ASSESSMENT OF THE BURIAL ENVIRONMENT AT STREET'S GARAGE, DROITWICH, A REVIEW OF THE DATA COLLECTED BETWEEN MAY 2006 AND AUGUST 2007

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Compiled and edited by Nicholas Daffern

06 June 2008
Revised 22 November 2011

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Project 3767
Report 1884
WSM 35076

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1. Introduction

This assessment is a continuation of the report, *Assessment of the burial environment at Street's Garage, Droitwich, Worcestershire* (Cheetham 2006a) with additional data collected beyond the baseline discussed in Cheetham (2006) and extensions to discuss measurement limitations and sources of errors.

A programme of monitoring and water testing was undertaken at Street's Garage, Droitwich, Worcestershire (National Grid Reference SO 9022 6346) by Wessex Archaeology and Worcestershire Historic Environment and Archaeology Service between May 2006 and August 2007. This report has been compiled on behalf of CgMs.

Proposed development on the site has been flagged as having the potential for causing an adverse impact upon an area that has demonstrated the potential for the preservation of valuable organic archaeological remains. Part of the site falls within Scheduled Ancient Monument 30097.

Monitoring of the burial environment has been carried out by means of piezometer clusters located in three locations on and near to the site. Each cluster consists of three piezometers located to different depths, all installed during coring for evaluation purposes.

The boreholes are located close together, but in different types of site. Borehole 100 (BH 100) is in parkland, surrounded by grass and trees, Borehole 101 (BH 101) is situated in disturbed ground with grass and trees on one side and asphalt on the other and Borehole 102 (BH 102) is located in the centre of an asphalt area and prone to flooding during very heavy rain.

Parameters monitored are redox potential (or ORP) from soil pore water pumped from the piezometers, water depth, temperature, pH, electrical conductivity, salinity and total dissolved solids. Additional baseline data being obtained was nitrates, nitrites, sulphates, sulphites, ammonia and pH taken from soil and water samples and sent for analysis to an external laboratory.

2. Aims

The aims and objectives of this report are to assess the burial environment present at Street's Garage, Droitwich, in terms of the potential for the preservation of organic archaeological remains and the potential impact of development if remains were identified.

3. Methods

3.1 Monitoring parameters

The level of the groundwater is measured in each of the piezometers, at the three boreholes by lowering a probe, on a tape graduated in millimetres, into the borehole, alongside the piezometer tube. The probe sounds when wet and the depth is read from the tape. The depths are converted to height OD for comparison between boreholes.

The gap between the wall and the inner piezometer tube is similar to the size of the probe and condensation or water droplets on the inner wall of the tube may cause too short a depth to be measured. The depth is monitored at the point of recording, and measurements are repeated where the data is inconsistent.

The pH, ORP (redox potential), temperature and conductivity have been measured by pumping water from the boreholes through a flow cell, within which the measurement electrodes are located. The total dissolved solids (TDS) and salinity are derived by the instrument from the conductivity value. The full description of the method is set out in the document, 'Christine's Groundwater Test Procedure'

The rate of flow of the groundwater restricts the quantity of water available for testing from some of the shorter piezometers, and this can influence the ORP results. If the supply is exhausted, air will be pumped through the tube which can cause oxidation of the sample, and change the ORP value.

Redox data is conventionally quoted with the Standard Hydrogen Electrode (SHE) as the reference. This electrode is difficult to use in practice, and the ORP probe uses an inbuilt silver/silver chloride reference electrode. To convert these measurements to the standard form, it is necessary to add 222mV to the readings obtained (Cheetham, 2006b). This correction has been applied to the data presented in the mV/pH plots in Figures 10-13.

The ORP values vary with pH, and to examine the variation over time, values must be adjusted to a standard value of pH, using the following equation:

$$Eh=Ep+222+59(7-pH)$$

Eh is the corrected redox potential in mV

Ep is the measured redox potential in mV (Cheetham, 2006b)

The values presented in Figures 7-9 have been treated in this way, and are presented in Table 3, along with comments recorded at the time of sampling.

As discussed in Cheetham (2006a), the data can be divided into categories as presented in Table 1 and this approach has been used to assess the variation in data over time.

The Eh/pH diagram, or stability field diagram is described in Cheetham (2006a). This representation maps the pH and redox characteristics of the samples within zones defined by the species that exist in solution under these conditions.

In the diagrams shown in this report, the blue line shows the limit of stability of water, which would be reduced below this line. The black line is defined by the equilibrium potential of the iron II/III couple, with the oxidised form (Fe3+) being present above the line and the reduced form (Fe2+) present below it. It is this change that produces the grey/green observed in gleyed soils, and provides a relative measure of the degree of oxidation/reduction within the burial environment. The red line in the diagram denotes the boundary between the oxidised form (sulphate) and reduced form (sulphide) of sulphur, (Cheetham, 2006a).

Cheetham (2006a) explains that in terms of the preservation of organic archaeological remains the sulphide/sulphate boundary has far greater significance than that of iron. This is because the reduction of sulphur occurs under greater reducing conditions and is mediated by the activity of sulphur reducing bacteria. These bacteria are obligate anaerobic bacteria, so observations that fall within this region of a stability diagram are indicative of true anaerobic conditions and are, in consequence, the conditions that are most suitable for the preservation of organic archaeological materials. Therefore results can be placed within three broad categories, depending on where they fall within the Eh / pH diagram. Above the black iron II/III line can be considered as oxidised conditions. Below the Iron II/II but above the red sulphate/sulphide line can be considered as moderately reduced. Below the sulphate/sulphide boundary can be considered highly reduced.

He also stresses that the boundaries shown on the Eh / pH diagram inherently suggest that a state of equilibrium exists within the burial environment when, in fact, this is not the case. Environmental measurements of redox potentials include mixed potentials of unknown and variable concentrations of chemical species, therefore readings obtained using this approach

can be considered as average figures for all the redox couples that are present. In this work, the diagram is used only to aid interpretation, as it does not fully define the burial environment.

3.2 Soil and water analysis

Chemical analysis of soil and water samples including Sulphate as SO_4 (water soluble), Ammonia as N, Nitrate as NO_3, Nitrite as NO_2, Sulphide as S and pH was undertaken by Severn Trent Laboratories (STL). A methodology for these works was not available at the time of this report being compiled.

The detailed results of this analysis are appended as Appendix 1.

4. Results

4.1 Piezometer readings

The water levels varied from the lowest reading of 26.99m OD at BH 100, piezometer 6.0m and the highest being 28.28m OD at BH 102, piezometer 2.8m. This gives a maximum range in water elevation of 1.29 m and a sample standard deviation value of 0.23m.

The average height of the water table across all data was found to be 27.35m. This is probably a slight overestimate, for two reasons.

1) The water table is reproducibly higher in the shallower piezometer tubes for boreholes 100 and 101, and may be the result of the addition of water from the ground surface. This is also indicated by changes in conductivity (See figures 16-18).
2) Although results were monitored when collected and any unexpected result confirmed before recording, errors in measurements can arise due to condensation within the outer piezometer tube. When this occurs, it results in an artificially high reading for the water table.

Unexpectedly low readings have been recorded for the 16 June 2006 in borehole 102 in the1.7m piezometer, and on 10 November 2006 in Borehole 102 in the 2.8m piezometer.

Notably high levels were recorded for all piezometers on 6 March 2007 when the testing was carried out following several days of heavy rain. The levels also reflect the low rainfall in April 2007 and the heavy rainfall from May to July 2007.

4.2 Temperature Measurements

The weather was recorded on each visit and is presented in Table 2.

The temperature data for the groundwater (see Figures 4-6) show a gradual increase from late May to mid August 2006. This temperature rise is in phase with the hot, dry conditions recorded in Table 2. There is a fall in temperature from September, and the temperatures start to rise again in April, with the shallower piezometers showing more pronounced temperature swings than the deeper levels. There is very little observed increase in water temperature during spring and early summer in BH100, which is a reflection on both the deeper piezometers and the unseasonably cool, wet summer.

4.3 ORP Results

4.3.1 Variation in ORP with time

Figures 7-9 show the changes in the ORP (redox) data over time. The data have been corrected to the Standard Hydrogen Electrode, and adjusted for pH.

The data presented in Table 4 have been highlighted according to the categories in Table 1, and it can be seen that the majority of the redox values are in the categories ‘reduced’ or ‘highly reduced’ . The data from the first two months on average show less reduced conditions than subsequent data. This is probably due to the effect of drilling the boreholes

into the strata and introducing air at these levels. Beyond this time, all data fall within 'reduced' or 'highly reduced' categories, with 23% in the reduced category and 76% highly reduced.

