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# Hydrogeological investigations at Morestead, Twyford, 2008-2009 (preliminary observations)

Groundwater Resources Programme

Open Report OR/09/009

BRITISH GEOLOGICAL SURVEY

GROUNDWATER RESOURCES PROGRAMME

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# Hydrogeological investigations at Morestead, Twyford, 2008-2009 (preliminary observations)

J P R Sorensen, A S Butcher, A J Gallagher and M E Stuart

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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, GALLAGHER A J AND STUART M E . 2009. Hydrogeological investigations at Morestead, Twyford, 2008-2009 (preliminary observations). *British Geological Survey Open Report*, OR/09/009. 33pp.

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☎ 0115 936 3143 Fax 0115 936 3276
email enquires@bgs.ac.uk

**Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG**
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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 second output from the BGS project "Nitrate fluctuations in groundwater" and describes the installation of the second research borehole at the site, and preliminary observations from the recharge period following completion.

# Acknowledgements

The authors are grateful to Barry Townsend (BGS) who contributed fieldwork support to the project. Additionally, we would particularly like to thank the following: Chris Chapman, owner of the Hazeley Estate, for access to the site; and Mike Davis of University College London (UCL) for his assistance with the geophysical work.

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# Summary

This report describes work undertaken at Morestead, Twyford as part of a BGS research project "Nitrate Fluctuations in Groundwater". The project uses the same site as that described in Stuart et al. (2008a) for the project "Nitrate Mass Balance in the Saturated Zone".

A new borehole (Borehole B) was drilled in October 2008, located 10 m to the west of the existing one (Borehole A) to complement the existing infrastructure. During drilling the cuttings were inspected but no systematic recording of lithology was undertaken, as this information was already available in detail from the adjacent borehole. Borehole B was completed to a depth of 70 m and was cased to a depth of 12.7 mbgl; remaining unsupported below this. It should be stated that the casing protruded approximately 0.16 m above ground level. Initial geophysical characterisation was undertaken to evaluate the hole and its suitability for further testing.

A multi-level sampler was installed in Borehole B during autumn 2008 when the groundwater level was low. The aim was to capture samples as the water table rose towards the anticipated spring 2009 high. The sampler worked well for most of the period, but there were issues with bottles not filling correctly, and the sampler length was insufficient to cope with rapid water level rise following heavy rainfall. A selection of the samples retrieved were analysed for nitrate, and provisional results ranged between 26.3 and 45.3 mg/l, with the exception of anomalous results. Concentrations of nitrate appeared to increase as the water table rose above 20.5 mbgl. However below this, nitrate concentration appeared to decrease with depth. Concentrations of sulphate and chloride both increased as the water table rose.

Gamma-ray and resistivity logging results obtained in March 2009 identified marl horizons which correlated with the core from Borehole A, as reported in Stuart et al. (2008a). Fluid and flow logs indicated hydraulic layering within the Chalk. Temperature and conductivity logs suggested downward flow below 26 m below datum (m bd where datum = casing top). Heat Pulse Flow Metre (HPFM) results also indicated downward flow between 28 and 45 m bd. During pumping at 0.5 l/s the HPFM data showed downward flow was still present between 24.8 and 26.3 m bd. A nitrate sonde was also run before and during pumping. The results are currently awaiting calibration and are not available at the time of reporting.

Groundwater levels were monitored in Borehole A and fluctuated 13.5 m, from around 10 to 23.5 mbgl, between December 2006 and the beginning of March 2009. However, numerous gaps in the data remain due to water levels exceeding the range of the pressure transducer initially installed in the borehole. Water levels were notably responsive to rainfall between December and February, for example between 25th January 2009 and 23rd February 2009 the water table rose by 8.7 m. The aquifer appears less responsive during summer and autumn when there is likely to be a greater soil moisture deficit.

# 1 Introduction

## 1.1 BACKGROUND AND OBJECTIVES

Concentrations of groundwater nitrate concentrations 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 more or less 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 was to determine which of the following mechanisms was 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 cutting off shallow high transmissivity flow paths during periods of low water levels.

## 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 has 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 18 mg N/l) in the unsaturated zone and declining concentrations in the saturated zone (up to 9 mg N/l), except in a 15 m thick zone of the Lewes Nodular Chalk about 25 m below the water table. 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 present landuse and agricultural regime. Moreover, much of the cultivated land is located in the upper part of the catchment and the nitrate is likely to be still present in the unsaturated 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 was 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. It was hoped that vertical mixing through the water column would also be minimal.
2. Instrument 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. Employ a range of borehole geophysical logging techniques to identify and characterise significant fracture horizons, including an assessment of nitrate concentrations at selected fractures.
4. Compare 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.
5. Adapt existing models 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.

## 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 completed 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 Installation of Borehole B

## 2.1 EXISTING INFRASTRUCTURE

The location of the existing borehole (Borehole A - SU 5073 2528) is illustrated in Figure 2. It lies 1.5 km east of the public supply borehole at Twyford, Hampshire on the Chalk of the South Downs. The borehole was completed as two piezometers (Figure 2.2); however, these were unsuitable for continuous nitrate monitoring being too narrow and slightly twisted.

Further details of the location, hydrogeological setting and borehole design are outlined in Stuart et al. (2008a).

