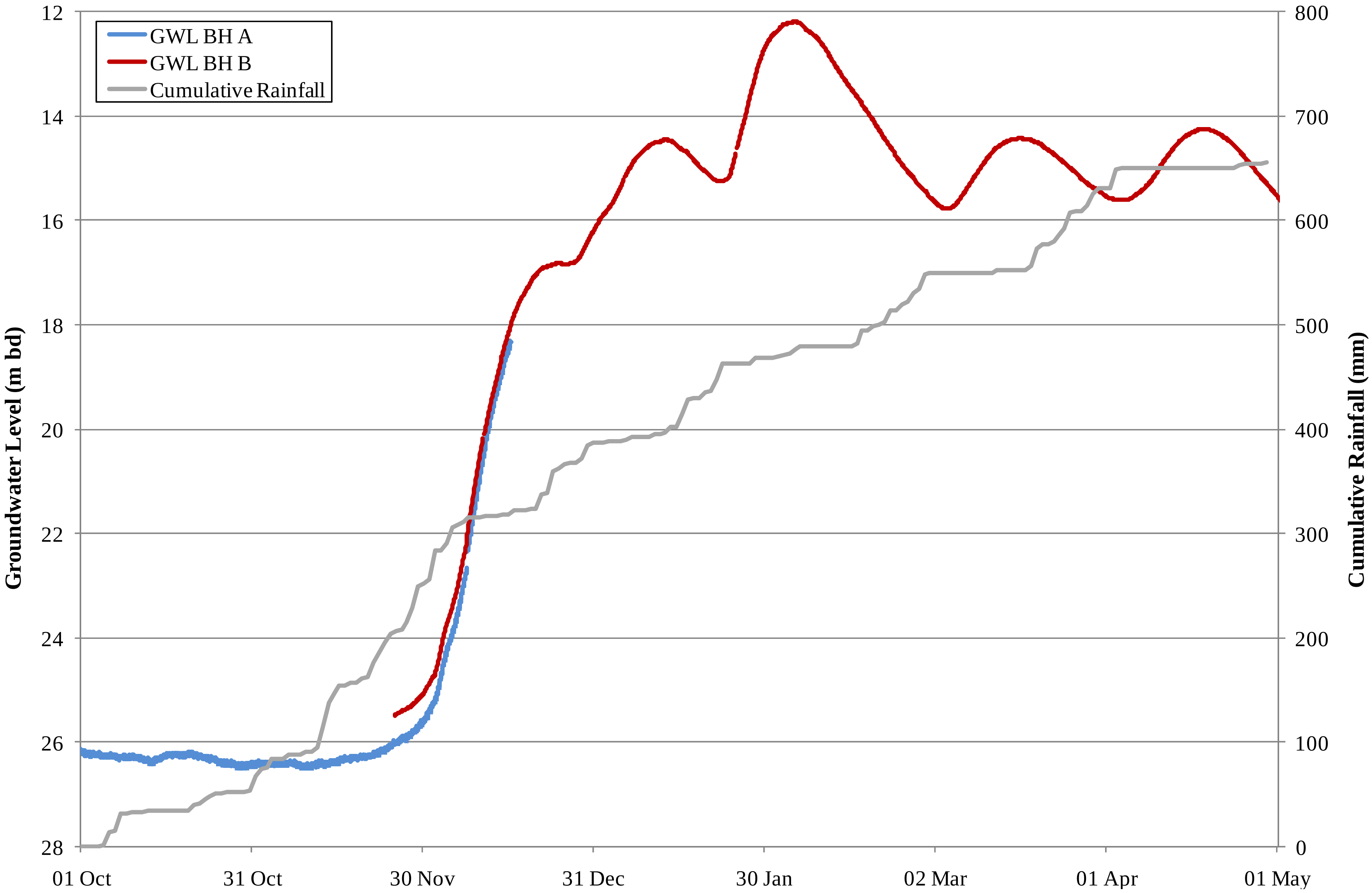


Figure 4.2 Comparison of groundwater level and cumulative rainfall between 1st October 2009 and 1st May 2010.

4.2 WATER SAMPLING

4.2.1 Site observations

During sample collection from the multi-level sampler a number of observations were recorded:

- On 25th November 2009 a unit was collected at the top of the sampler despite the water level rising only 0.3 m, i.e the sample was from above the water table. It was brown and only contained about 15 ml.
- On 16th December 2009 a further Sterilin above the water table contained a sample. This was 2.7 m up the sampler and the water was opaque.
- On three occasions (8th and 16th December 2009, and 5th January 2010) it was not possible to exactly tally the rise in water level with the correct number of samples. It has been assumed that the sampler was positioned correctly when estimating sample depths and sample capture dates. Consequently, there could be 0.05 m, 0.05 m and 0.20 m error in the sample depths from those dates, respectively. Sample capture dates would only be out by a maximum of 24 hours.
- On 5th January 2010 three Sterilins had failed to fill in amongst full samples. This was likely to have been a result of units being packed too tightly together

4.2.2 Variation in water sample chemistry

Water quality data are presented as Appendix A. Concentrations of chloride, sulphate and nitrate (as NO_3) range between 14.6 and 39.5 mg/l, 9.9 and 37.3 mg/l, and 21.8 and 62.2 mg/l, respectively. These concentration ranges exclude the 'brown' sample collected from above the water table on 25th November 2009. This sample contained a chloride concentration of 85.3 mg/l, sulphate of 104 mg/l and nitrate of 123.7 mg/l. Moreover there were 68.4 mg/l of HPO_4^{2-}, indicating the sample is likely to be derived from the near surface. Previously at the site, anomalously high concentrations of nitrate (57.1 mg/l) and chloride (68.8 mg/l) were also recorded in a sample collected above the water table on 27th January 2010 when the water level was around 18.5 m bd (Sorensen *et al*. 2010). However, HPO_4^{2-} was below the limits of detection for this sample.

There were no anomalously low nitrate readings (<10 mg/l) which had previously been recorded in the 2008/9 recharge season (Sorensen *et al*. 2010).

4.2.3 Depth profiles

General trends

Depth profiles of the data suggest generally increasing concentrations of all determinands as the water level rises from 26 to 20.7 m bd (Figure 4.3 and Figure 4.4). At 20.7 m bd there are small sudden increases in concentration, and the concentration gradients also subsequently increase as the water level rises towards 20 m bd. At this depth there are more dramatic sudden increases in concentration from 20.5 to 25.0 mg/l, 16.7 to 24.4 mg/l and 38.9 to 49.8 mg/l, for chloride, sulphate and nitrate respectively. The relative order and relative range in concentrations of the species also changes at this depth (Figure 4.4). Subsequently concentrations fall towards 18 m bd, before rising to peak at 17.5 m bd, and then falling again towards 16.5 m bd where several samples have unusually lower concentrations of all species, particularly nitrate. Concentrations then rise towards around 14.3 m bd, with a sudden increase in concentration between 15.5 and 15.1 m bd (chloride concentrations also jump at

14.45 m bd). Above 14.3 m bd concentrations are fairly stable, around the annual maxima, before receding at around 13.4 m bd. Concentrations then increase slightly when the water level reaches the casing at 12.7.

Unfortunately three of the sudden increases in concentration outlined above coincide with site visits (Figure 4.4), and therefore could be a result of contamination. This could have been a consequence of raising the sampler to the surface and re-installing it, although the lack of noise in the data suggests this is unlikely.

There are also some more subtle features in the depth profiles:

- Samples with sudden apparently ‘fresher’ water which are then followed by a decrease in concentration as the water table rises further, e.g. 18.50 and 13.39 m bd.
- A relatively rapid increase in concentration of all determinands around 24.1 m bd which does not coincide with a site visit.

Interestingly, repeated samples at similar depths show higher concentrations after the initial rise in water level.

Correlation with geophysical logs

Geophysical borehole OPTV undertaken in 2009 (Appendix B) identified several open fractures which appear to correlate with features in the depth profiles (Table 4.2). This indicates that fractures could be delivering both relatively high and low concentrations of nitrate to the borehole. Although these fractures were noted in the OPTV log, there is no indication that these were active in the fluid and flow logs, with the exception of 25.3 m bd. (Woods 2010). Additionally the samples around 25.3 m bd could have been influenced by contamination from the surface, as indicated by the ‘brown’ sample collected during that site visit.

Table 4.2 Relating nitrate depth profile to open fractures observed in the borehole OPTV log

Fracture depth (m bd)	Features in nitrate depth profile
16.8	Nitrate is falling and several relatively low nitrate samples are noted
19.2	No observable features
20.1	Sudden increase in nitrate of 10.9 mg/l
20.7	Small sudden increase in nitrate, followed by rising concentrations subsequently
25.3	Two anomalously high nitrate samples at 25.3 and 25.5 m bd

Comparison with 2008/9 recharge season

The depth profile does not correlate particularly well with the previous year’s nitrate dataset, although the general rising concentration of nitrate with groundwater elevation is evident (Figure 4.3). Nevertheless there is a sudden increase of around 9.3 mg/l in nitrate concentration between 20.3 and 20.1 m bd. Unfortunately data resolution and the number of samples in the 2008/9 data limits comparison.