The three boreholes had different characteristics over time. The shortest piezometer from borehole 100, as shown in Figure 7, initially had a less reduced ORP, which I attributed to the contribution from oxygen-containing surface run-off. As the rainfall declined and the temperature increased, the ORP became more reduced until it reached the same level as the longer piezometers. This level was maintained in subsequent tests. The deepest piezometer showed highly reduced conditions except for the initial reading, and the mid depth piezometer fluctuated around the reduced/highly reduced boundary. The readings from this borehole appear stable, but data is not available from the deepest piezometer after January 2007 because the piezometer tube collapsed and filled with gravel.

In Figure 8, borehole 101, after the initial settling down period, the results were all in the highly reduced category, (except for result in the reduced category which was measured in the shortest piezometer on 14th September 2006 during torrential rain, and can be attributed to local oxygenated run-off). All three piezometers showed a trend of increasing reduction over time. A sulphurous smell, and greyish colour to the water has been noted on many of the tests, which may be consistent with the highly reduced characteristics observed. The colour of the samples from this borehole varied from visit to visit, with some samples recorded as dark, and some exceptionally clear.

The results for borehole 102 are presented in Figure 9. These show an unexpected trend. While results the two deeper boreholes are mainly within the reduced category initially, becoming more reduced over time, the shortest piezometer, at 1.7m is more reduced than the shallower piezometers throughout most of the measurement period. The highly reduced values are unexpected at these levels and may be due to post-medieval, industrial fuel residues. A sulphurous smell from the shortest piezometer was recorded on many of the visits (Table 3).

4.3.2 Eh / pH Diagrams

In Figures 10-12, the adjusted ORP data are plotted on Eh / pH diagrams. For borehole 100 the majority of data points fall between the iron and sulphur lines, indicating moderately reduced conditions. For the deepest piezometer, some of the data falls into the highly reduced category between the sulphur and lower aqueous lines.

The data for borehole 101 has data in moderately reduced and highly reduced categories, with results in both categories from all three piezometer levels.

Borehole 102 shows similar results to borehole 100, but the data in the highly reduced category is from the shallowest borehole.

4.4 Range of pH Values

The variation in pH over time is presented in Figures 13-15. The pH values are close to neutral, within the range of 6.1 and 7.6 for all piezometers at the three boreholes. Borehole 100 showed an average value of 6.6 and 6.7 for the deeper piezometers, and a slightly alkaline result (7.2) for the shortest tube. Boreholes 101 and 102 showed a tighter spread of pH across the three piezometers, with values the range 6.8 to 7.0.

Two pH values of 5.56 and 5.55 were obtained on 3rd January 2007 and 17th July 2007, during heavy rainstorms, and are considered to be instrument errors due to the rain.

4.5 Conductivity

Very high conductivity measurements, indicating very high salt content, have been observed at all three boreholes, and at each location there is good agreement between the readings for the two deeper piezometers. Values of 246 milli-Siemens per centimetre (mScm-1) are obtained for borehole 100, and around 238 mScm-1 for borehole 101. The values for 102 (which is a more shallow borehole) was around 187 mScm-1. The shortest piezometer at each location has considerably lower salt content, as shown in Figures 16-18, indicating a

component of this water derived from surface run-off. The lowest salt concentration is measured in the shortest piezometer from BH 101, with a conductivity of 24 mScm-1. This is the site closest to the river Salwarpe, and the relatively low conductivity may be a demonstration of the influence of the river on the local groundwater aquifer.

The data for borehole 102 is intermittent, because the location of the borehole makes it prone to flooding during heavy rain. The results for borehole 102 show more variability than other boreholes, and an unexpected rise in conductivity is observed between January and June 2007.

4.6 Soil Analysis

4.6.1 Ammonia

Ammonia levels in all soil samples were below recordable limits with all returning a value of < 100 mg kg-1.

4.6.2 pH

pH conditions are generally more alkaline but those obtained from depth show significantly elevated values, some being greater than pH 12.

4.6.3 Sulphate and Sulphide

Sulphate results show increasing amounts with the depth of sample. This is in fact the opposite pattern than would be expected as sulphate is reduced under anoxic conditions leading to its removal.

Sulphide was not detected from any soil samples

4.6.4 Nitrate and nitrite and ammonia

Nitrite has only been recorded at any level in the shallowest soil samples taken from the site, Nitrate levels recorded in soil samples indicate a slight reduction with depth.

4.7 Water Sample Analysis

4.7.1 pH

The pH values in the first set of solutions, although slightly more alkaline than measurements in the field, were still broadly neutral. The data for the second set of water samples included four readings of extremely alkaline conditions. As the readings in the field do not show significant changes in pH over time, the accuracy of the reported values was questioned. Subsequent sets of data were much closer to the values measured in the field, but the day-to-day variability is greater than for samples measured in the field. Data for 6/3/07 was between 7.1 and 7.7, whereas data for 18/6/07 was between 4.9 and 7.4

4.7.2 Sulphate and Sulphide

Although sulphate concentrations had been requested, there was some doubt about the form of sulphur measured in the first two sets of test data. Subsequent measurements have specified sulphate as SO42- and the concentrations were typically a factor of 10 higher than previous results. The discussion is based on the latter data sets.

Levels of sulphate in the deeper two piezometer tubes for boreholes 100 and 101 were all between 5 and 6 grams per litre (g/l), with lower values for the shorter tubes. The results for borehole 102 are slightly lower than this, with average data between 3.5 and 4 g/l in the longer two tubes.

It is expected that the level of sulphate would be increased at shallower levels, as sulphide is oxidised to sulphate in the presence of oxygen, but this is the reverse of the trend observed.

A series of problems has occurred with sulphide analysis. Initial samples were tested, but during discussion with the testing company it emerged that the sulphide is volatile it will not

remain in solution for prolonged periods. From 9th January 07 samples with fixative for retaining sulphides were sent for analysis, but did not show any measurable sulphide levels. On further discussion with the testing company, it appears that the fixed samples were not used for testing, and reliable sulphide levels had not been recorded. More reliable data have been obtained between March and August 2007. This shows average sulphide levels for each borehole between 0.08 and 0.5mg/l . Repeat samplings have shown wide variability: a value of 0.13mg/l was 0.04mg/l in the repeat sample. For this reason, the average values have been plotted in Figure 19, rather than individual data.

A negative correlation between sulphide and sulphate could be expected from the inter-conversion between sulphide and sulphate in reduced conditions. Figure 20 shows that this trend is not observed.

Figure 21 looks at the correlation between conductivity and sulphate. This plot indicates that the sulphate measured in the samples is proportional to the conductivity across the boreholes, even when the shallower piezometers show dilution with surface water. This suggests that the sulphate arises from the salts in the aquifer, and the concentration is not significantly altered by redox processes. This interpretation comes with the caveat that at these salt concentrations, the variation in conductivity with concentration is not linear, and for an absolute correlation, accurate salt concentrations are required.

4.7.3 Nitrate and nitrite and ammonia

Nitrate levels in water samples were below recordable limits of 2.5mg/l and most of the nitrite samples were below the detection levels of 0.07mg/l. Borehole 100 pz 3.5 did contain measurable levels of nitrite on four occasions. These ranged between 0.3 and 1.6mg/l.

The levels of ammonia recorded in all boreholes were low (below 10mg/l), with levels in the deeper tubes typically between 3.5 and 9mg/l. There was significantly less ammonia in the shallowest samples, with values typically between 1 and 3mg/l. This is expected as there will be an aerobic metabolism within the upper levels of the soil, which causes decomposition of ammonia in the presence of oxygen.

Ammonia accumulates within the burial environment in anoxic conditions, as oxygen is required for its breakdown, indicating the presence of more anoxic conditions with depth. In this situation, ammonia levels may prove to be a good indicator of the local conditions within the archaeological environment.

5. Characterisation (from Cheetham 2006a)

The stratigraphy at each of the three monitoring locations has been described elsewhere. However, significant factors that may influence the interpretation of the results are apparent at each of the locations.

No known archaeological materials exist within the extent of the development area although certain elements of the stratigraphy have been identified as having potential. Where archaeological materials have been identified during previous investigations they have included well-preserved organic remains, sensitive to changes within the burial environment. Where these exist they must have been subjected to continually saturated, anoxic, stable burial conditions. These are characterised by highly reduced conditions, although these may only exist within the areas immediately surrounding the archaeological materials.