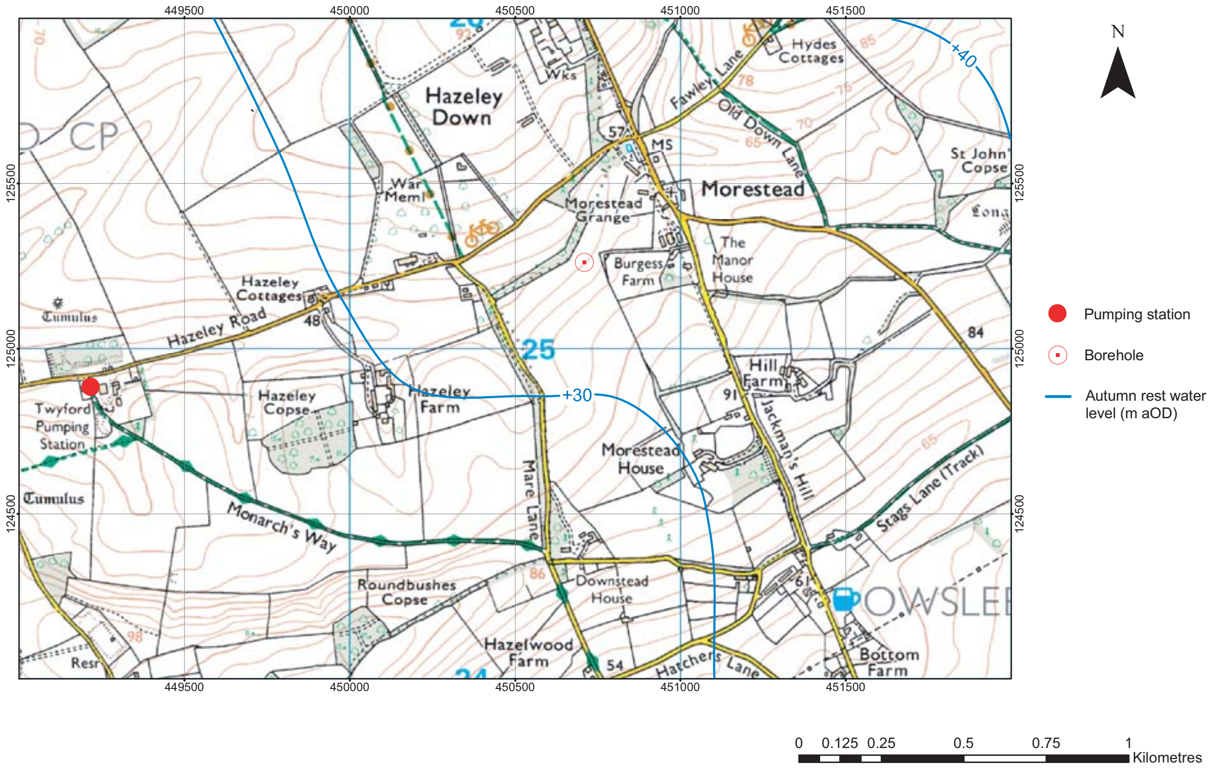
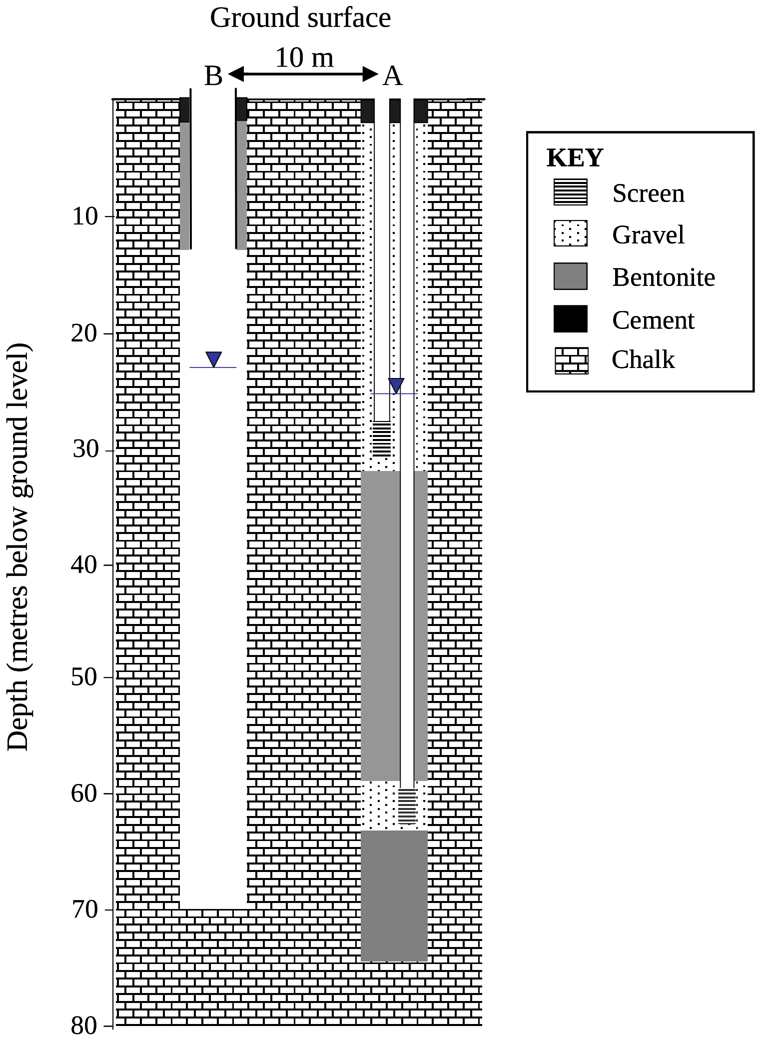


Figure 2.1 Site location and autumn rest water levels (1973) from the Hampshire and Isle of Wight hydrogeological map (IGS, 1979)

## 2.2 DRILLING AND LOGGING

Drilling of the new Morestead borehole (Borehole B) commenced on 13th October 2008 around 10 m west of the existing piezometers. A 200 mm rotary tri-cone bit drilling with air-flush was utilised. Drilling continued to a total depth of 47 m below the water table and the hole was completed at 70 m on 15th October 2008. Permanent steel casing was installed to the base of the weathered Chalk at 12.7 metres below ground level (mbgl), with the hole remaining unsupported below this depth. The casing was fixed using a bentonite grout. The upper 1 m of casing was left protruding by 0.16 above the ground surface so that it could be removed at the end of the project. The drilling cuttings were inspected during drilling but no systematic recording was undertaken, as Borehole A had been cored and logged.



*Note: water levels are shown from time of drilling; ground level at Borehole A is elevated above Borehole B by approximately 0.3 m; Borehole A datum is ground level; Borehole B datum is top of the casing, which protrudes 0.16 m above ground level.*

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

# 3 Testing methodology

## 3.1 RAINFALL

Rainfall data were retrieved from the Meteorological Office Database – MIDAS for selected currently operational stations near Morestead (UK Meteorological Office, 1853-current). These are shown in Table 3.1. At the time of reporting, only rainfall data up to the 1st or, sometimes, 31st of December 2008 were available.

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. It was noted that between 1st October 2006 and 1st December 2008, i.e. the period when water levels were monitored, total precipitation differed by around 5% (over 100 mm) between the two time series. Data from the rainfall station were deemed the most suitable as there were no gaps in the record.

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 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 piezometer (30 metres below ground level) on 11th April 2008.

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.

## 3.3 GEOPHYSICAL LOGGING

### 3.3.1 Initial characterisation

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. This involved running:

- a temperature and conductivity multiple electrode sonde (TCME);
- a natural gamma ray sonde (NGRS);
- a borehole optical televiewer (OPTV); and
- a calliper log.

### 3.3.2 Post water level rise

An additional investigation was undertaken on 12th March 2009. This constituted:

- initial profiling with a TCME sonde to identify potential flowing fracture horizons;
- logging the unstressed borehole flow regime with a heat pulse flow metre sonde (HPFM) (Figure 3.1);
- running a nitrate sonde to investigate changes in concentration through the water column; and
- repeating the nitrate sonde and HPFM measurements when pumping at a low flow rate (Figure 3.2). Water samples were obtained before and during pumping for ICP-OES and nitrate analysis by ion chromatography.

Figure 3.1 Running the nitrate sonde in stack with the HPFM (12th March 2009)

Figure 3.2 Running the nitrate sonde whilst pumping at a low rate (12th March 2009)

## 3.4 WATER SAMPLING

### 3.4.1 Completion water

On completion of the borehole on 15th October 2008 a sample was pumped from Borehole B. This was scheduled for nitrate analysis by ion chromatography and ICP-OES analysis (Appendix A).

### 3.4.2 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 3.3). The sampler originally had 18 bottles fixed at regular intervals along two 1-m adjoined sections of slotted plastic tracking (Figure 3.4). Two additional bottles were later added to increase the total to 20 sample bottles; the distance between sampling units was thus around 0.1 m.

The sampler was suspended just above the water table at 22.8 mbgl on 3rd November 2008 when the groundwater level was low, with the aid of borehole CCTV. The aim was to capture groundwater samples from known depths as the water table rose towards the bottom of the borehole casing; anticipated to be in spring 2009. The site was periodically visited following rainfall events and individual units containing groundwater were removed from the sampler. Subsequently the device was re-suspended at the new water level with fresh sample bottles in place. It should be noted that heavy snowfall prevented any site visit between 11th and 20th February 2009.

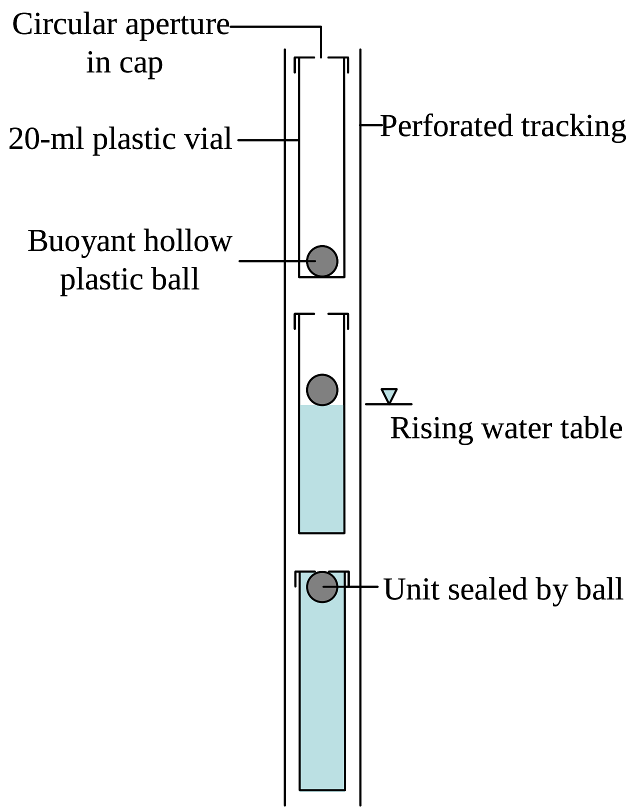


Figure 3.3 Schematic diagram of multi-level sampler bottle

All collected samples were to be scheduled for nitrate analysis by ion chromatography. However, it was decided to withhold some samples and send only a limited selection. These initial samples would identify if a general trend was present and, thus, whether the analysis of all samples was worthwhile. A full list of samples collected and those selected for nitrate analysis is presented in Appendix A. Any remaining samples will be analysed in the forthcoming financial year.