4.2.4 Nitrate time series

There is some evidence to suggest a tentative relationship between the rate of groundwater rise and nitrate concentration: as the rising limb of a recharge event begins to slow towards the peak, then the rate of rise in nitrate concentration also beings to level off. This is based on the groundwater level peaks on 12th January, 12th March and 17th April 2010. This behaviour is not evident for the 24th December 2009 and 4th February 2010 peaks where nitrate concentration falls during the recharge event.

4.2.5 Comparison of groundwater and porewater chemistry

Porewater samples were not collected during the construction of Borehole B, but data are available from the neighbouring Borehole A. These were collected during 2006 and the profile is likely to have been modified slightly by subsequent recharge through the matrix. Therefore an estimated current porewater profile is displayed assuming a vertical nitrate movement of 0.8 m per annum (Figure 4.6), a figure previously determined by Gale *et al.* (1994) in borehole core profiles from the Wiltshire Chalk.

There is a reasonable correlation between the groundwater and estimated current porewater nitrate with concurrent peaks in concentration at c. 14.5-15.0, 19.5 and 24.0 m bd. These peaks in groundwater nitrate do not correlate with fracture horizons, further suggesting they are a result of higher porewater concentrations at these depths. Additionally, there is no large decrease in concentration between 17 and 16 m bd in the porewater concentration, indicating the lower observed groundwater nitrate must be influenced by another factor, e.g. fracture delivering fresher water as discussed above.

There is also an offset between the two datasets with groundwater concentrations always lower than porewaters. This was also observed in the previous recharge year where it was postulated this could be a result of (Sorensen *et al*., 2010):

- Evaporation of water from the core prior to porewater analysis.
- Groundwater nitrate concentrations falling over time as a result of reduced nitrate applications to the surface – particularly as the site has been set-a-side.
- Mixing of higher and lower nitrate groundwaters – perhaps reflecting the degree of recharge through the matrix and bypass flow through the fractures.

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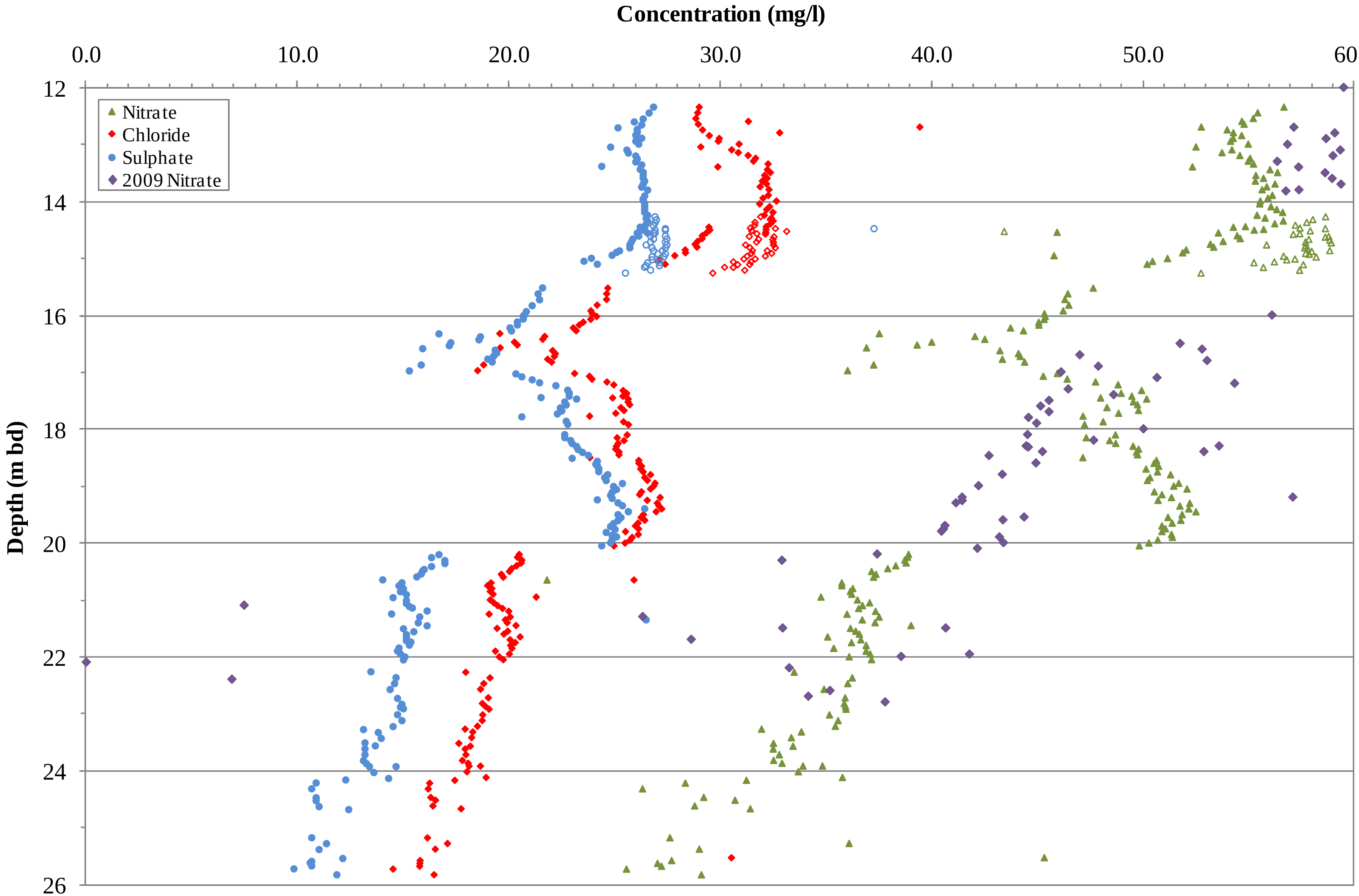


Note: Unfilled data points relate to repeated samples at similar depths after the initial water level rise; 2008/9 nitrate data shown for comparative purposes.

Figure 4.3 Depth profiles of chloride, sulphate and nitrate concentrations in Borehole B.