The pH of the site is broadly neutral with all values obtained during monitoring clustered around pH 7. These values are supported by those obtained samples sent away for analysis. pH values derived from soils samples exhibit highly alkaline conditions, especially from those taken at depth. These are likely to be erroneous and the result of post sampling changes resulting from exposure to air.

Piezometer levels suggest that unconfined conditions exist within the soil profile. Elevated water levels in the shallowest piezometers at BHCP 100 and 101 suggest that there is an element of surface water contribution and percolation. This is most likely explained by the increased precipitation on the site prior to monitoring taking place. Readings obtained from

BHCP 102 on the 31st May show higher levels from the deepest piezometer at 4.3m. As this is a single reading, its significance is unknown at this time.

Lower values for electrical conductivity, salinity, and total dissolved solids obtained from the shallower piezometers at all three monitoring locations suggest the presence of water derived from precipitation as the groundwater in this area has a high salt level.

The piezometer levels obtained so far do not exhibit large changes between monitoring visits, apart from the deepest piezometer (4.3m) at BHCP 102. This suggests that saturated conditions exist below approximately 27.5m OD This level is probably largely determined by the level of the River Salwarpe. The level of the river was recorded at the time of the monitoring and gives values of 27.54 and 27.47m OD for the 24 and 31 May consecutively.

A significant proportion of the soil profile on the site is made up of post-medieval fuel waste. Such material is will be relatively unconsolidated and allow the lateral and vertical movement of water through it. Such material with a high saturated hydraulic conductivity will therefore be influenced by the adjacent river. It would therefore be expected that the main level of the water table closely follows the level of the River Salwarpe.

Redox measurements indicate moderately reduced to reduced conditions across the site. Such values reflect saturated conditions within deposits that hold little organic material. Within organic soils, through the process of sequential reduction, highly reduced conditions can develop. However, due to the coarse nature of the monitoring being carried out and the likely localised effects of any organic archaeological remains that exist, the absence of such highly reduced conditions does not remove the possibility of preserved archaeological materials.

Chemical analysis has been useful in identifying the presence of aerobic metabolism within the upper levels of the soil profile. This is shown by less ammonia being present in samples obtained nearer to the ground surface. Ammonia accumulates within the burial environment in anoxic conditions as oxygen is required for its breakdown indicating the presence of more anoxic conditions with depth.

Similarly, shallower samples revealed greater levels of sulphate. Under anoxic conditions sulphate is reduced by anaerobic sulphate-reducing bacteria and therefore removed from the environment. Lower recorded levels of sulphate indicate the possible presence of sulphate reducing conditions at depth.

Nitrate follows a similar pattern as sulphate with a reduction in the recorded levels with depth. Nitrate is chemically reduced under anaerobic conditions leading to its removal.

The monitoring data has indicated that normal conditions exist within the soil profile on this site. This takes the form of increasingly reduced conditions with depth and a simple hydrostratigraphy with unconfined conditions yielding a water table that exists relatively close to the ground surface. Chemical analysis show the presence of aerobic metabolic activity near to the ground surface which lessens with depth. Reduced sulphate levels suggest the possibility of anaerobic conditions that exist even though such levels are not supported in redox monitoring data. This is probably a reflection of the relatively low resolution approach to the monitoring of the burial environment.

6. Conclusions

The conclusions for this work are in line with those presented by Cheetham (2006a), but, with the additional data available, the burial environment has been shown to be more reduced than initially indicated, as the conditions settle after the disturbance from drilling the boreholes. The majority of the data falls into the highly reduced category on the scale indicated in Patrick. & Mahapatra (1968).

When the Eh/pH diagram is used for interpretation, the deepest tube in borehole 100, all tubes in 101, and the shallowest piezometer in 102 show at least half the measurements in the highly reduced category. These results would indicate good conditions for preservation of archaeological remains.

The sulphate measured arises from the salts in the aquifer, and the concentration is not significantly altered by redox processes, but ammonia levels appear to provide a better indicator of the local conditions within the archaeological environment.

7. Acknowledgements

The report, Assessment of the burial environment at Street's Garage, Droitwich, Worcestershire, Ref.: 63350, June 2006, compiled by James Cheetham formerly of Wessex Archaeology, has been used as the framework for further data analysis presented in this document.

The Service would like to thank the following for their assistance in the conclusion of this project: James Cheetham for guidance and support in the conversion of data to the standard format, Lisa Moffett (English Heritage) for support and advice and Ian Panter for guidance and for reviewing and Nicholas Daffern for compiling editing this report.

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Tables

Oxidation/Reduction status	Range of redox potential
Oxidised	> +400 mV
Moderately reduced	+100 to +400 mV
Reduced	-100 to +100 mV
Highly reduced -300 to -100 mV	

Table 1 Categories of redox potential (Derived from Patrick & Mahapatra, 1968)

Date	Weather
24/5/06	Showers, after 5 wet days
31/5/06	Dry after a week of wet weather
16/6/06	Hot and dry after two dry weeks
13/7/07	Sunny
26/7/06	Sunny after 2 weeks heatwave
8/8/06	Hot and dry
29/8/06	Dry initially then heavy storms
14/9/06	Torrential rain after prolonged dry spell
28/9/06	Cloudy, slight showers
17/10/06	Overcast, with light showers later
10/11/06	Overcast, with light showers later
22/11/06	Fine and Sunny
7/12/06	Heavy showers, after days of prolonged rain
19/12/06	Dry and overcast
3/1/07	Dull with rain later, following days of heavy rain
16/1/07	Wet initially, dry later. Severn in flood due to recent rain
31/1/07	Fine and dry after a dry week
6/3/07	Fine and sunny after several days of very heavy rain
17/4/07	Dry and bright after two hot, dry weeks
18/6/07	Overcast with heavy showers after overnight rain
17/7/07	Heavy rain after seven weeks of heavy rain
6/8/07	Fine and dry, two weeks after substantial flooding of site

Table 2 Weather conditions on monitoring days

Piezometer	24/05/06	31/05/06	16/06/06	13/07/06	26/07/06	08/08/06	29/08/06	14/09/06	28/09/06	17/10/06	10/11/06
BH100 Pz 8.6	-84	-136	-104	-173	-181	-218	-180	-148	-181	-303	-238
BH100 Pz 6.0	38	-17	-83	-86	-120	-106	-73	-153	-94	-92	-190
BH100 Pz 3.5	114	106	75	-26	-151	-12	78	13	22	-181	-141
BH101 Pz 6.7	18	-74	-89	-203	-150	-223	-127	-233	-232	-299	-203
BH101 Pz 4.0	-46	-112	-81	-182	-202	-226	-189	-207	-206	-256	-240
BH101 Pz 2.0	-148	-105	-30	-115	-130	-117	-158	-53	-138	-244	-208
BH102 Pz 4.6	27	10	-29	-40	-33	-21	-64		-60	-53	-79
BH102 Pz 2.8	68	77	4	18	48	19	41		-54	-7	-83
BH102 Pz 1.7	133	109	107	55	-32	-146	-65		-190	-198	-99

Piezometer	22/11/06	07/12/06	19/12/06	03/01/07	16/01/07	31/01/07	06/03/07	17/04/07	18/06/07	17/07/07	06/08/07
BH100 Pz 8.6	-227	-263	-229	-246		-253					
BH100 Pz 6.0	-176	-163	-145	-116	-123	-196	-140	-144	-91	-290	-123
BH100 Pz 3.5	-198	-107	-131	-119	-165	-208	-237	-164	-241	-184	-189
BH101 Pz 6.7	-259	-254	-255	-322	-317	-383	-409	-429	-361	-423	-448
BH101 Pz 4.0	-265	-267	-230	-282	-321	-298	-368	-360	-347	-369	-400
BH101 Pz 2.0	-240	-186	-198	-301	-267	-238	-307	-285	-309	-335	-350
BH102 Pz 4.6	-69		-90	-91	-146	-175	-16	-269	-172		-273
BH102 Pz 2.8	-46		-78	-88	-123	-107	-77	-118	-119		-113
BH102 Pz 1.7	-261		-222	-279	-233	-222	-261	-264	-220		-220