The sampler was removed on 20th February 2009 when the water table was recorded in the casing and subsequently re-installed on 12th March 2009 after the water level had receded back below the casing.

### 3.4.3 Bailer

Periodically a bailer was used to sample groundwater from the water table in Borehole B. The bailer was lowered into the water column gently, with the assistance of the borehole CCTV camera, to avoid excessive mixing. The samples were subsequently scheduled for nitrate ion chromatography and ICP-OES analyses (Appendix A).

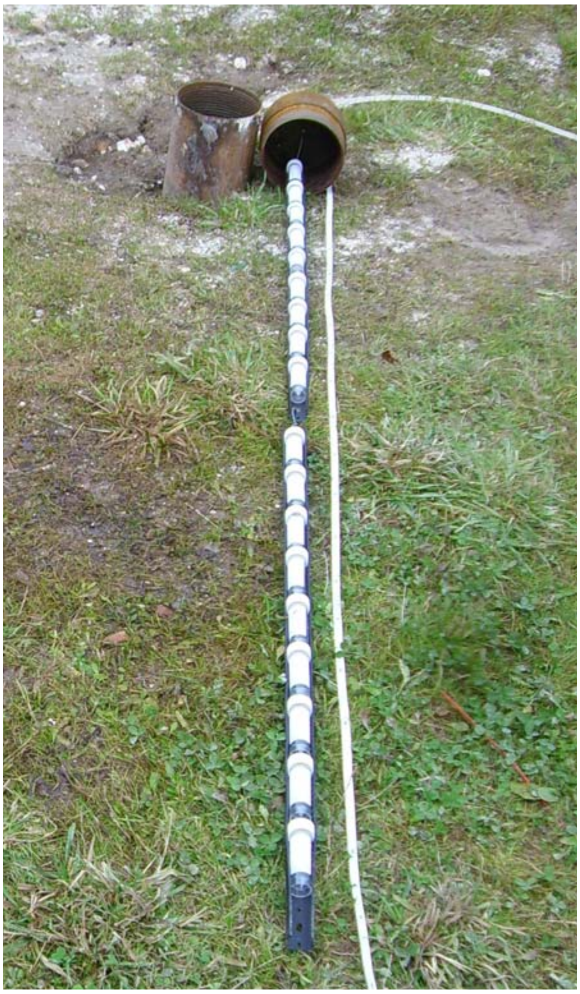


Figure 3.4 The multilevel sampler hanging via a cable from the cap of Borehole B prior to lowering down the hole.

# 4 Results and discussion

## 4.1 WATER LEVEL RECORDING

The raw water level data are annotated in Figure 4.1. These data were processed to remove the highlighted spurious water levels and combined with rainfall data from Otterbourne Water Works (Figure 4.2). Monthly totals of the rainfall data are shown for 2007 and 2008 in Table 4.1.

The hydrograph shows annual water level maxima in March during 2007 and February in 2009. 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 2008. There is an absence of data where the lows of 2007 and 2008 are likely to have occurred.

Between December 2007 and March 2009, available water levels ranged between 23.5 and around 10 mbgl, although a manual dip undertaken in October 2006 recorded a level of 27.6 mbgl.

Notably, water levels rose around 8.7 m, from 19.6 to 10.9 mbgl, between 25th January 2009 and 23rd February 2009. There is no rainfall data presently available for this period, although heavy snowfalls did occur in early February. The aquifer also appears to be responsive to precipitation events in December 2006, and January and February 2007; with relatively rapid water level rises and recessions. However during summer and autumn, when soil moisture deficits are likely to be greater, the aquifer is less responsive. This is noted in the lack of water level rise following precipitation events in summer and autumn 2008, indicating little recharge over this period

The most significant summer storms were in July 2007. Unfortunately there is no data available to assess the impacts of this summer recharge, as the water level had receded beyond the range of the diver between early April and mid-August. Nevertheless a peak of around 13.2 mbgl is identifiable at the end of August 2007, which is markedly higher than in August 2008. However it should be noted that there is a degree of uncertainty surrounding the August 2007 groundwater level data.

Table 4.1 Rainfall data from Otterbourne Water Works.