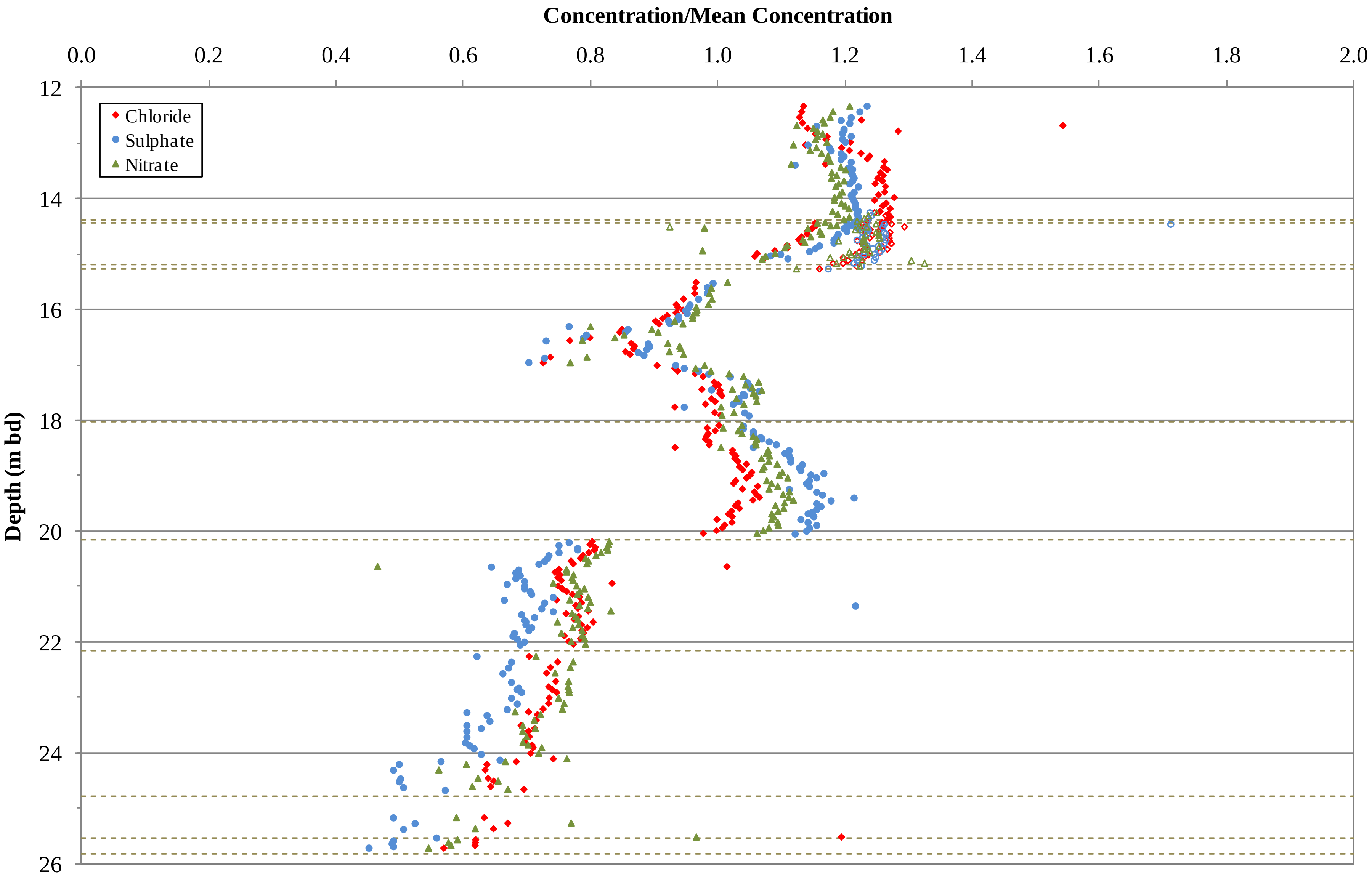
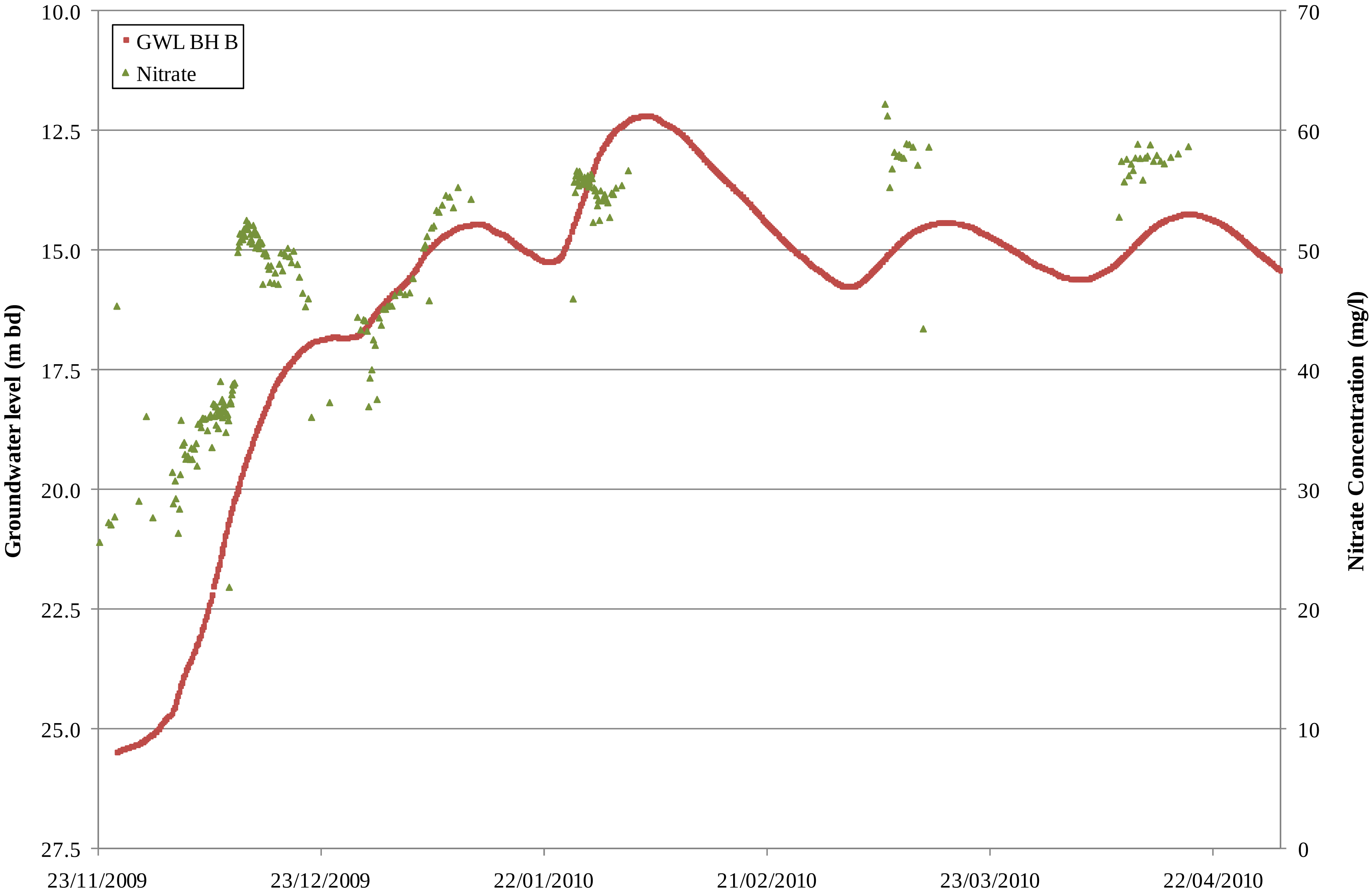
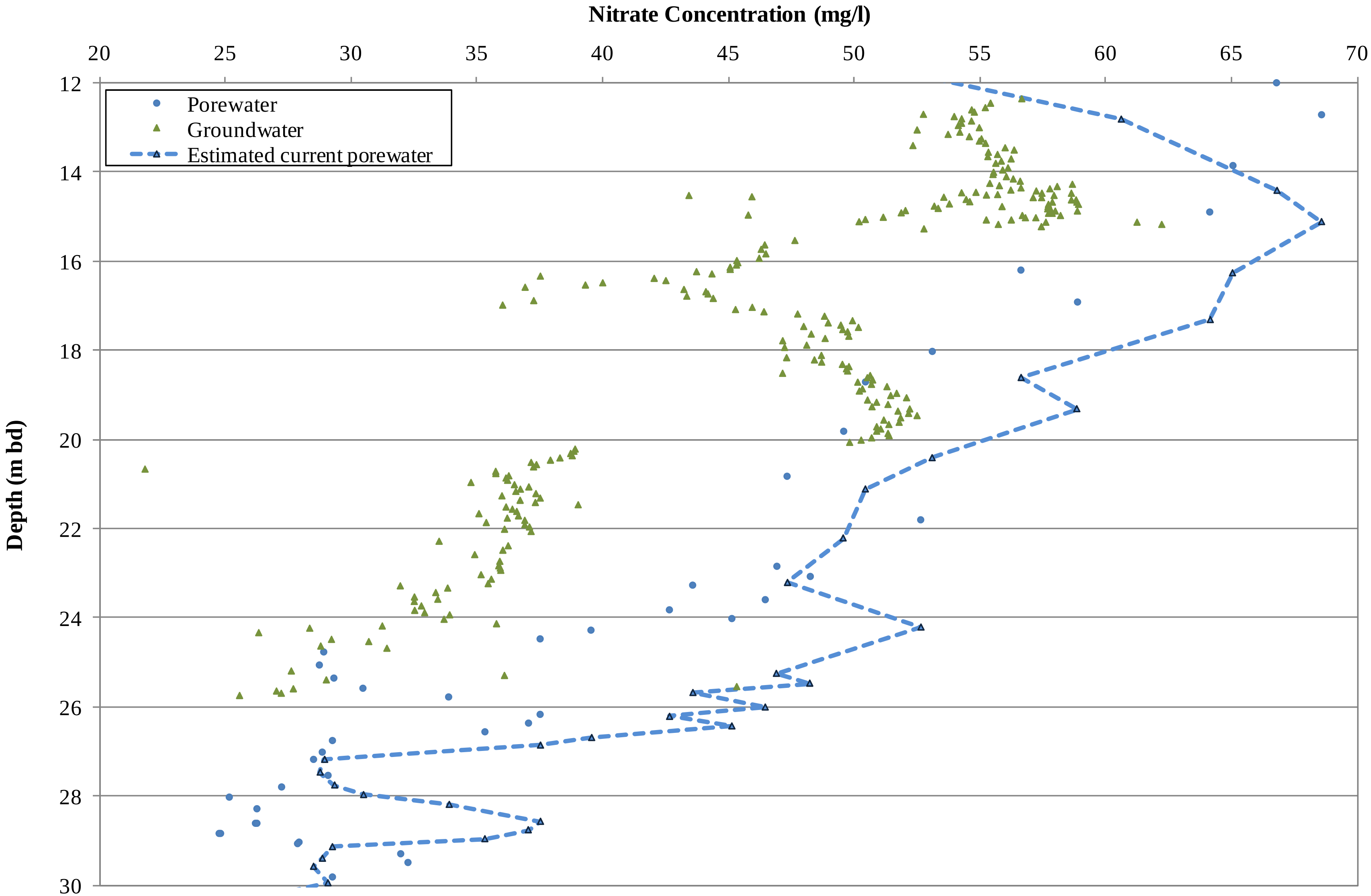


Figure 4.4 Normalised depth profiles of chloride, sulphate and nitrate with sampling dates shown as dotted horizontal lines.



Note: Date of sample capture is estimated from water levels recorded in Borehole B.

Figure 4.5 Relating nitrate concentrations in Borehole B to groundwater level over the sampling period.



Note: Porewater data are from Borehole A and groundwater data from Borehole B; estimated current porewaters assume a vertical movement of 0.8 m yr^{-1}.

Figure 4.6 Depth profiles of groundwater nitrate concentrations from 2008-9 (Borehole B) and porewater nitrate concentrations from 2006 (Borehole A).

5 Conclusions and future programme

5.1 CONCLUSIONS

The improved hanging sampler was successfully deployed in Borehole B in associated with a GPRS telemetry system. This allowed the visualisation of water levels in the office which facilitated targeted, more efficient site visits. The attached Druck PDCR 1830 also provided superior quality water level data in comparison to the CTD Diver.