Table 3 ORP data in mV, corrected to Standard Hydrogen Electrode and pH

Air in tube
Drifting
Sulphurous smell
Mud from flooding
Dark solution

Key to Table 3

Piezometer	24/05/06	31/05/06	16/06/07	13/07/06	26/07/06	08/08/06	29/08/06	14/09/06	28/09/06	17/10/06	10/11/06
BH100 Pz 8.6	-84	-136	-104	-173	-181	-218	-180	-148	-181	-303	-238
BH100 Pz 6.0	38	-17	-83	-86	-120	-106	-73	-153	-94	-92	-190
BH100 Pz 3.5	114	106	75	-26	-151	-12	78	13	22	-181	-141
BH101 Pz 6.7	18	-74	-89	-203	-150	-223	-127	-233	-232	-299	-203
BH101 Pz 4.0	-46	-112	-81	-182	-202	-226	-189	-207	-206	-256	-240
BH101 Pz 2.0	-148	-105	-30	-115	-130	-117	-158	-53	-138	-244	-208
BH102 Pz 4.6	27	10	-29	-40	-33	-21	-64		-60	-53	-79
BH102 Pz 2.8	68	77	4	18	48	19	41		-54	-7	-83
BH102 Pz 1.7	133	109	107	55	-32	-146	-65		-190	-198	-99

Piezometer	22/11/06	07/12/06	19/12/06	03/01/07	16/01/07	31/01/07	06/03/07	17/04/07	18/06/07	17/07/07	06/08/07
BH100 Pz 8.6	-227	-263	-229	-246		-253					
BH100 Pz 6.0	-176	-163	-145	-116	-123	-196	-140	-144	-91	-290	-123
BH100 Pz 3.5	-198	-107	-131	-119	-165	-208	-237	-164	-241	-184	-189
BH101 Pz 6.7	-259	-254	-255	-322	-317	-383	-409	-429	-361	-423	-448
BH101 Pz 4.0	-265	-267	-230	-282	-321	-298	-368	-360	-347	-369	-400
BH101 Pz 2.0	-240	-186	-198	-301	-267	-238	-307	-285	-309	-335	-350
BH102 Pz 4.6	-69		-90	-91	-146	-175	-16	-269	-172		-273
BH102 Pz 2.8	-46		-78	-88	-123	-107	-77	-118	-119		-113
BH102 Pz 1.7	-261		-222	-279	-233	-222	-261	-264	-220		-220

Table 4 ORP data, oxidation and reduction categories

Oxidation/Reduction status	Range of redox potential
Oxidised	> +400 mV
Moderately reduced	+100 to +400 mV
Reduced	-100 to +100 mV
Highly reduced	< -100 mV

Key to Table 4

Figures

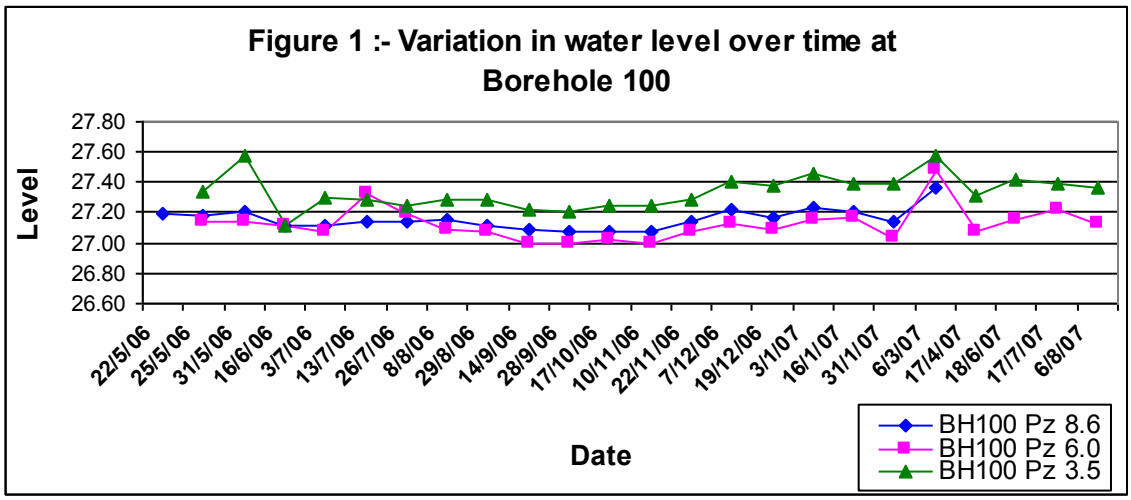


Figure 1 :- Variation in water level over time at Borehole 100
Level
27.80
27.60
27.40
27.20
27.00
26.80
26.60
22/5/06
25/5/06
31/5/06
16/6/06
3/7/06
13/7/06
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/07
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH100 Pz 8.6
BH100 Pz 6.0
BH100 Pz 3.5

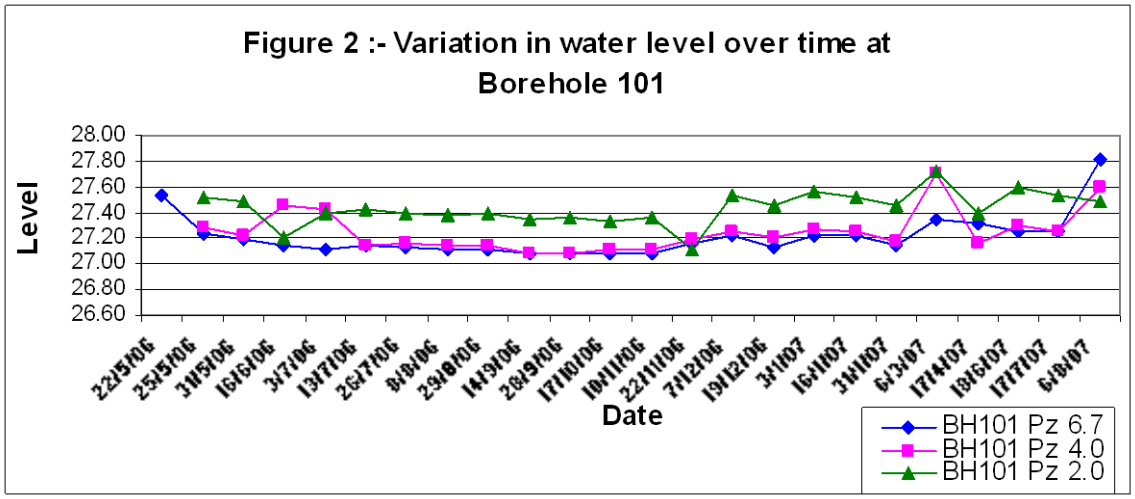


Figure 2 :- Variation in water level over time at Borehole 101
Level
28.00
27.80
27.60
27.40
27.20
27.00
26.80
26.60
Date
BH101 Pz 6.7
BH101 Pz 4.0
BH101 Pz 2.0

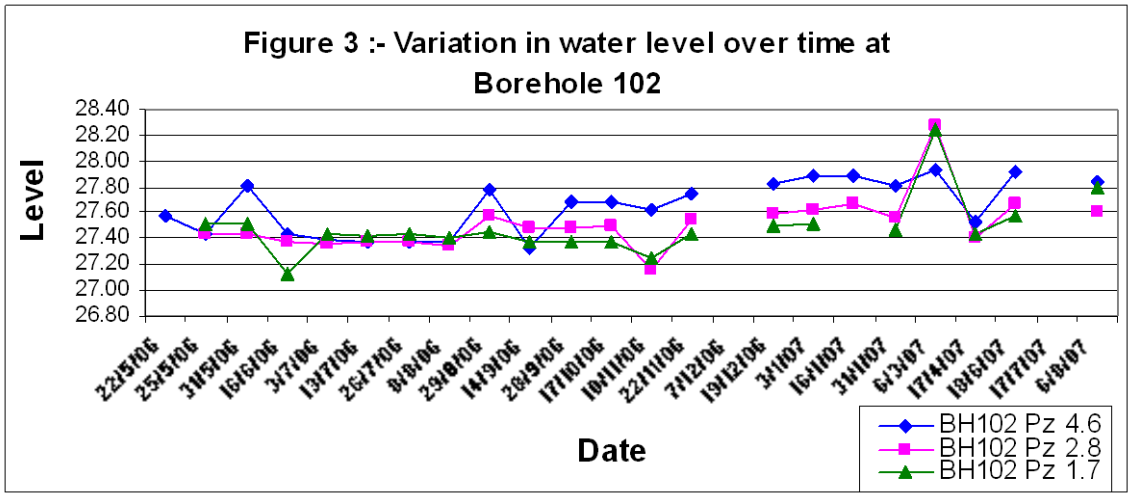


Figure 3 :- Variation in water level over time at Borehole 102
Level
28.40
28.20
28.00
27.80
27.60
27.40
27.20
27.00
26.80
Date
BH102 Pz 4.6
BH102 Pz 2.8
BH102 Pz 1.7