| **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 | - |

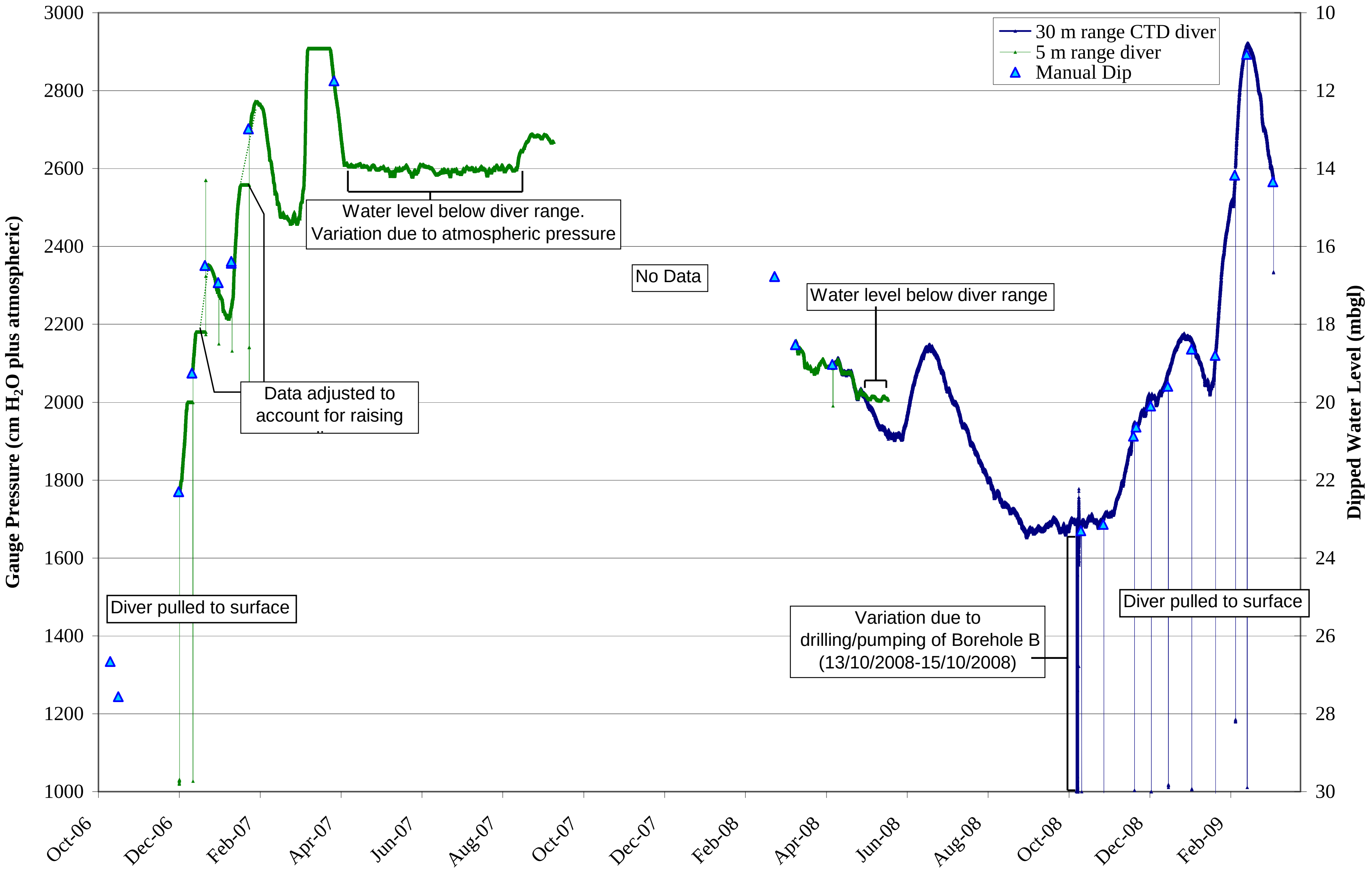


Figure 4.1 Annotated raw groundwater level data

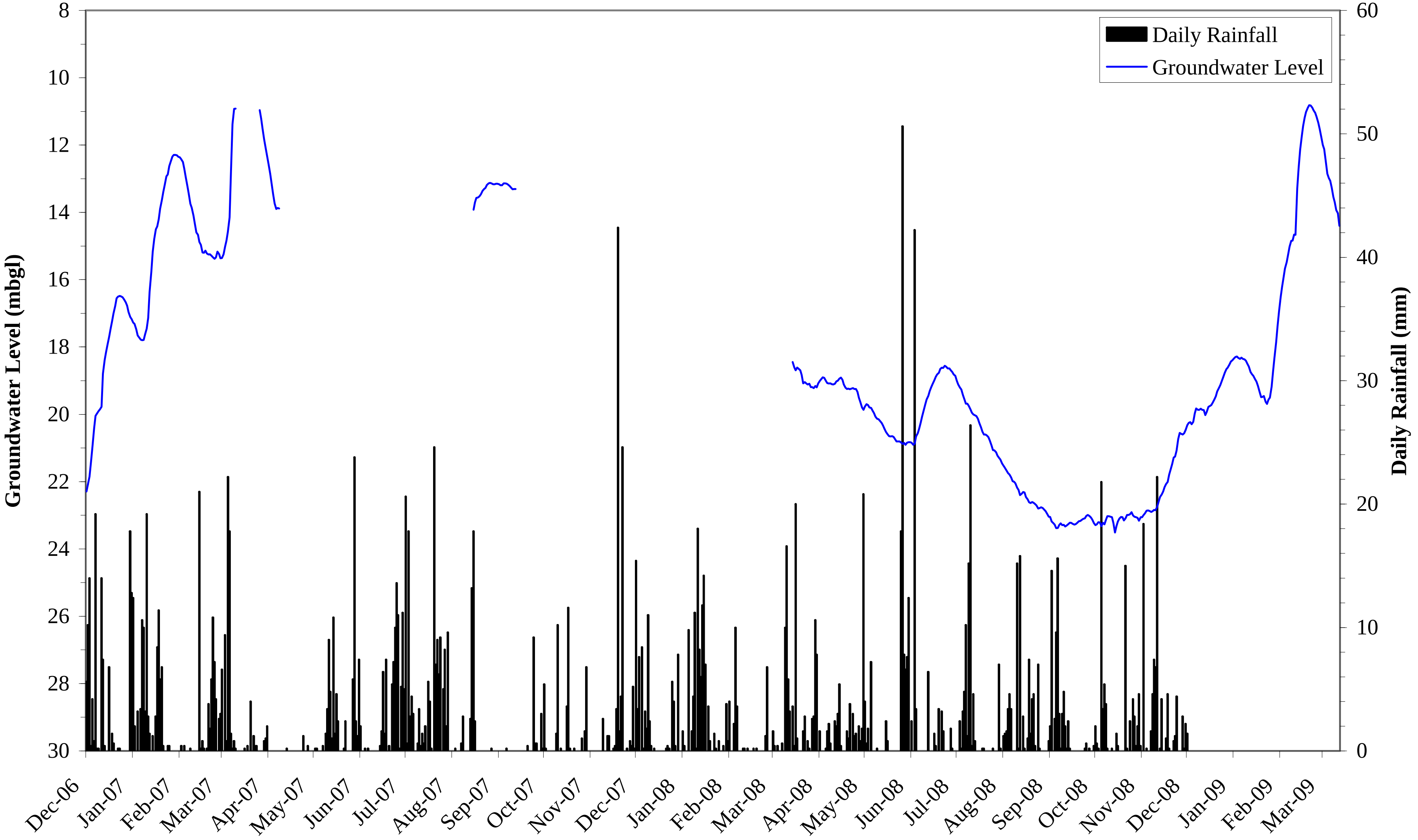


Figure 4.2 Daily groundwater hydrograph for Borehole A and rainfall from Otterbourne Water Works

## 4.2 GEOPHYSICAL LOGGING

The Borehole B OPTV imagery is presented as Appendix B. This confirmed the depth of the hole and casing position. More detailed discussion and interpretation will be reported in an updated report.

Preliminary geophysical results are presented in Appendix C. The nitrate sonde requires further calibration work and data collected are not shown. Many of the gamma-highs and resistivity-lows recorded correlate with marl horizons identified in the core obtained from Borehole A (see Stuart et al. 2008a). Inspection of the fluid and flow logs suggests hydraulic layering within the Chalk at the site.

Below 36 m below datum (bd) the unpumped fluid temperature and fluid conductivity logs are relatively featureless. Between 26 m bd and approximately 58 m bd the temperature profile, in particular, is quite flat suggesting that there is vertical flow below 26 m bd to the base of the borehole during ‘ambient’ or unpumped conditions. This is confirmed, to an extent, by the HPFM results obtained prior to pumping which show that down-flow occurs over the interval 28 to 45 m bd. No flow was recorded above 28 m bd.

Unusually, a component of down-flow persists during pumping. HPFM results show that a flow divide occurs between 24.8 and 26.3 m bd; above this interval water flows up towards the pump, and below it flows down the borehole. Time did not permit a complete pumped HPFM profile, although (repeatable) down-flow was recorded at two different depths below 26.3 m bd. The borehole was pumped at approximately 0.5 l/s, and it is probable that the flow divide would move down the borehole, or disappear altogether, at higher pumping rates.

## 4.3 WATER SAMPLING

### 4.3.1 Site Observations

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

- frequently bottles were only partially full, despite having been completely submerged;
- on one occasion a unit (K5) was partially filled despite no rise in groundwater level; and
- samples were often opaque, but occasionally brown (K1).