A total of 252 groundwater samples were collected between 25.73 and 12.34 m bd at a typical depth resolution of 0.05 m. These indicated concentrations of chloride, sulphate and nitrate (as NO_3) range between 14.6 and 39.5 mg/l, 9.9 and 37.3 mg/l, and 21.8 and 62.2 mg/l, respectively. Additionally a discoloured sample was retrieved from above the water table which contained a chloride concentration of 85.3 mg/l, sulphate of 104 mg/l and nitrate of 123.7 mg/l. The high levels of $H_2PO_4^{2-}$ indicated that this sample was derived from the near surface suggesting pollution of the borehole from the surface is possible at the site.

Analysis of the groundwater samples indicated:

- A general rising trend in nitrate groundwater concentration with water level towards a maxima around 14.3 m bd, although concentrations decreased between 17.5 and 16.5 m bd, and 19.5 and 18 m bd.
- Sudden increases in concentration at several depths, notably at around 20 m bd and 15.5 m bd corresponding to site visits and/or open fractures.
- Fractures could be delivering high levels (e.g. 20 m bd) or low levels (16.8 m bd) of nitrate to the water table.
- A reasonable correlation with an estimated current nitrate porewater profile with concurrent peaks at 14.5-15.0, 19.5 and 24.0 m bd.
- Concentrations always below the porewater concentration at the estimated same depth.

5.2 FUTURE PROGRAMME

During the forthcoming year the sampling procedure will be repeated. However, it is planned to implement additional measures to reduce current uncertainties in the dataset and with the sampling methodology:

- In order to investigate the sudden increases in concentration that have been associated with site visits this year, the sampler will not be removed and repositioned at 15.5 and 20 m bd. This will help identify whether the increases this year were a sampling artefact.
- Potential contamination will be investigated by processing blank samples through the current sampling procedure.
- A second set of Sterilin lids and balls will be obtained to allow cleaned lids and balls to be installed when full samples are retrieved.
- A plastic or tarpaulin sheet will be placed on the ground surface to avoid the hanging sampler contacting the ground surface when checking/removing samples.
- All samples will pass through individual filters following collection, rather than sequential filtering through a large-diameter Swinnex filter holder.

- A depth sample will be collected from the screened interval in Borehole A on every site visit to investigate changing nitrate concentrations at the same water level depth throughout the recharge season.

Additionally geophysical logging, when stressing the borehole to a greater degree than previously, and/or dilution tests will be employed to infer the borehole regime at the end of the upcoming recharge year. The water quality sonde will also calibrated and re-run to produce a nitrate depth profile at this time. Furthermore soil samples will be collected to investigate current nitrate concentrations at the surface.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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Appendix A – Water quality samples and results

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
23/07/2009 Bulk WL 23.92	23/07/2009	23/07/2009 12:00	23.92	18.7	14.7	34.8	0.065	0.024	-0.100	0.072
01/10/2009 Bulk WL 25.83	01/10/2009	01/10/2009 12:00	25.83	16.5	11.9	29.1	0.065	0.019	-0.100	0.073
25/11/2009 10	25/11/2009	23/11/2009 08:20	25.73	14.6	9.86	25.6	0.065	0.017	-0.100	0.066
25/11/2009 15	25/11/2009	24/11/2009 13:00	25.68	15.8	10.7	27.2	0.054	-0.010	-0.100	0.076
25/11/2009 20	25/11/2009	24/11/2009 21:00	25.63	15.8	10.6	27.0	0.043	0.019	-0.100	0.072
25/11/2009 25	25/11/2009	25/11/2009 09:00	25.58	15.8	10.7	27.7	0.054	0.338	-0.100	0.071
25/11/2009 30	25/11/2009	25/11/2009 16:00	25.53	30.6	12.1	45.3	0.111	0.021	-0.100	0.078
25/11/2009 390 C	25/11/2009	?	21.93	85.3	104.0	123.7	0.071	-0.020	68.4	0.229
02/12/2009 15	02/12/2009	28/11/2009 15:00	25.38	16.6	11.0	29.0	0.060	0.060	-0.100	0.073
02/12/2009 25	02/12/2009	29/11/2009 15:00	25.28	17.1	11.4	36.1	0.050	-0.010	-0.100	0.075
02/12/2009 35	02/12/2009	30/11/2009 12:00	25.18	16.2	10.7	27.6	0.062	-0.010	-0.100	0.070
08/12/2009 10	08/12/2009	03/12/2009 03:00	24.67	17.8	12.5	31.4	0.060	0.077	-0.100	0.081
08/12/2009 15	08/12/2009	03/12/2009 06:00	24.62	16.4	11.0	28.8	0.063	0.067	-0.100	0.067
08/12/2009 25	08/12/2009	03/12/2009 12:00	24.52	16.6	10.9	30.7	0.058	0.105	-0.100	0.073
08/12/2009 30	08/12/2009	03/12/2009 14:00	24.47	16.4	10.9	29.2	0.062	-0.010	-0.100	0.073
08/12/2009 45	08/12/2009	03/12/2009 22:00	24.32	16.2	10.7	26.3	0.043	-0.010	-0.100	0.072
08/12/2009 55	08/12/2009	04/12/2009 02:00	24.22	16.3	10.9	28.4	0.039	-0.010	-0.100	0.069
08/12/2009 60	08/12/2009	04/12/2009 04:30	24.17	17.5	12.3	31.2	0.078	-0.010	-0.100	0.072
08/12/2009 65	08/12/2009	04/12/2009 07:00	24.12	19.0	14.3	35.8	0.052	-0.010	-0.100	0.071
08/12/2009 75	08/12/2009	04/12/2009 12:00	24.02	18.1	13.7	33.7	0.054	-0.010	-0.100	0.065
08/12/2009 85	08/12/2009	04/12/2009 17:00	23.92	18.2	13.4	33.9	0.047	-0.010	-0.100	0.066
08/12/2009 90	08/12/2009	04/12/2009 19:30	23.87	18.1	13.3	32.9	0.041	-0.010	-0.100	0.067
08/12/2009 95	08/12/2009	04/12/2009 22:30	23.82	17.8	13.1	32.5	0.063	-0.010	-0.100	0.077
08/12/2009 105	08/12/2009	05/12/2009 05:00	23.72	18.0	13.2	32.8	0.057	-0.010	-0.100	0.077
08/12/2009 115	08/12/2009	05/12/2009 12:00	23.62	18.0	13.2	32.5	0.065	-0.010	-0.100	0.074
08/12/2009 120	08/12/2009	05/12/2009 16:00	23.57	18.2	13.7	33.5	0.060	0.049	-0.100	0.073
08/12/2009 125	08/12/2009	05/12/2009 19:00	23.52	17.7	13.2	32.5	0.052	0.027	-0.100	0.076
08/12/2009 135	08/12/2009	06/12/2009 02:00	23.42	18.3	14.0	33.4	0.068	0.035	-0.100	0.077