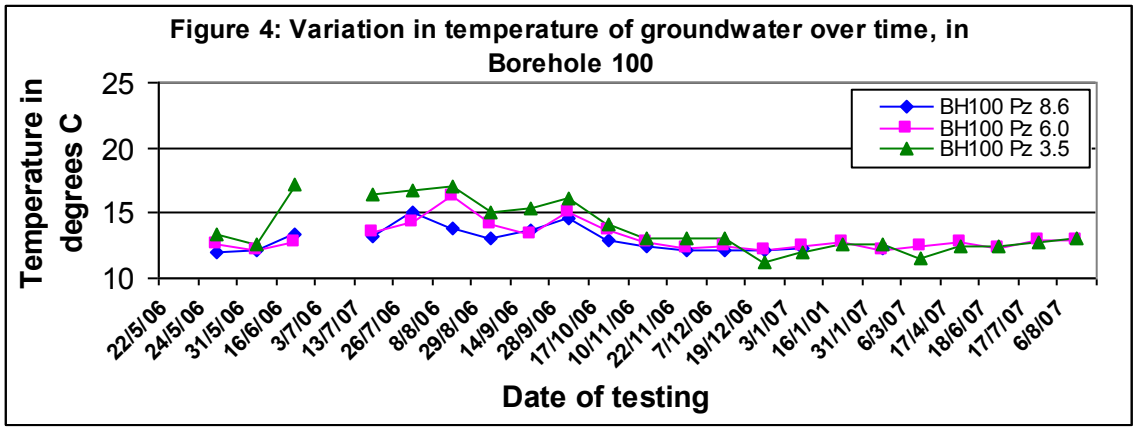


Figure 4: Variation in temperature of groundwater over time, in Borehole 100
Temperature in degrees C
25
20
15
10
BH100 Pz 8.6
BH100 Pz 6.0
BH100 Pz 3.5
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date of testing

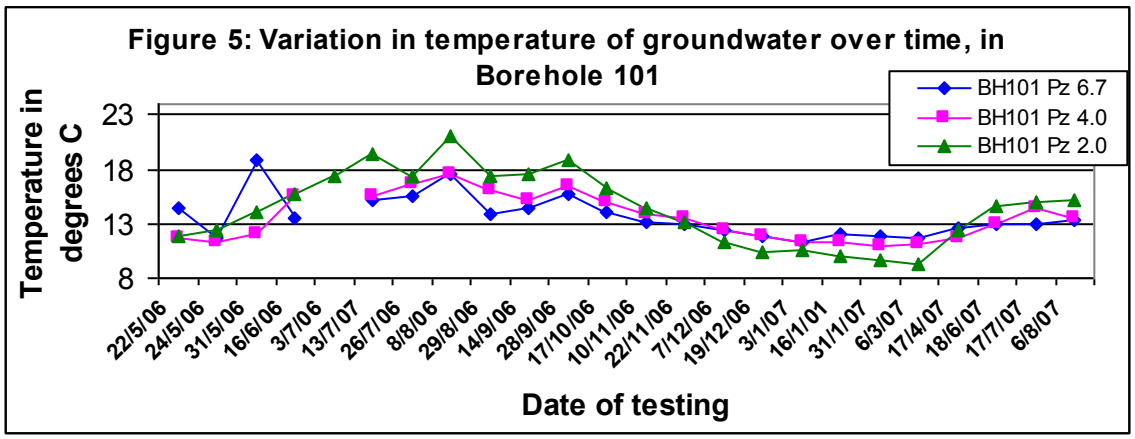


Figure 5: Variation in temperature of groundwater over time, in Borehole 101
Temperature in degrees C
23
18
13
8
BH101 Pz 6.7
BH101 Pz 4.0
BH101 Pz 2.0
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date of testing

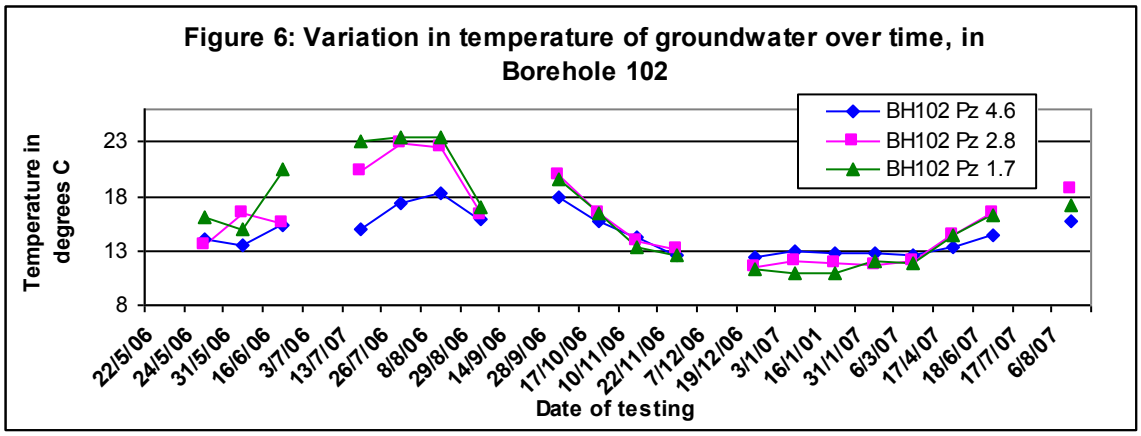


Figure 6: Variation in temperature of groundwater over time, in Borehole 102
Temperature in degrees C
23
18
13
8
BH102 Pz 4.6
BH102 Pz 2.8
BH102 Pz 1.7
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date of testing

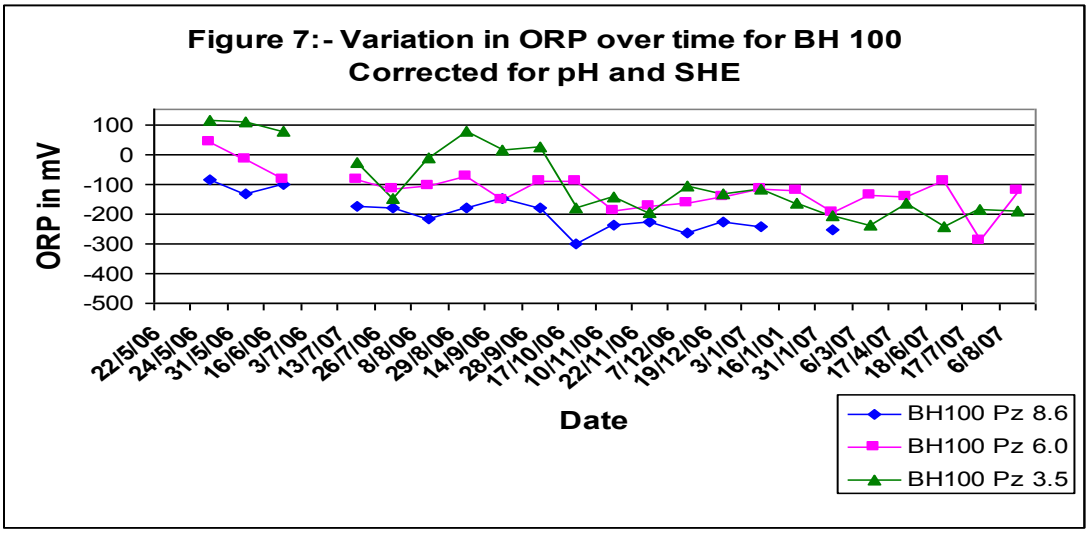


Figure 7:- Variation in ORP over time for BH 100
Corrected for pH and SHE
ORP in mV
100
0
-100
-200
-300
-400
-500
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH100 Pz 8.6
BH100 Pz 6.0
BH100 Pz 3.5