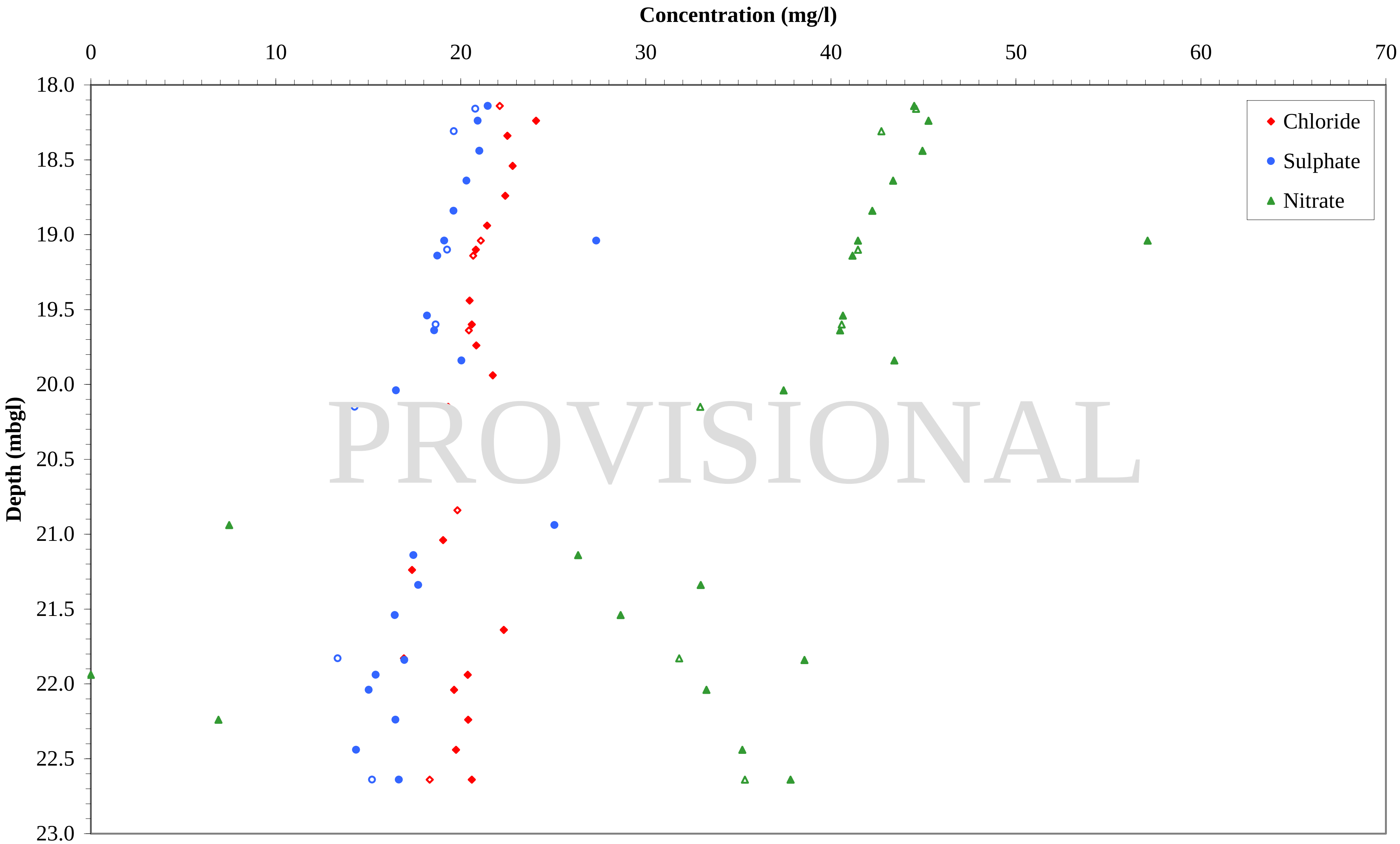
### 4.3.2 Water Quality

Provisional water quality data are presented as Appendix C. Concentrations of chloride, sulphate and nitrate (as $NO_3$) range between 16.9 and 68.8 mg/l, 13.3 and 27.3 mg/l, and <0.6 and 57.1 mg/l, respectively. The greatest concentration of all three determinands was recorded in sample unit K5. As stated above, this bottle had partially filled despite no rise in groundwater level and is, therefore, not representative of water within the phreatic zone. The concentration of nitrate in this sample exceeded the drinking water standard of 50 mg/l.

There are also three anomalously low nitrate readings recorded between 20.9 and 22.2 mbgl (samples B1, K1 and N1). Additionally, B1 appears to have an elevated concentration of sulphate. These samples were all retrieved on the same monitoring round on 26th November 2008.

Depth profiles of the data suggest concentrations of all determinands may increase with elevation above around 20.5 mbgl (Figure 4.3). Below this depth the data points are more scattered; the sulphate and chloride possible showing a slight increase between around 22.6 and 20.5 mbgl, but nitrate showing a decline in concentration. Figure 4.4 illustrates increasing groundwater nitrate concentration as the water table rises from mid-October 2008 to the end of January 2009.

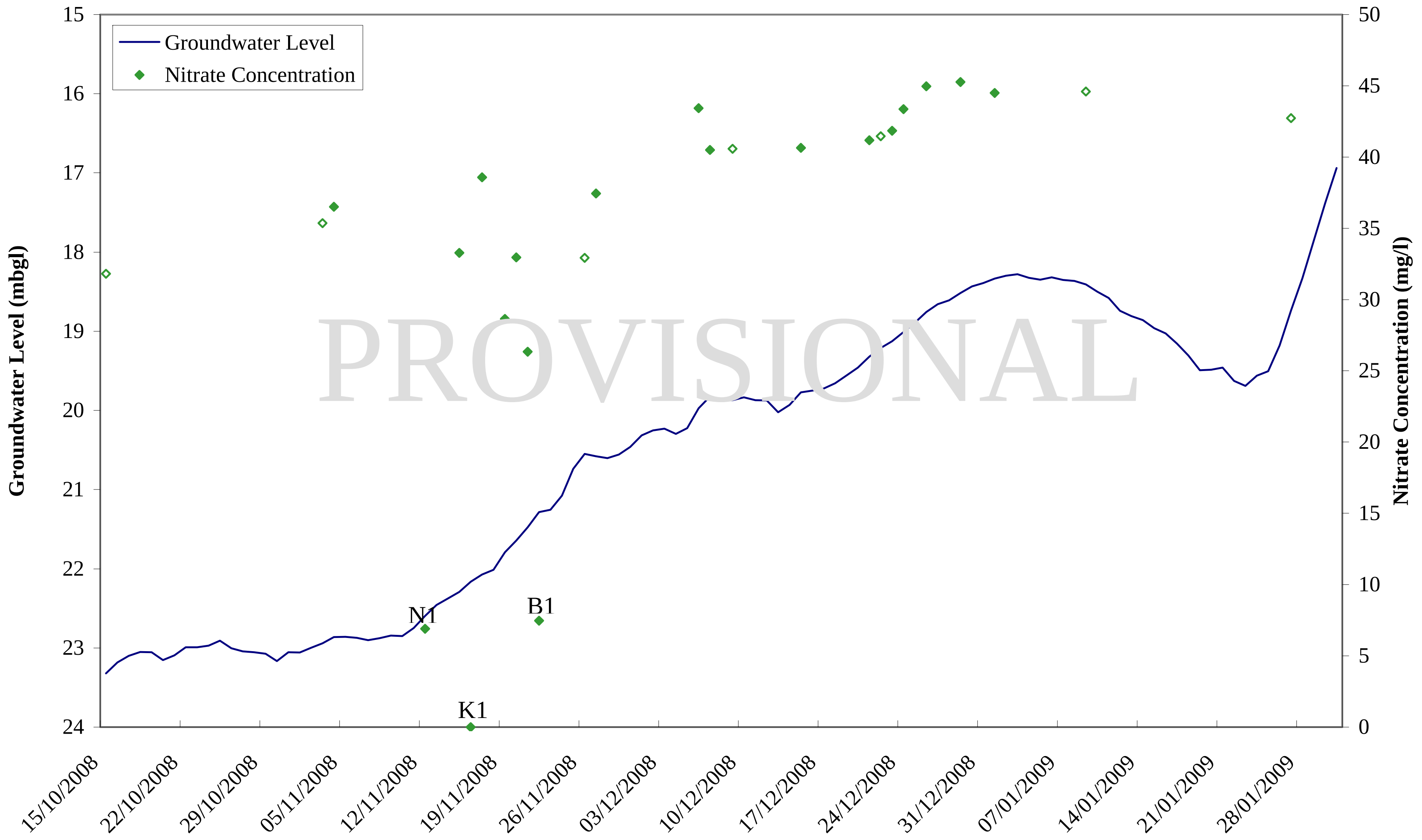
Interpretation, which includes the analysis of the remaining samples collected and results yet to be received, will follow in an updated report.