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl$^-$ (mg l^{-1})	SO$_4^{2-}$ (mg l^{-1})	NO$_3^-$ (mg l^{-1})	Br$^-$ (mg l^{-1})	NO$_2^-$ (mg l^{-1})	HPO$_4^{2-}$ (mg l^{-1})	F$^-$ (mg l^{-1})
08/12/2009 145	08/12/2009	06/12/2009 07:30	23.32	18.3	13.9	33.8	0.058	-0.010	-0.100	0.074
08/12/2009 150	08/12/2009	06/12/2009 10:30	23.27	18.0	13.2	32.0	0.060	-0.010	-0.100	0.066
08/12/2009 155	08/12/2009	06/12/2009 13:30	23.22	18.6	14.6	35.5	0.069	-0.010	-0.100	0.074
08/12/2009 165	08/12/2009	06/12/2009 19:30	23.12	18.8	14.9	35.6	0.062	-0.010	-0.100	0.077
08/12/2009 175	08/12/2009	07/12/2009 00:00	23.02	18.8	14.7	35.2	0.077	-0.010	-0.100	0.076
08/12/2009 185	08/12/2009	07/12/2009 04:00	22.92	19.1	15.1	36.0	0.063	-0.010	-0.100	0.069
08/12/2009 190	08/12/2009	07/12/2009 07:00	22.87	18.9	14.9	35.9	0.107	-0.010	-0.100	0.071
08/12/2009 195	08/12/2009	07/12/2009 09:00	22.82	18.8	14.9	35.9	0.066	-0.010	-0.100	0.069
08/12/2009 205	08/12/2009	07/12/2009 13:00	22.72	19.1	14.7	35.9	0.065	0.033	-0.100	0.080
08/12/2009 220	08/12/2009	07/12/2009 20:00	22.57	18.7	14.4	34.9	0.047	0.044	-0.100	0.065
08/12/2009 230	08/12/2009	08/12/2009 01:00	22.47	18.9	14.6	36.0	0.067	0.015	-0.100	0.076
08/12/2009 240	08/12/2009	08/12/2009 06:00	22.37	19.1	14.7	36.3	0.061	0.032	-0.100	0.071
08/12/2009 250	08/12/2009	08/12/2009 10:30	22.27	18.0	13.5	33.5	0.061	0.048	-0.100	0.061
11/12/2009 10	11/12/2009	08/12/2009 15:00	22.05	19.8	15.0	37.2	0.060	0.021	-0.100	0.070
11/12/2009 15 soil	11/12/2009	08/12/2009 18:00	22.00	19.6	15.1	36.1	0.052	0.053	-0.100	0.062
11/12/2009 20	11/12/2009	08/12/2009 19:30	21.95	20.1	14.9	37.1	0.069	-0.010	-0.100	0.071
11/12/2009 25	11/12/2009	08/12/2009 22:00	21.90	19.4	14.8	36.9	0.063	-0.010	-0.100	0.073
11/12/2009 30	11/12/2009	09/12/2009 00:00	21.85	20.2	14.8	35.4	0.074	0.025	-0.100	0.071
11/12/2009 35	11/12/2009	09/12/2009 01:30	21.80	20.1	15.3	36.9	0.052	-0.010	-0.100	0.070
11/12/2009 40	11/12/2009	09/12/2009 03:30	21.75	20.3	15.4	36.2	0.064	-0.010	-0.100	0.073
11/12/2009 45	11/12/2009	09/12/2009 05:00	21.70	20.1	15.2	36.7	0.069	-0.010	-0.100	0.074
11/12/2009 50	11/12/2009	09/12/2009 07:00	21.65	20.6	15.2	35.1	0.059	0.072	-0.100	0.067
11/12/2009 55	11/12/2009	09/12/2009 09:00	21.60	19.8	15.2	36.6	0.065	-0.010	-0.100	0.073
11/12/2009 60	11/12/2009	09/12/2009 11:00	21.55	20.0	15.5	36.4	0.070	-0.010	-0.100	0.037
11/12/2009 65	11/12/2009	09/12/2009 12:30	21.50	19.5	15.1	36.2	0.061	-0.010	-0.100	0.071
11/12/2009 70	11/12/2009	09/12/2009 14:00	21.45	20.4	16.2	39.0	0.060	-0.020	-0.200	0.098
11/12/2009 75	11/12/2009	09/12/2009 16:00	21.40	20.0	15.8	37.3	0.068	-0.010	-0.100	0.069
11/12/2009 80	11/12/2009	09/12/2009 18:00	21.35	19.9	26.5	36.7	-0.020	-0.010	-0.100	0.056
11/12/2009 85	11/12/2009	09/12/2009 19:30	21.30	20.1	15.8	37.5	0.060	-0.010	-0.100	0.070
11/12/2009 90	11/12/2009	09/12/2009 21:00	21.25	19.1	14.5	36.0	0.053	-0.010	-0.100	0.044
11/12/2009 95	11/12/2009	09/12/2009 22:30	21.20	20.0	16.1	37.4	0.037	-0.010	-0.100	0.063
11/12/2009 100	11/12/2009	10/12/2009 00:30	21.15	19.7	15.4	36.6	0.059	0.019	-0.100	0.069

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
11/12/2009 105	11/12/2009	10/12/2009 02:00	21.10	19.5	15.3	36.7	0.051	-0.010	-0.100	0.070
11/12/2009 110	11/12/2009	10/02/2009 04:00	21.05	19.3	15.1	37.1	0.059	-0.010	-0.100	0.071
11/12/2009 115	11/12/2009	10/02/2009 06:00	21.00	19.2	15.2	36.5	0.068	0.022	-0.100	0.061
11/12/2009 120	11/12/2009	10/12/2009 07:30	20.95	21.3	14.6	34.8	0.055	0.976	-0.100	0.061
11/12/2009 125	11/12/2009	10/12/2009 09:30	20.90	19.3	15.2	36.2	0.064	-0.010	-0.100	0.070
11/12/2009 130	11/12/2009	10/12/2009 11:30	20.85	19.2	14.9	36.2	0.050	-0.010	-0.100	0.061
11/12/2009 135	11/12/2009	10/12/2009 13:00	20.80	19.2	15.0	36.3	0.066	-0.010	-0.100	0.067
11/12/2009 140	11/12/2009	10/12/2009 15:00	20.75	19.0	14.8	35.8	0.065	-0.010	-0.100	0.069
11/12/2009 145	11/12/2009	10/12/2009 16:30	20.70	19.2	15.0	35.8	0.058	-0.010	-0.100	0.070
11/12/2009 150	11/12/2009	10/12/2009 18:15	20.65	26.0	14.0	21.8	0.081	0.239	-0.100	0.055
11/12/2009 155	11/12/2009	10/12/2009 20:30	20.60	19.8	15.6	37.3	0.067	0.010	-0.100	0.067
11/12/2009 160	11/12/2009	10/12/2009 22:30	20.55	19.7	15.9	37.4	0.063	0.011	-0.100	0.062
11/12/2009 165	11/12/2009	11/12/2009 00:15	20.50	20.1	15.9	37.2	0.053	-0.010	-0.100	0.064
11/12/2009 170	11/12/2009	11/12/2009 02:30	20.45	20.2	16.0	37.9	0.090	-0.010	-0.100	0.067
11/12/2009 175	11/12/2009	11/12/2009 04:30	20.40	20.4	16.3	38.3	0.055	0.016	-0.100	0.068
11/12/2009 180	11/12/2009	11/12/2009 06:00	20.35	20.6	17.0	38.8	0.172	-0.010	-0.100	0.068
11/12/2009 185	11/12/2009	11/12/2009 07:30	20.30	20.7	17.0	38.7	0.059	0.017	-0.100	0.068
11/12/2009 190	11/12/2009	11/12/2009 09:30	20.25	20.4	16.3	38.9	0.056	-0.010	-0.100	0.063
11/12/2009 195	11/12/2009	11/12/2009 12:00	20.20	20.5	16.7	38.9	0.054	-0.010	-0.100	0.064
16/12/2009 10	16/12/2009	11/12/2009 22:00	20.05	25.0	24.4	49.8	0.061	0.024	-0.100	0.056
16/12/2009 15	16/12/2009	12/12/2009 00:30	20.00	25.5	24.8	50.3	0.079	0.015	-0.100	0.052
16/12/2009 20	16/12/2009	12/12/2009 03:00	19.95	25.8	24.9	50.7	0.066	-0.010	-0.100	0.056
16/12/2009 25	16/12/2009	12/12/2009 04:30	19.90	25.9	25.1	51.4	0.066	0.015	-0.100	0.056
16/12/2009 30	16/12/2009	12/12/2009 07:00	19.85	26.2	24.9	51.4	0.075	0.021	-0.100	0.052
16/12/2009 35	16/12/2009	12/12/2009 09:00	19.80	25.6	24.6	50.9	0.069	0.011	-0.100	0.054
16/12/2009 40	16/12/2009	12/12/2009 11:00	19.75	26.2	25.0	51.1	0.083	0.022	-0.100	0.049
16/12/2009 45	16/12/2009	12/12/2009 14:00	19.70	26.0	24.9	50.9	0.069	0.019	-0.100	0.058
16/12/2009 50	16/12/2009	12/12/2009 16:00	19.65	26.1	25.0	51.4	0.067	0.039	-0.100	0.052
16/12/2009 55	16/12/2009	12/12/2009 18:15	19.60	26.5	25.2	51.8	0.077	0.056	-0.100	0.053
16/12/2009 60	16/12/2009	12/12/2009 21:00	19.55	26.3	25.3	51.2	0.063	0.076	-0.100	0.056
16/12/2009 65	16/12/2009	12/12/2009 23:30	19.50	26.4	25.2	51.9	0.057	0.027	-0.100	0.051
16/12/2009 70	16/12/2009	13/12/2009 02:00	19.45	27.0	25.6	52.5	0.065	-0.010	-0.100	0.057