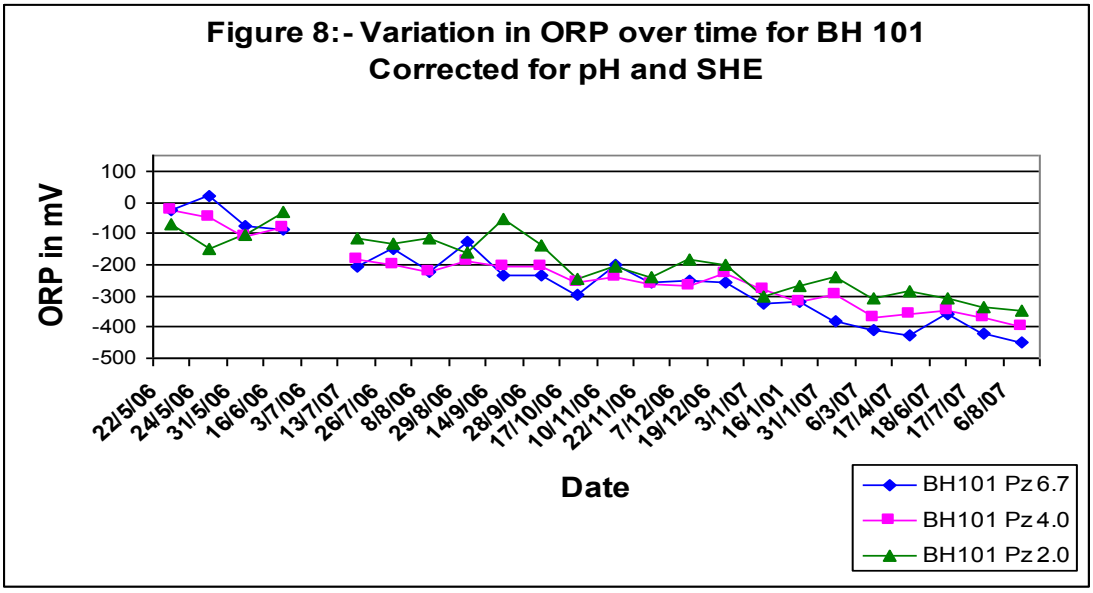


Figure 8:- Variation in ORP over time for BH 101
Corrected for pH and SHE
ORP in mV
100
0
-100
-200
-300
-400
-500
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH101 Pz6.7
BH101 Pz4.0
BH101 Pz2.0

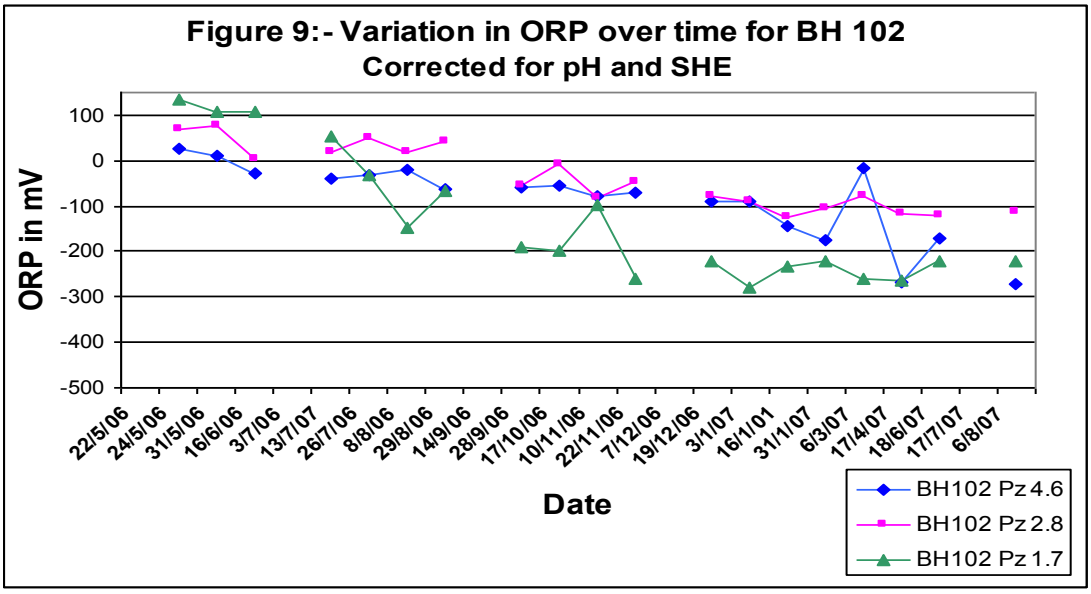


Figure 9:- Variation in ORP over time for BH 102
Corrected for pH and SHE
ORP in mV
100
0
-100
-200
-300
-400
-500
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH102 Pz4.6
BH102 Pz2.8
BH102 Pz1.7

Figure 10:- Eh/pH diagram for Borehole 100, relative to SHE

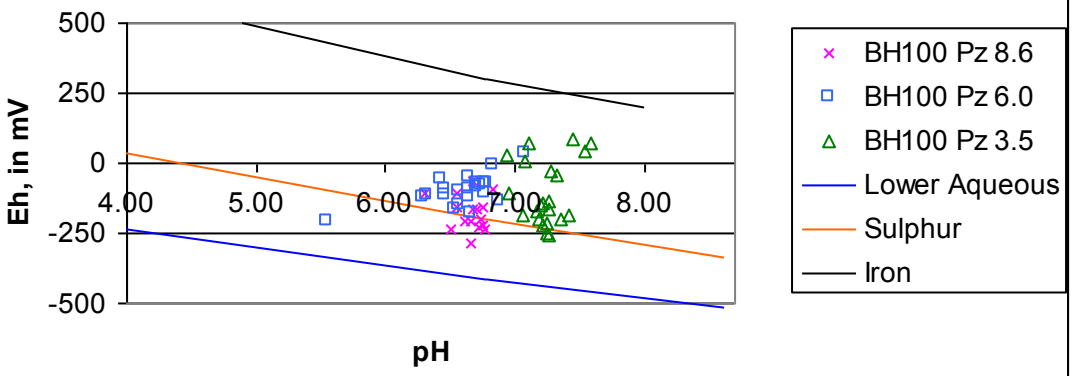


Figure 11:- Eh/pH diagram for Borehole 101, relative to SHE

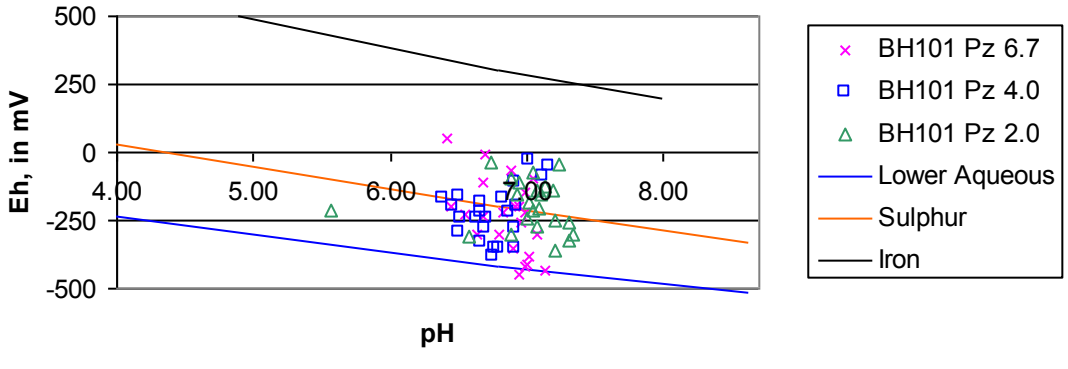
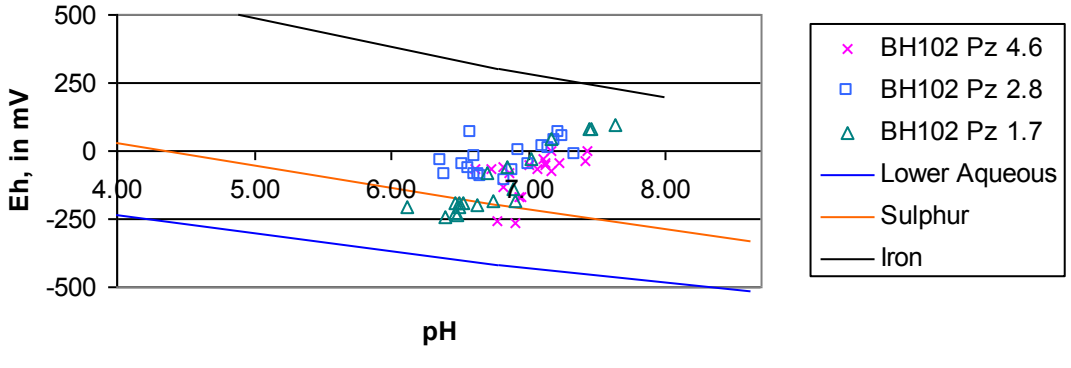