PROVISIONAL

*Note: Unfilled data points relate to bailed samples, including completion water at a depth of 21.83 mbgl*

Figure 4.3 Depth profiles of chloride, sulphate and nitrate



PROVISIONAL

*Note: Unfilled data points relate to bailed samples; completion water on 15th October 2008; K5 excluded from figure as not attributable to groundwater rise*

Figure 4.4 Relating nitrate concentration to groundwater level

# 5 Conclusions and future programme

## 5.1 CONCLUSIONS

The hanging sampler was successfully deployed in borehole B at Morestead. Groundwater levels were monitored in the existing piezometer. A selection of the samples retrieved were analysed for nitrate and provisional results indicated a range between 26.3 and 45.3 mg/l, with the exception of anomalous results. Concentrations of nitrate appeared to increase as the water table rose above 20.5 mbgl. Below this depth, the concentration appeared to decrease between 22.6 and 20.5 mbgl. Concentrations of sulphate and chloride both increased with water rise.

The sampler requires modifying to reduce the number of bottles which fail to fill correctly and to operate during periods of rapid and large water level rise where site access is not possible due to adverse weather conditions, such as the heavy snowfall in early February 2009.

Gamma and resistivity logs identified marl horizons which correlated with the Borehole A core as reported in Stuart et al. (2008a). Fluid and flow logs also indicate hydraulic layering within the Chalk. Temperature and conductivity logs suggested vertical flow below 26 m bd. HPFM results also indicated downward flow between 28 and 45 m bd. During pumping at 0.5 l/s the HPFM data show a flow divided between 24.8 and 26.3 m bd. A nitrate sonde was also run before and during pumping. The results are currently awaiting calibration and are not available at the time of reporting.

## 5.2 FUTURE PROGRAMME

During the forthcoming year it is planned that the following activities will be undertaken:

- The hanging sampler and geophysical data will be interpreted in greater detail when the full suite of results and rainfall data becomes available.
- Water levels will be continually monitored in Borehole A.
- The multi-level hanging sampler will be modified to allow collection of samples at a greater resolution or to provide duplicates. It will also be lengthened to cover periods of rapid large water level rises.
- The sampler will be re-positioned during the summer of 2009 to remain just above the water table in Borehole B, with the aim of capturing groundwater samples following any intense summer/autumn storms. Subsequently the sampler will be used to obtain samples as the water table rises towards the anticipated spring 2010.
- Further geophysical testing will be carried out during the period of high water levels in early April/May 2009 and in the period of autumn minimum water levels.
- It may be possible to conduct a tracer test between Borehole A and Borehole B to identify interconnecting fractures at a depth of around 30 mbgl. This may be undertaken at high and low groundwater levels to assess how the flow regime between the boreholes varies.

# 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.

INSTITUTE OF GEOLOGICAL SCIENCES. 1979. Hydrogeological map of Hampshire and the Isle of Wight. Institute of Geological Sciences and Southern Water Authority.

STUART, M.E., CHILTON, P.J., NEWELL, A.N. and BUTCHER, A.S. 2008a. Nitrate concentrations in the Morestead borehole, Twyford. BGS Open Report OR/08/041.

STUART, M.E., CHILTON, P.J. and BUTCHER, A.S. 2008b. Nitrate fluctuations in groundwater: review of potential mechanisms and case studies. BGS Open Report OR/08/046.

UK METEOROLOGICAL OFFICE. MIDAS Land Surface Stations data (1853-current), [Internet]. British Atmospheric Data Centre, 2006, *17th March 2009*. Available from http://badc.nerc.ac.uk/data/ukmo-midas

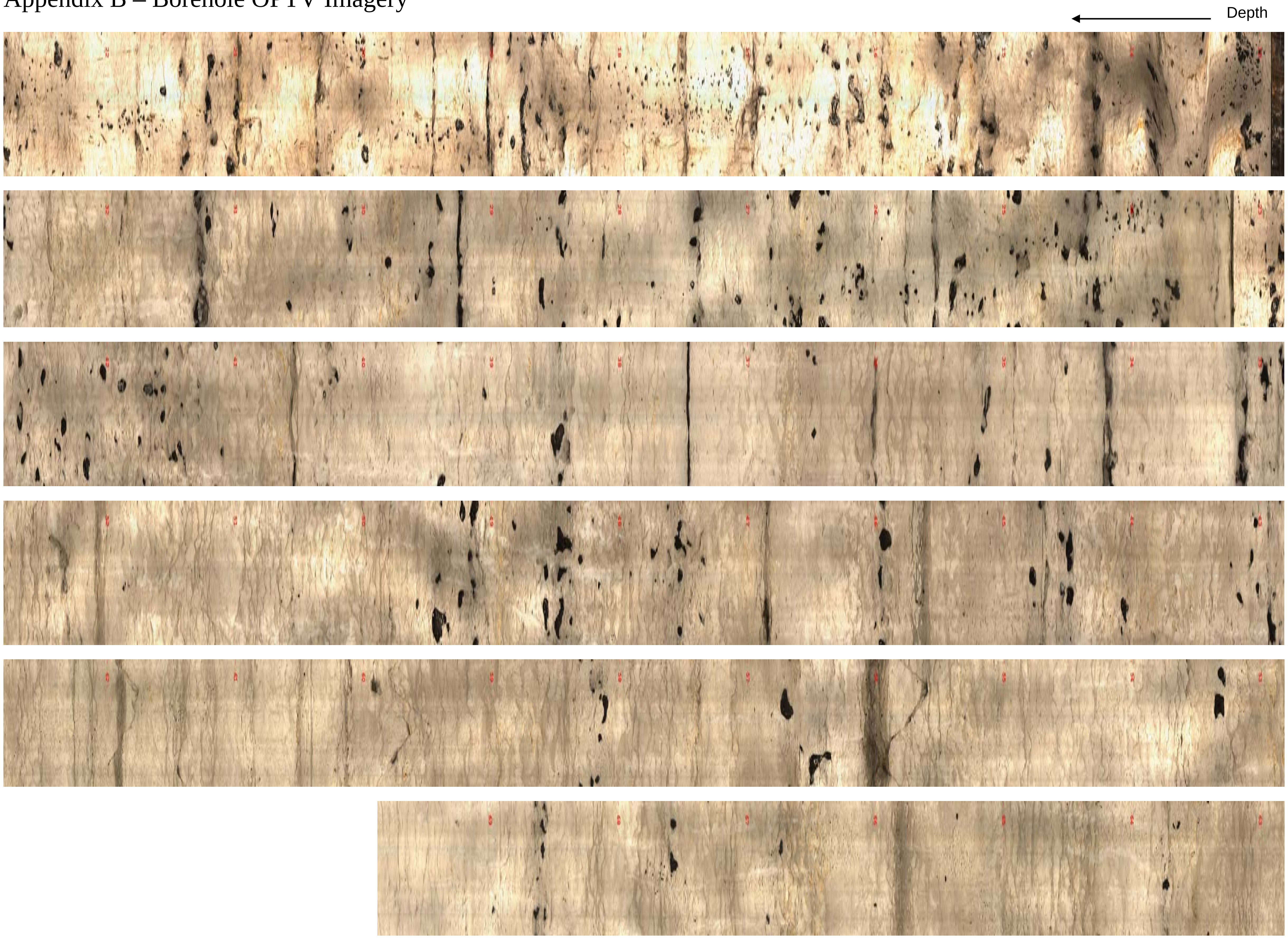
# Appendix A – Collected samples and scheduled analysis