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
16/12/2009 75	16/12/2009	13/12/2009 05:00	19.40	27.3	26.4	52.2	0.071	-0.010	-0.100	0.046
16/12/2009 80	16/12/2009	13/12/2009 07:00	19.35	27.1	25.4	51.7	0.074	0.010	-0.100	0.056
16/12/2009 85	16/12/2009	13/12/2009 10:00	19.30	27.1	25.1	52.2	0.061	-0.010	-0.100	0.047
16/12/2009 90	16/12/2009	13/12/2009 12:30	19.25	26.6	24.2	50.7	0.066	0.041	-0.100	0.052
16/12/2009 95	16/12/2009	13/12/2009 15:00	19.20	27.2	24.9	51.4	0.058	0.024	-0.100	0.053
16/12/2009 100	16/12/2009	13/12/2009 18:00	19.15	26.2	24.8	50.9	0.061	0.013	-0.100	0.053
16/12/2009 105	16/12/2009	13/12/2009 21:00	19.10	26.3	24.9	50.5	0.071	0.049	-0.100	0.040
16/12/2009 110	16/12/2009	13/12/2009 23:45	19.05	26.7	25.1	52.1	0.074	0.043	-0.100	0.063
16/12/2009 115	16/12/2009	14/12/2009 02:30	19.00	26.9	25.0	51.5	0.065	-0.010	-0.100	0.044
16/12/2009 120	16/12/2009	14/12/2009 04:30	18.95	26.9	25.4	51.7	0.055	-0.010	-0.100	0.044
16/12/2009 125	16/12/2009	14/12/2009 07:30	18.90	26.6	24.6	50.2	0.073	-0.010	-0.100	0.050
16/12/2009 130	16/12/2009	14/12/2009 10:30	18.85	26.5	24.5	50.3	0.065	-0.010	-0.100	0.050
16/12/2009 135	16/12/2009	14/12/2009 13:00	18.80	26.7	24.7	51.3	0.065	-0.010	-0.100	0.051
16/12/2009 140	16/12/2009	14/12/2009 17:00	18.75	26.4	24.3	50.7	0.061	0.020	-0.100	0.051
16/12/2009 145	16/12/2009	14/12/2009 19:30	18.70	26.3	24.3	50.1	0.066	0.018	-0.100	0.051
16/12/2009 150	16/12/2009	14/12/2009 22:00	18.65	26.3	24.2	50.7	0.070	0.032	-0.100	0.051
16/12/2009 155	16/12/2009	15/12/2009 00:30	18.60	26.2	24.1	50.5	0.070	0.027	-0.100	0.051
16/12/2009 160	16/12/2009	15/12/2009 03:30	18.55	26.2	24.2	50.6	0.069	0.052	-0.100	0.051
16/12/2009 165	16/12/2009	15/12/2009 06:30	18.50	23.9	23.0	47.2	0.060	0.243	-0.100	0.048
16/12/2009 170	16/12/2009	15/12/2009 09:30	18.45	25.2	23.8	49.7	0.070	-0.010	-0.100	0.051
16/12/2009 175	16/12/2009	15/12/2009 12:30	18.40	25.2	23.5	49.7	0.048	0.051	-0.100	0.052
16/12/2009 180	16/12/2009	15/12/2009 16:30	18.35	25.1	23.3	49.8	0.070	-0.010	-0.100	0.052
16/12/2009 185	16/12/2009	15/12/2009 19:30	18.30	25.1	23.2	49.5	0.070	-0.010	-0.100	0.053
16/12/2009 190	16/12/2009	15/12/2009 23:45	18.25	25.2	23.0	48.7	0.066	0.013	-0.100	0.062
16/12/2009 195	16/12/2009	16/12/2009 02:30	18.20	25.5	23.0	48.4	0.066	-0.010	-0.100	0.059
16/12/2009 200	16/12/2009	16/12/2009 05:45	18.15	25.2	22.7	47.3	0.077	0.049	-0.100	0.059
16/12/2009 205	16/12/2009	16/12/2009 09:00	18.10	25.6	22.7	48.7	0.072	-0.010	-0.100	0.060
16/12/2009 270	16/12/2009	?	17.45	24.9	21.6	48.0	0.077	0.018	-0.100	0.053
05/01/2010 10	05/01/2010	16/12/2009 19:00	17.92	25.7	22.8	47.2	0.073	0.031	-0.100	0.052
05/01/2010 15	05/01/2010	16/12/2009 22:30	17.87	25.5	22.7	48.1	0.068	0.088	-0.100	0.058
05/01/2010 25	05/01/2010	17/12/2009 08:00	17.77	23.9	20.6	47.2	0.061	0.013	-0.100	0.058
05/01/2010 30	05/01/2010	17/12/2009 12:00	17.72	25.1	22.3	48.9	0.070	0.123	-0.100	0.059

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
05/01/2010 35	05/01/2010	17/12/2009 17:00	17.67	25.5	22.5	49.8	0.074	0.032	-0.100	0.056
05/01/2010 40	05/01/2010	17/12/2009 22:00	17.62	25.3	22.5	48.3	0.068	0.122	-0.100	0.061
05/01/2010 45	05/01/2010	18/12/2009 03:00	17.57	25.8	22.7	49.7	0.078	-0.010	-0.100	0.062
05/01/2010 50	05/01/2010	18/12/2009 09:00	17.52	25.7	22.6	49.5	0.075	0.013	-0.100	0.058
05/01/2010 55	05/01/2010	18/12/2009 15:00	17.47	25.7	23.2	50.2	0.069	0.036	-0.100	0.060
05/01/2010 60	05/01/2010	18/12/2009 21:00	17.42	25.4	22.9	49.5	0.078	0.217	-0.100	0.059
05/01/2010 65	05/01/2010	19/12/2009 03:00	17.37	25.6	22.9	49.0	0.064	0.073	-0.100	0.059
05/01/2010 70	05/01/2010	19/12/2009 10:00	17.32	25.4	22.8	49.9	0.068	0.133	-0.100	0.054
05/01/2010 80	05/01/2010	19/12/2009 22:00	17.22	25.0	22.2	48.8	0.074	0.109	-0.100	0.059
05/01/2010 85	05/01/2010	20/12/2009 04:30	17.17	24.7	21.5	47.8	0.069	0.038	-0.100	0.059
05/01/2010 90	05/01/2010	20/12/2009 15:00	17.12	24.0	21.1	46.4	0.068	0.137	-0.100	0.058
05/01/2010 95	05/01/2010	21/12/2009 00:00	17.07	23.9	20.6	45.3	0.048	0.103	-0.100	0.055
05/01/2010 100	05/01/2010	21/12/2009 09:00	17.02	23.1	20.3	46.0	0.069	0.078	-0.100	0.061
05/01/2010 105	05/01/2010	21/12/2009 19:30	16.97	18.6	15.3	36.0	0.062	-0.010	-0.100	0.055
05/01/2010 115	05/01/2010	24/12/2009 06:00	16.87	18.9	15.9	37.3	0.054	-0.010	-0.100	0.047
05/01/2010 120	05/01/2010	28/12/2009 00:00	16.82	22.1	19.2	44.4	0.065	0.039	-0.100	0.058
05/01/2010 125	05/01/2010	28/12/2009 10:00	16.77	21.9	19.0	43.4	0.063	0.019	-0.100	0.062
05/01/2010 130	05/01/2010	28/12/2009 19:30	16.72	22.2	19.3	44.2	0.074	0.033	-0.100	0.062
05/01/2010 135	05/01/2010	29/12/2009 01:00	16.67	22.2	19.4	44.1	0.070	0.021	-0.100	0.060
05/01/2010 140	05/01/2010	29/12/2009 07:00	16.62	22.1	19.4	43.2	0.067	-0.010	-0.100	0.062
05/01/2010 145	05/01/2010	29/12/2009 12:00	16.57	19.6	15.9	36.9	0.059	0.030	-0.100	0.055
05/01/2010 150	05/01/2010	29/12/2009 16:00	16.52	20.4	17.2	39.3	0.066	0.051	-0.100	0.055
05/01/2010 155	05/01/2010	29/12/2009 22:00	16.47	20.3	17.3	40.0	0.055	-0.010	-0.100	0.060
05/01/2010 160	05/01/2010	30/12/2009 03:00	16.42	21.6	18.6	42.5	0.058	0.093	-0.100	0.062
05/01/2010 165	05/01/2010	30/12/2009 09:00	16.37	21.7	18.7	42.1	0.076	0.019	-0.100	0.059
05/01/2010 170	05/01/2010	30/12/2009 15:00	16.32	19.6	16.7	37.5	0.059	0.081	-0.100	0.057
05/01/2010 175	05/01/2010	30/12/2009 22:00	16.27	23.2	20.1	44.4	0.071	0.047	-0.100	0.061
05/01/2010 180	05/01/2010	31/12/2009 04:30	16.22	23.1	20.1	43.7	0.068	0.049	-0.100	0.060
05/01/2010 185	05/01/2010	31/12/2009 11:00	16.17	23.4	20.4	45.1	0.079	0.030	-0.100	0.064
05/01/2010 190	05/01/2010	31/12/2009 18:00	16.12	23.6	20.4	45.1	0.080	0.042	-0.100	0.059
05/01/2010 195	05/01/2010	01/01/2010 00:00	16.07	23.9	20.7	45.3	0.077	0.014	-0.100	0.063
05/01/2010 200	05/01/2010	01/01/2010 08:00	16.02	24.2	20.7	45.4	0.071	0.062	-0.100	0.063