Figure 12:- Eh/pH diagram for Borehole 102, relative to SHE



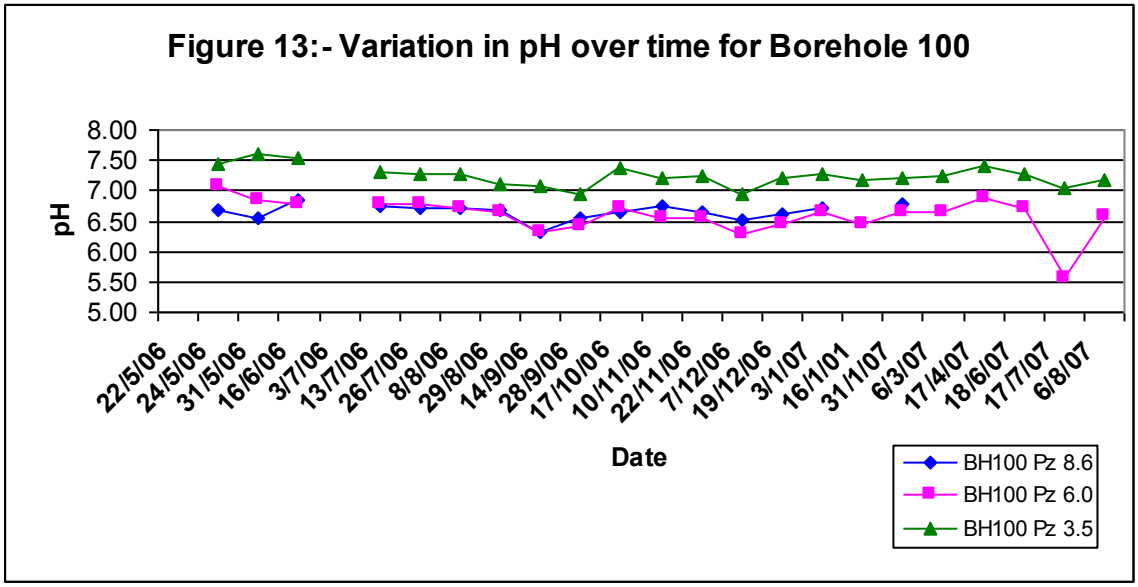


Figure 13:- Variation in pH over time for Borehole 100
pH
8.00
7.50
7.00
6.50
6.00
5.50
5.00
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/06
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH100 Pz 8.6
BH100 Pz 6.0
BH100 Pz 3.5

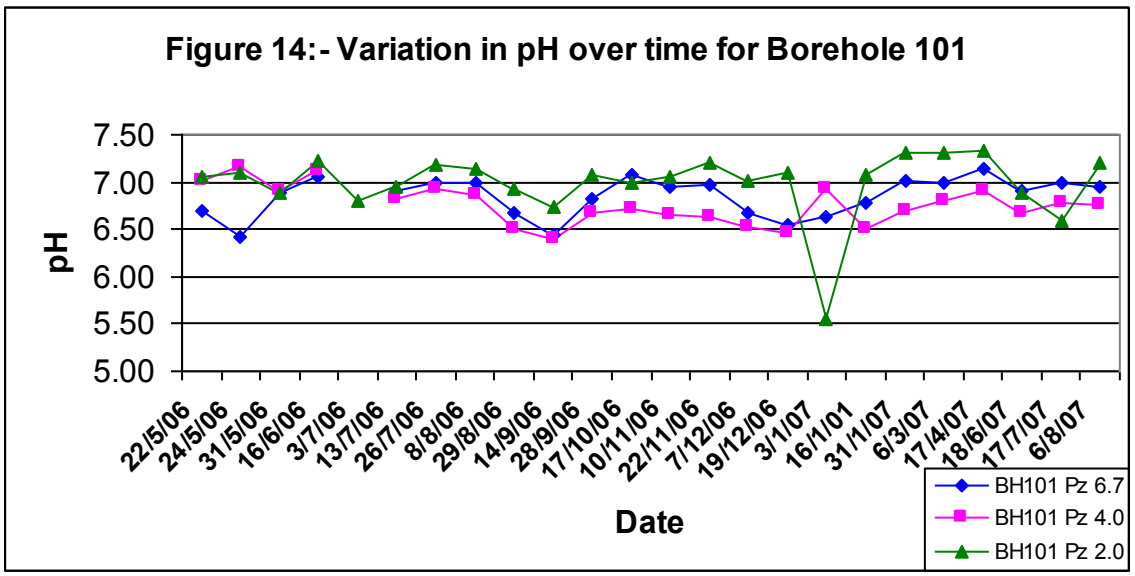


Figure 14:- Variation in pH over time for Borehole 101
pH
7.50
7.00
6.50
6.00
5.50
5.00
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/06
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH101 Pz 6.7
BH101 Pz 4.0
BH101 Pz 2.0

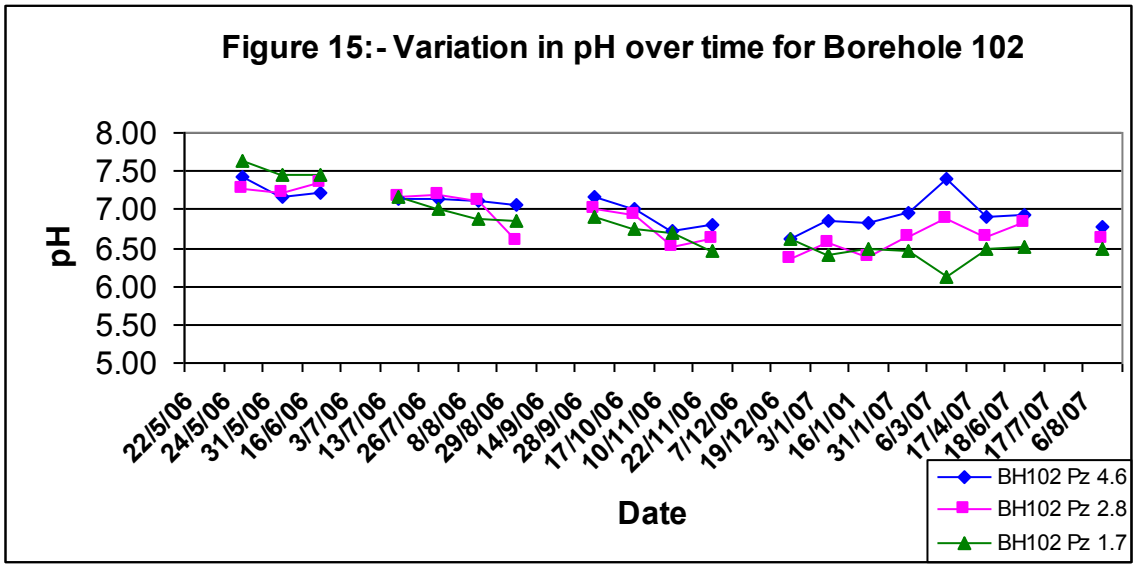


Figure 15:- Variation in pH over time for Borehole 102
pH
8.00
7.50
7.00
6.50
6.00
5.50
5.00
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/06
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH102 Pz 4.6
BH102 Pz 2.8
BH102 Pz 1.7

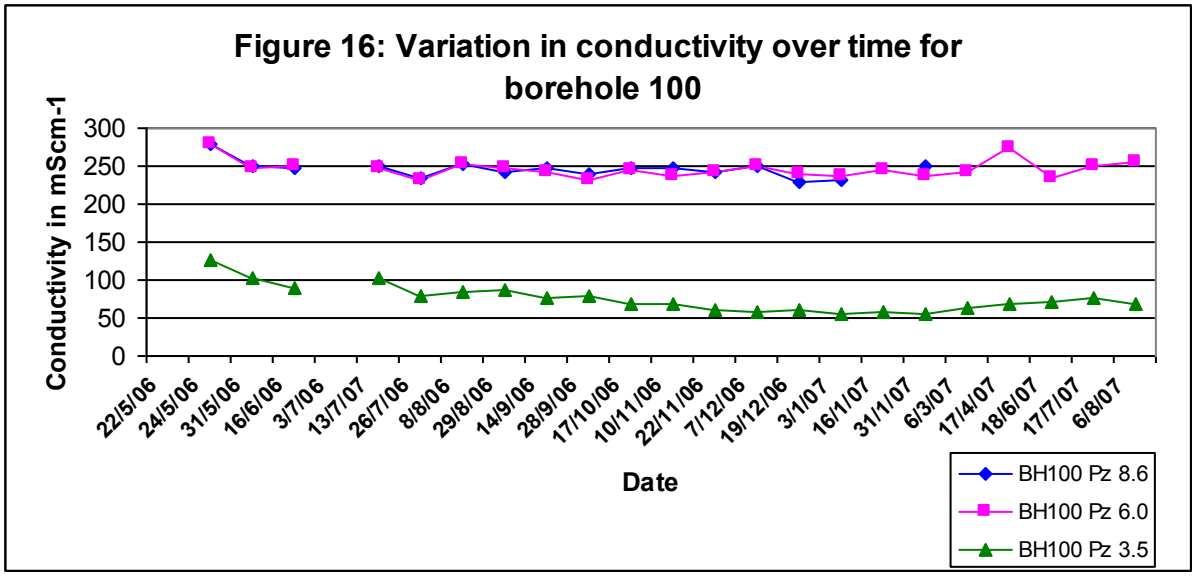


Figure 16: Variation in conductivity over time for borehole 100
Conductivity in mScm-1
300
250
200
150
100
50
0
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/07
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH100 Pz 8.6
BH100 Pz 6.0
BH100 Pz 3.5