| Sample ID | Site ID | Sample Type | Sample Depth (m bd) | Sample Date | Sent for analysis |
|---|---|---|---|---|---|
| S08-01453 | | BH pumped clearout bulk sample | 21.99 | 16-Oct-08 | ✓ |
| S08-01454 | BULKWT | bail sample @wt pre ML sampler | 22.8 | 03-Nov-08 | ✓ |
| S08-01455 | R1 | ML Sampler | 22.8 | 26-Nov-08 | ✓ |
| S08-01456 | Q1 | ML Sampler | 22.7 | 26-Nov-08 | |
| S08-01457 | P1 | ML Sampler | 22.6 | 26-Nov-08 | ✓ |
| S08-01458 | O1 | ML Sampler | 22.5 | 26-Nov-08 | |
| S08-01459 | N1 | ML Sampler | 22.4 | 26-Nov-08 | ✓ |
| S08-01460 | no M | | | 26-Nov-08 | |
| S08-01461 | L1 | ML Sampler | 22.2 | 26-Nov-08 | ✓ |
| S08-01462 | K1 | ML Sampler | 22.1 | 26-Nov-08 | ✓ |
| S08-01463 | J1 | ML Sampler | 22 | 26-Nov-08 | ✓ |
| S08-01464 | I1 | ML Sampler | 21.8 | 26-Nov-08 | |
| S08-01465 | H1 | ML Sampler | 21.7 | 26-Nov-08 | ✓ |
| S08-01466 | no G | | | 26-Nov-08 | |
| S08-01467 | F1 | ML Sampler | 21.5 | 26-Nov-08 | ✓ |
| S08-01468 | no E | | 21.4 | 26-Nov-08 | |
| S08-01469 | D1 | ML Sampler | | 26-Nov-08 | ✓ |
| S08-01470 | no C | | 21.2 | 26-Nov-08 | |
| S08-01471 | B1 | ML Sampler | 21.1 | 26-Nov-08 | ✓ |
| S08-01472 | A1 | ML Sampler | 21 | 26-Nov-08 | |
| S08-01473 | BULKWT | grab bulk sample@ WL | 20.31 | 28-Nov-08 | ✓ |
| S08-01474 | T2 | ML Sampler | 20.2 | 09-Dec-08 | ✓ |
| S08-01475 | S2 | ML Sampler | 20.1 | 09-Dec-08 | |
| S08-01476 | R2 | ML Sampler | 20 | 09-Dec-08 | ✓ |
| S08-01477 | Q2 | ML Sampler | 19.9 | 09-Dec-08 | |
| S08-01478 | P2 | ML Sampler | 19.8 | 09-Dec-08 | ✓ |
| S08-01479 | BULKWT | Bail sample at water table | 19.76 | 09-Dec-08 | ✓ |
| S08-01480 | T3 | ML Sampler | 19.7 | 22-Dec-08 | ✓ |
| S08-01481 | S3 | ML Sampler | 19.6 | 22-Dec-08 | |
| S08-01482 | P3 | ML Sampler | 19.3 | 22-Dec-08 | ✓ |
| S08-01483 | BULKWT | Bail sample at water table | 19.26 | 22-Dec-08 | ✓ |
| S08-01484 | T4 | ML Sampler | 19.2 | 09-Jan-09 | ✓ |
| S08-01485 | S4 | ML Sampler | 9.1 | 09-Jan-09 | |
| S08-01486 | R4 | ML Sampler | 19 | 09-Jan-09 | ✓ |
| S08-01487 | Q4 | ML Sampler | 18.9 | 09-Jan-09 | |
| S08-01488 | P4 | ML Sampler | 18.8 | 09-Jan-09 | ✓ |
| S08-01489 | O4 | ML Sampler | 18.7 | 09-Jan-09 | |
| S08-01490 | N4 | ML Sampler | 18.6 | 09-Jan-09 | ✓ |
| S08-01491 | M4 | ML Sampler | 18.5 | 09-Jan-09 | |
| S08-01492 | L4 | ML Sampler | 18.4 | 09-Jan-09 | ✓ |
| S08-01493 | K4 | ML Sampler | 18.3 | 09-Jan-09 | ✓ |
| S08-01494 | BULKWT | Bail sample at water table | 18.32 | 09-Jan-09 | ✓ |
| S08-01495 | K5 | ML Sampler | 19.2 | 27-Jan-09 | ✓ |
| S08-01496 | BULKWT | Bail sample at water table | 18.47 | 27-Jan-09 | ✓ |
| S08-1244 | T5 | ML Sampler | 18.4 | 11-Feb-09 | ✓ |
| S08-1245 | S5 | ML Sampler | 18.3 | 11-Feb-09 | ✓ |

| Sample ID | Site ID | Sample Type | Sample Depth (m bd) | Sample Date | Sent for analysis |
|---|---|---|---|---|---|
| | R5 | ML Sampler | 18.2 | 11-Feb-09 | |
| | Q5 | ML Sampler | 18.1 | 11-Feb-09 | |
| | P5 | ML Sampler | 18 | 11-Feb-09 | |
| S08-1246 | O5 | ML Sampler | 17.9 | 11-Feb-09 | ✓ |
| | N5 | ML Sampler | 17.8 | 11-Feb-09 | |
| | M5 | ML Sampler | 17.7 | 11-Feb-09 | |
| | L5 | ML Sampler | 17.6 | 11-Feb-09 | |
| S08-1247 | K6 | ML Sampler | 17.5 | 11-Feb-09 | ✓ |
| | J2 | ML Sampler | 17.4 | 11-Feb-09 | |
| | I3 | ML Sampler | 17.3 | 11-Feb-09 | |
| | H2 | ML Sampler | 17.2 | 11-Feb-09 | |
| S08-1248 | G2 | ML Sampler | 17.1 | 11-Feb-09 | ✓ |
| | F2 | ML Sampler | 17 | 11-Feb-09 | |
| | E2 | ML Sampler | 16.9 | 11-Feb-09 | |
| | D2 | ML Sampler | 16.8 | 11-Feb-09 | |
| S08-1249 | C2 | ML Sampler | 16.7 | 11-Feb-09 | ✓ |
| | B2 | ML Sampler | 16.6 | 11-Feb-09 | |
| S08-1250 | A2 | ML Sampler | 16.5 | 11-Feb-09 | ✓ |
| S08-1257 | BULKWT | Bail sample at water table | 13.82 | 11-Feb-09 | ✓ |
| S08-1251 | T6 | ML Sampler | 13.8 | 20-Feb-09 | ✓ |
| | S6 | ML Sampler | 13.7 | 20-Feb-09 | |
| | R6 | ML Sampler | 13.6 | 20-Feb-09 | |
| | Q6 | ML Sampler | 13.5 | 20-Feb-09 | |
| S08-1252 | P6 | ML Sampler | 13.4 | 20-Feb-09 | ✓ |
| | O6 | ML Sampler | 13.3 | 20-Feb-09 | |
| | N6 | ML Sampler | 13.2 | 20-Feb-09 | |
| | M6 | ML Sampler | 13.1 | 20-Feb-09 | |
| S08-1253 | L6 | ML Sampler | 13 | 20-Feb-09 | ✓ |
| | K7 | ML Sampler | 12.9 | 20-Feb-09 | |
| | J3 | ML Sampler | 12.8 | 20-Feb-09 | |
| S08-1254 | I3 | ML Sampler | 12.7 | 20-Feb-09 | ✓ |
| | H3 | ML Sampler | 12.6 | 20-Feb-09 | |
| | G3 | ML Sampler | 12.5 | 20-Feb-09 | |
| | F3 | ML Sampler | 12.4 | 20-Feb-09 | |
| S08-1255 | E3 | ML Sampler | 12.3 | 20-Feb-09 | ✓ |
| | D3 | ML Sampler | 12.2 | 20-Feb-09 | |
| | C3 | ML Sampler | 12.1 | 20-Feb-09 | |
| | B3 | ML Sampler | 12 | 20-Feb-09 | |
| S08-1256 | A3 | ML Sampler | 11.9 | 20-Feb-09 | ✓ |
| S08-1258 | BULKWT | Bail sample at water table | 10.76 | 20-Feb-09 | ✓ |
| S08-1259 | BULKWT | Bail sample at water table | 14.01 | 12-Mar-09 | ✓ |
| S08-1260 | BULKWT | Pumped from 16 m after 1 min | 16 | 12-Mar-09 | ✓ |
| S08-1261 | BULKWT | Pumped from 16 m after 10 min | 16 | 12-Mar-09 | ✓ |
| S08-1262 | BULKWT | Pumped from 16 m after 2.5hr | 16 | 12-Mar-09 | ✓ |