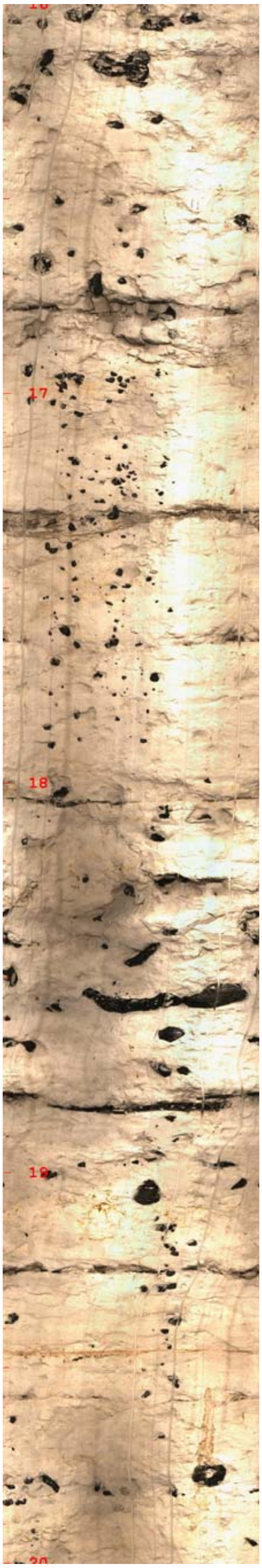
Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
05/01/2010 205	05/01/2010	01/01/2010 15:00	15.97	24.0	20.8	45.3	0.079	0.021	-0.100	0.061
05/01/2010 210	05/01/2010	02/01/2010 00:00	15.92	23.9	20.8	46.2	0.071	0.033	-0.100	0.062
05/01/2010 220	05/01/2010	02/01/2010 18:00	15.82	24.2	21.1	46.5	0.065	0.034	-0.100	0.055
05/01/2010 230	05/01/2010	03/01/2010 09:00	15.72	24.7	21.4	46.3	0.075	-0.010	-0.100	0.058
05/01/2010 240	05/01/2010	04/01/2010 00:00	15.62	24.7	21.4	46.5	0.069	-0.010	-0.100	0.060
05/01/2010 250	05/01/2010	04/01/2010 11:00	15.52	24.7	21.6	47.6	0.082	0.016	-0.100	0.060
25/01/2010 10	25/01/2010	05/01/2010 21:00	15.10	27.4	24.2	50.2	0.079	-0.010	-0.100	0.054
25/01/2010 15	25/01/2010	06/01/2010 02:00	15.05	27.1	23.6	50.5	0.070	-0.010	-0.100	0.057
25/01/2010 20	25/01/2010	06/01/2010 08:00	15.00	27.2	23.9	51.2	0.070	-0.010	-0.100	0.056
25/01/2010 25	25/01/2010	06/01/2010 15:00	14.95	27.9	24.9	45.8	0.080	-0.010	-0.100	0.048
25/01/2010 30	25/01/2010	06/01/2010 22:30	14.90	28.4	25.1	51.9	0.068	-0.010	-0.100	0.053
25/01/2010 35	25/01/2010	07/01/2010 06:00	14.85	28.4	25.3	52.0	0.068	-0.010	-0.100	0.060
25/01/2010 40	25/01/2010	07/01/2010 14:30	14.80	28.9	25.8	53.3	0.080	0.020	-0.100	0.059
25/01/2010 45	25/01/2010	07/01/2010 22:30	14.75	28.8	25.7	53.2	0.077	0.010	-0.100	0.055
25/01/2010 50	25/01/2010	08/01/2010 09:00	14.70	29.0	25.8	53.8	0.075	0.022	-0.100	0.054
25/01/2010 55	25/01/2010	08/01/2010 21:00	14.65	29.2	25.9	54.6	0.070	0.026	-0.100	0.054
25/01/2010 60	25/01/2010	09/01/2010 09:00	14.60	29.2	26.2	54.5	0.080	-0.010	-0.100	0.054
25/01/2010 65	25/01/2010	09/01/2010 21:00	14.55	29.4	26.1	53.6	0.075	0.019	-0.100	0.055
25/01/2010 70	25/01/2010	10/01/2010 12:00	14.50	29.5	26.2	55.3	0.069	0.035	-0.100	0.053
25/01/2010 75	25/01/2010	12/01/2010 06:00	14.45	29.5	26.2	54.3	0.072	0.191	-0.100	0.055
02/02/2010 10	02/02/2010	25/01/2010 23:00	14.54	32.2	26.6	45.9	0.066	2.64	-0.100	0.054
02/02/2010 15	02/02/2010	26/01/2010 02:30	14.49	32.2	26.3	55.7	0.073	-0.010	-0.100	0.054
02/02/2010 20	02/02/2010	26/01/2010 06:00	14.44	32.2	26.4	54.8	0.075	-0.010	-0.100	0.054
02/02/2010 25	02/02/2010	26/01/2010 08:00	14.39	32.4	26.5	56.2	0.076	-0.010	-0.100	0.054
02/02/2010 30	02/02/2010	26/01/2010 11:00	14.34	32.5	26.6	56.6	0.075	-0.010	-0.100	0.054
02/02/2010 35	02/02/2010	26/01/2010 13:30	14.29	32.4	26.5	55.8	0.074	-0.010	-0.100	0.054
02/02/2010 40	02/02/2010	26/01/2010 16:30	14.24	32.1	26.6	55.4	0.082	-0.010	-0.100	0.058
02/02/2010 45	02/02/2010	26/01/2010 19:30	14.19	32.5	26.5	56.6	0.079	0.058	-0.100	0.053
02/02/2010 50	02/02/2010	26/01/2010 22:30	14.14	32.2	26.5	56.3	0.079	-0.010	-0.100	0.053
02/02/2010 55	02/02/2010	27/01/2010 01:30	14.09	32.4	26.5	56.1	0.078	-0.010	-0.100	0.056
02/02/2010 60	02/02/2010	27/01/2010 04:00	14.04	31.9	26.5	55.5	0.073	-0.010	-0.100	0.056
02/02/2010 65	02/02/2010	27/01/2010 06:30	13.99	32.7	26.4	55.5	0.080	0.012	-0.100	0.056

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
02/02/2010 70	02/02/2010	27/01/2010 09:30	13.94	32.1	26.4	55.9	0.076	-0.010	-0.100	0.053
02/02/2010 75	02/02/2010	27/01/2010 12:00	13.89	32.3	26.4	56.1	0.076	0.013	-0.100	0.058
02/02/2010 85	02/02/2010	27/01/2010 17:00	13.79	32.3	26.6	55.6	0.073	-0.010	-0.100	0.055
02/02/2010 90	02/02/2010	27/01/2010 19:30	13.74	31.9	26.3	55.9	0.077	-0.010	-0.100	0.054
02/02/2010 95	02/02/2010	27/01/2010 22:30	13.69	32.2	26.4	56.2	0.078	-0.010	-0.100	0.054
02/02/2010 100	02/02/2010	28/01/2010 01:00	13.64	32.0	26.4	55.3	0.081	-0.010	-0.100	0.054
02/02/2010 105	02/02/2010	28/01/2010 03:30	13.59	32.2	26.4	55.7	0.073	-0.010	-0.100	0.058
02/02/2010 110	02/02/2010	28/01/2010 06:30	13.54	32.1	26.3	55.3	0.080	-0.010	-0.100	0.057
02/02/2010 115	02/02/2010	28/01/2010 09:30	13.49	32.4	26.4	56.4	0.084	-0.010	-0.100	0.053
02/02/2010 120	02/02/2010	28/01/2010 12:30	13.44	32.3	26.2	56.0	0.081	-0.010	-0.100	0.055
02/02/2010 125	02/02/2010	28/01/2010 15:30	13.39	29.9	24.4	52.3	0.081	-0.010	-0.100	0.054
02/02/2010 130	02/02/2010	28/01/2010 18:30	13.34	32.3	26.3	55.2	0.073	-0.010	-0.100	0.052
02/02/2010 135	02/02/2010	28/01/2010 21:45	13.29	31.6	26.0	55.0	0.072	0.010	-0.100	0.048
02/02/2010 140	02/02/2010	29/01/2010 00:00	13.24	31.7	26.1	55.1	0.075	-0.010	-0.100	0.048
02/02/2010 145	02/02/2010	29/01/2010 02:30	13.19	31.3	26.0	54.6	0.081	-0.010	-0.100	0.048
02/02/2010 150	02/02/2010	29/01/2010 05:30	13.14	30.9	25.6	53.7	0.073	-0.010	-0.100	0.049
02/02/2010 155	02/02/2010	29/01/2010 08:45	13.09	30.6	25.6	54.2	0.069	-0.010	-0.100	0.050
02/02/2010 160	02/02/2010	29/01/2010 12:00	13.04	29.1	24.8	52.5	0.066	-0.010	-0.100	0.050
02/02/2010 165	02/02/2010	29/01/2010 16:00	12.99	30.9	26.1	55.0	0.082	-0.010	-0.100	0.050
02/02/2010 170	02/02/2010	29/01/2010 20:00	12.94	29.9	26.0	54.1	0.071	-0.010	-0.100	0.051
02/02/2010 175	02/02/2010	30/01/2010 01:00	12.89	30.0	26.3	54.3	0.081	0.037	-0.100	0.050
02/02/2010 180	02/02/2010	30/01/2010 05:00	12.84	29.5	26.0	54.7	0.086	-0.010	-0.100	0.050
02/02/2010 185	02/02/2010	30/01/2010 10:00	12.79	32.8	26.1	54.3	0.073	-0.010	-0.100	0.053
02/02/2010 190	02/02/2010	30/01/2010 15:00	12.74	29.2	26.1	54.0	0.068	-0.010	-0.100	0.052
02/02/2010 195	02/02/2010	30/01/2010 21:00	12.69	39.5	25.2	52.8	0.070	-0.010	-0.100	0.048
02/02/2010 200	02/02/2010	31/01/2010 03:00	12.64	29.0	26.3	54.8	0.076	-0.010	-0.100	0.052
02/02/2010 205	02/02/2010	31/01/2010 09:00	12.59	31.4	26.0	54.7	0.067	-0.010	-0.100	0.050
02/02/2010 210	02/02/2010	31/01/2010 17:00	12.54	28.9	26.3	55.2	0.067	-0.010	-0.100	0.048
02/02/2010 220	02/02/2010	01/02/2010 12:00	12.44	29.0	26.6	55.4	0.080	-0.010	-0.100	0.051
02/02/2010 230	02/02/2010	02/02/2010 09:00	12.34	29.0	26.9	56.7	0.073	-0.010	-0.100	0.052
16/3/10 10	16/03/2010	08/03/2004 21:00	15.16	30.2	26.4	62.2	0.078	0.046	-0.100	0.041
16/3/10 15	16/03/2010	09/03/2004 04:30	15.11	31.4	27.1	61.3	0.086	0.043	-0.100	0.040

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
16/3/10 20	16/03/2010	09/03/2004 12:00	15.06	31.5	27.2	55.3	0.083	0.033	-0.100	0.042
16/3/10 25	16/03/2010	09/03/2004 19:30	15.01	31.7	27.1	56.8	0.084	0.021	-0.100	0.043
16/3/10 30	16/03/2010	10/03/2004 03:00	14.96	32.1	27.3	58.2	0.089	0.025	-0.100	0.041
16/3/10 35	16/03/2010	10/03/2004 11:30	14.91	32.4	27.4	57.9	0.085	0.029	-0.100	0.039
16/3/10 40	16/03/2010	10/03/2004 18:00	14.86	32.2	27.3	58.0	0.072	0.013	-0.100	0.042
16/3/10 45	16/03/2010	11/03/2004 01:30	14.81	32.6	27.5	57.8	0.089	-0.010	-0.100	0.043
16/3/10 50	16/03/2010	11/03/2004 09:00	14.76	32.5	27.5	57.7	0.080	0.011	-0.100	0.043
16/3/10 55	16/03/2010	11/03/2004 18:00	14.71	32.5	27.4	58.9	0.080	0.052	-0.100	0.044
16/3/10 60	16/03/2010	12/03/2004 03:00	14.66	32.5	27.5	58.9	0.067	0.017	-0.100	0.038
16/3/10 65	16/03/2010	12/03/2004 15:00	14.61	32.5	27.5	58.6	0.089	0.015	-0.100	0.042
16/3/10 70	16/03/2010	13/03/2004 06:00	14.56	32.1	26.9	57.1	0.087	0.012	-0.100	0.045
16/3/10 75	16/03/2010	14/03/2004 00:00	14.51	33.1	27.4	43.4	0.085	0.022	0.293	0.041
16/3/10 80	16/03/2010	14/03/2004 18:00	14.46	32.6	27.4	58.6	0.088	-0.010	-0.100	0.042
19/4/10 10	19/04/2010	09/04/2010 07:30	15.26	29.7	25.5	52.8	0.077	0.054	-0.100	0.039
19/4/10 15	19/04/2010	09/04/2010 15:00	15.21	31.2	26.7	57.4	0.090	0.023	-0.100	0.042
19/4/10 20	19/04/2010	10/04/2010 00:00	15.16	30.6	26.5	55.7	0.082	0.113	-0.100	0.043
19/4/10 25	19/04/2010	10/04/2010 07:30	15.11	30.8	26.5	57.6	0.085	0.013	-0.100	0.044
19/4/10 30	19/04/2010	10/04/2010 15:00	15.06	30.6	26.6	56.3	0.089	0.271	-0.100	0.041
19/4/10 35	19/04/2010	10/04/2010 22:30	15.01	31.1	26.8	57.2	0.087	0.034	-0.100	0.043
19/4/10 40	19/04/2010	11/04/2010 04:30	14.96	31.3	26.8	56.7	0.081	0.013	-0.100	0.042
19/4/10 45	19/04/2010	11/04/2010 12:00	14.91	31.5	27.1	57.7	0.088	0.012	-0.100	0.045
19/4/10 50	19/04/2010	11/04/2010 19:30	14.86	31.5	26.9	58.9	0.092	0.029	-0.100	0.043
19/4/10 55	19/04/2010	12/04/2010 03:00	14.81	31.4	26.8	57.7	0.083	0.031	-0.100	0.044
19/4/10 60	19/04/2010	12/04/2010 12:00	14.76	31.2	26.5	55.9	0.078	0.049	-0.100	0.042
19/4/10 65	19/04/2010	12/04/2010 19:30	14.71	31.7	26.7	57.7	0.089	0.034	-0.100	0.050
19/4/10 70	19/04/2010	13/04/2010 03:00	14.66	31.8	26.9	57.9	0.082	0.017	-0.100	0.044
19/4/10 75	19/04/2010	13/04/2010 12:00	14.61	31.4	26.8	58.8	0.086	0.019	-0.100	0.042
19/4/10 80	19/04/2010	13/04/2010 22:30	14.56	31.7	26.9	57.5	0.087	0.015	-0.100	0.044
19/4/10 85	19/04/2010	14/04/2010 09:00	14.51	31.5	26.9	58.0	0.085	0.028	-0.100	0.043
19/4/10 90	19/04/2010	14/04/2010 21:00	14.46	31.4	37.3	57.5	0.092	0.077	-0.100	0.085
19/4/10 95	19/04/2010	15/04/2010 09:00	14.41	31.6	26.9	57.2	0.088	0.019	-0.100	0.044
19/4/10 100	19/04/2010	16/04/2010 06:00	14.36	31.6	26.9	57.8	0.093	-0.010	-0.100	0.041

Sample ID	Collection Date	Estimated Sample Capture Time	Sample Depth (m bd)	Cl^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	NO_3^- (mg l^{-1})	Br^- (mg l^{-1})	NO_2^- (mg l^{-1})	HPO_4^{2-} (mg l^{-1})	F^- (mg l^{-1})
19/4/10 105	19/04/2010	17/04/2010 06:00	14.31	32.4	27.0	58.1	0.083	-0.010	-0.100	0.046
19/4/10 110	19/04/2010	18/04/2010 15:00	14.26	31.9	27.0	58.7	0.082	0.017	-0.100	0.044

Appendix B – Borehole B OPTV imagery



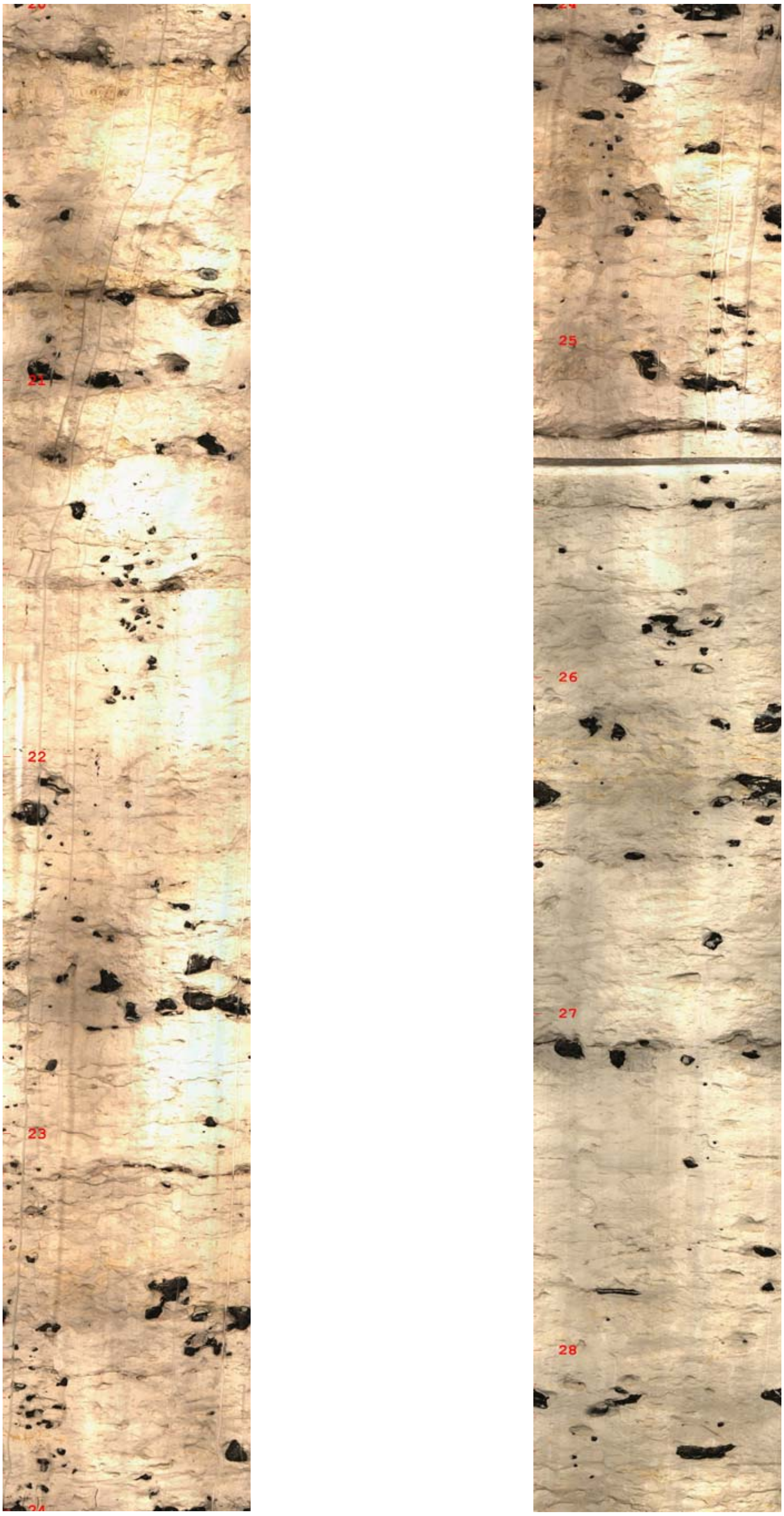


Image below 28 m bd is available in Sorensen *et al*. (2010)