m bd = metres below datum - datum = casing top

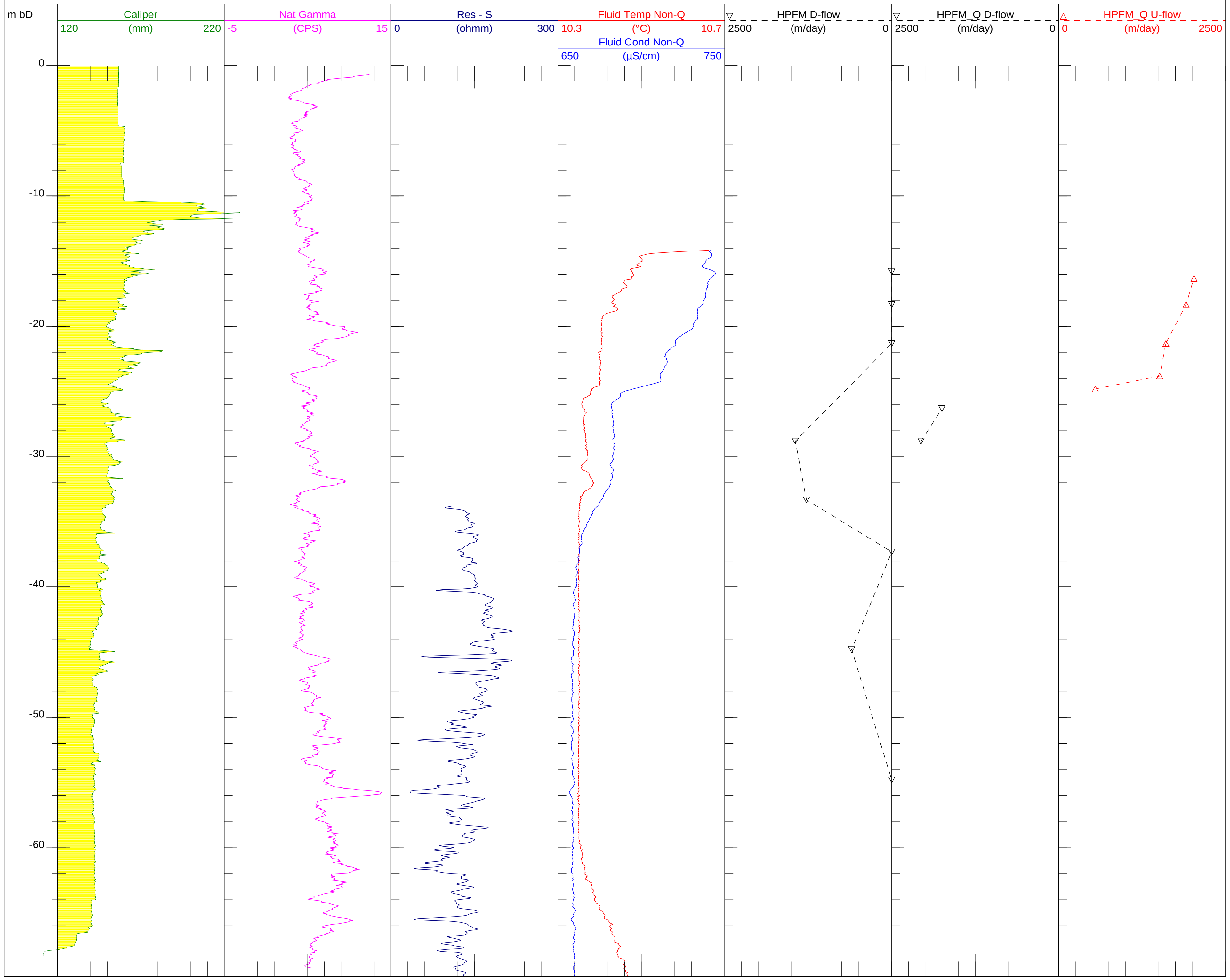
# Appendix B – Borehole OPTV Imagery



# Appendix C – Geophysical logs

Well Name: Morestead BH2
Location: 450722 125285

Formation and fluid logs recorded by the BGS on the 17/10/08 and 12/03/09 respectively.
Datum = Casing Top = 0.2 m aGL.
SWL on 17/10/08 = 22.99 m bD, SWL on 12/03/09 = 14.05 m bGL, PWL = 14.10, Q = 0.5 l/s.
Flow-meter logs record linear velocity, i.e. are not area corrected.
Optical image of borehole also recorded.
BGS UV-Nitrate sonde used but requires recalibration.



# Appendix D – Provisional Water Quality Results

| **Sample Code** | **Site ID** | **Sample Depth (mbgl)** | **$Cl^-$ (mg/l)** | **$SO_4^{2-}$ (mg/l)** | **$NO_3^-$ (mg/l)** |
|---|---|---|---|---|---|
| S08-01453 | Completion | 21.83 | 16.9 | 13.3 | 31.8 |
| S08-01454 | BULKWT | 22.64 | 18.3 | 15.2 | 35.4 |
| S08-01455 | R1 | 22.64 | 20.6 | 16.7 | 37.8 |
| S08-01457 | P1 | 22.44 | 19.7 | 14.3 | 35.2 |
| S08-01459 | N1 | 22.24 | 20.4 | 16.5 | 6.9 |
| S08-01461 | L1 | 22.04 | 19.6 | 15.0 | 33.3 |
| S08-01462 | K1 | 21.94 | n.d. | 15.4 | <0.6 |
| S08-01463 | J1 | 21.84 | 20.4 | 16.9 | 38.6 |
| S08-01465 | H1 | 21.54 | 22.3 | 16.4 | 28.6 |
| S08-01467 | F1 | 21.34 | 23.2 | 17.7 | 33.0 |
| S08-01469 | D1 | 21.14 | 17.4 | 17.4 | 26.3 |
| S08-01471 | B1 | 20.94 | 19.0 | 25.1 | 7.5 |
| S08-01473 | BULKWT | 20.15 | 19.8 | 14.3 | 32.9 |
| S08-01474 | T2 | 20.04 | 19.3 | 16.5 | 37.4 |
| S08-01476 | R2 | 19.84 | 21.7 | 20.0 | 43.4 |
| S08-01478 | P2 | 19.64 | 20.8 | 18.6 | 40.5 |
| S08-01479 | BULKWT | 19.6 | 20.4 | 18.6 | 40.6 |
| S08-01480 | T3 | 19.54 | 20.6 | 18.2 | 40.7 |
| S08-01482 | P3 | 19.14 | 20.5 | 18.7 | 41.2 |
| S08-01483 | BULKWT | 19.1 | 20.7 | 19.3 | 41.5 |
| S08-01484 | T4 | 19.04 | 20.8 | 19.1 | 41.5 |
| S08-01486 | R4 | 18.84 | 21.4 | 19.6 | 42.2 |
| S08-01488 | P4 | 18.64 | 22.4 | 20.3 | 43.4 |
| S08-01490 | N4 | 18.44 | 22.8 | 21.0 | 45.0 |
| S08-01492 | L4 | 18.24 | 22.5 | 20.9 | 45.3 |
| S08-01493 | K4 | 18.14 | 24.1 | 21.5 | 44.5 |
| S08-01494 | BULKWT | 18.16 | 22.1 | 20.8 | 44.6 |
| S08-01495 | K5 | 19.04 | 68.8 | 27.3 | 57.1 |
| S08-01496 | BULKWT | 18.31 | 21.1 | 19.6 | 42.7 |

*Note: n.d. is not determined*