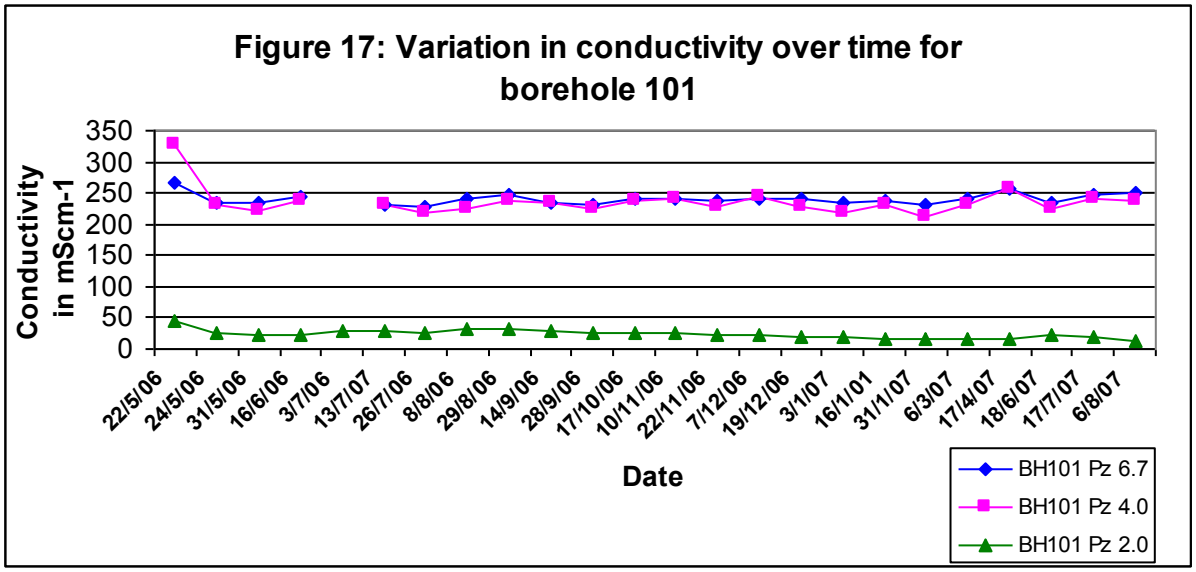


Figure 17: Variation in conductivity over time for borehole 101
Conductivity in mScm-1
350
300
250
200
150
100
50
0
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH101 Pz 6.7
BH101 Pz 4.0
BH101 Pz 2.0

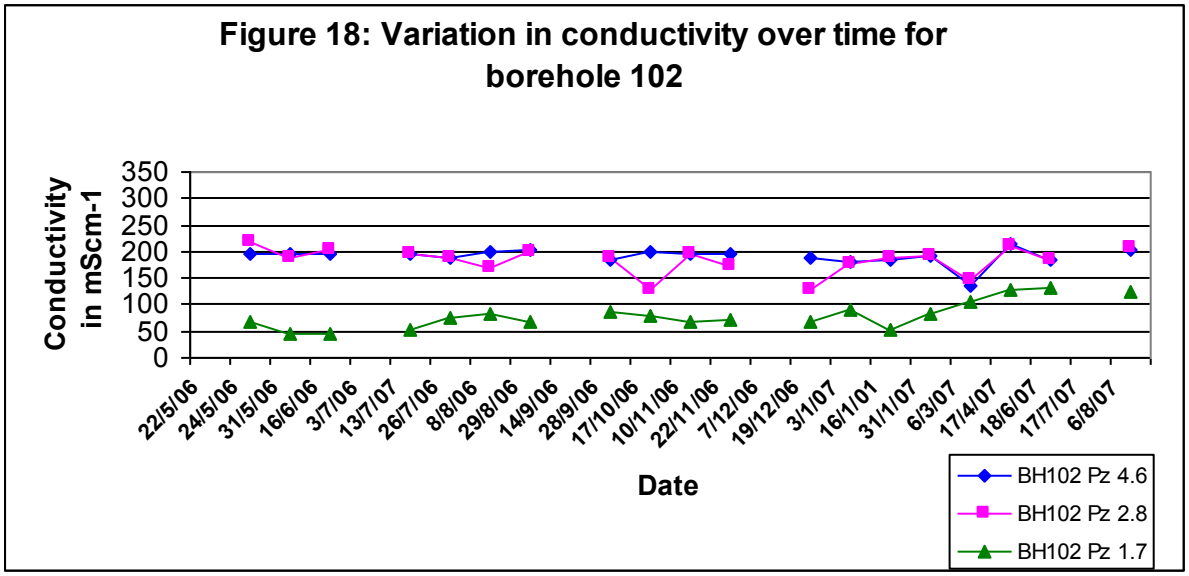


Figure 18: Variation in conductivity over time for borehole 102
Conductivity in mScm-1
350
300
250
200
150
100
50
0
22/5/06
24/5/06
31/5/06
16/6/06
3/7/06
13/7/07
26/7/06
8/8/06
29/8/06
14/9/06
28/9/06
17/10/06
10/11/06
22/11/06
7/12/06
19/12/06
3/1/07
16/1/01
31/1/07
6/3/07
17/4/07
18/6/07
17/7/07
6/8/07
Date
BH102 Pz 4.6
BH102 Pz 2.8
BH102 Pz 1.7

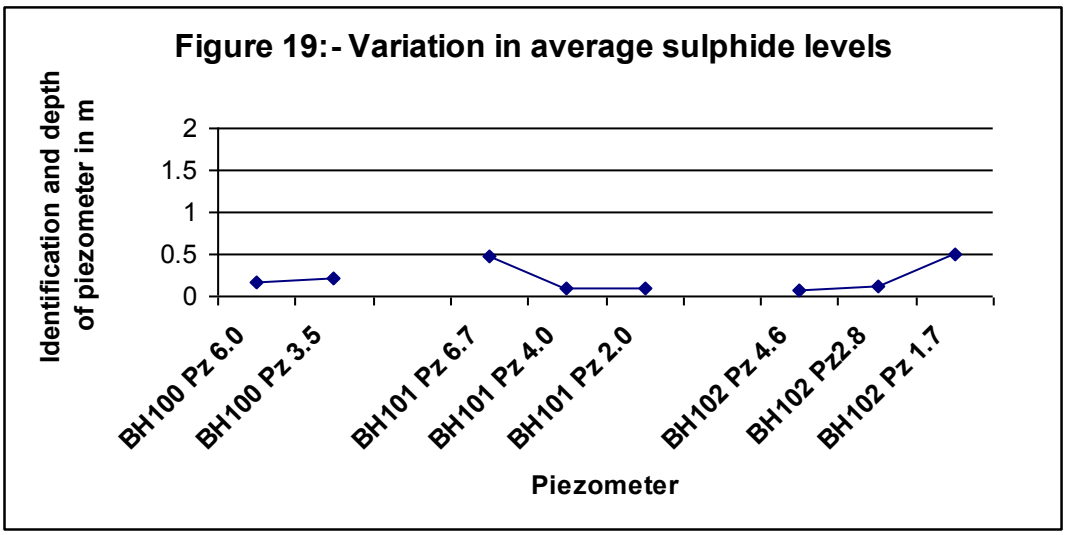


Figure 19:- Variation in average sulphide levels
Identification and depth of piezometer in m
2
1.5
1
0.5
0
BH100 Pz 6.0
BH100 Pz 3.5
BH101 Pz 6.7
BH101 Pz 4.0
BH101 Pz 2.0
BH102 Pz 4.6
BH102 Pz2.8
BH102 Pz 1.7
Piezometer

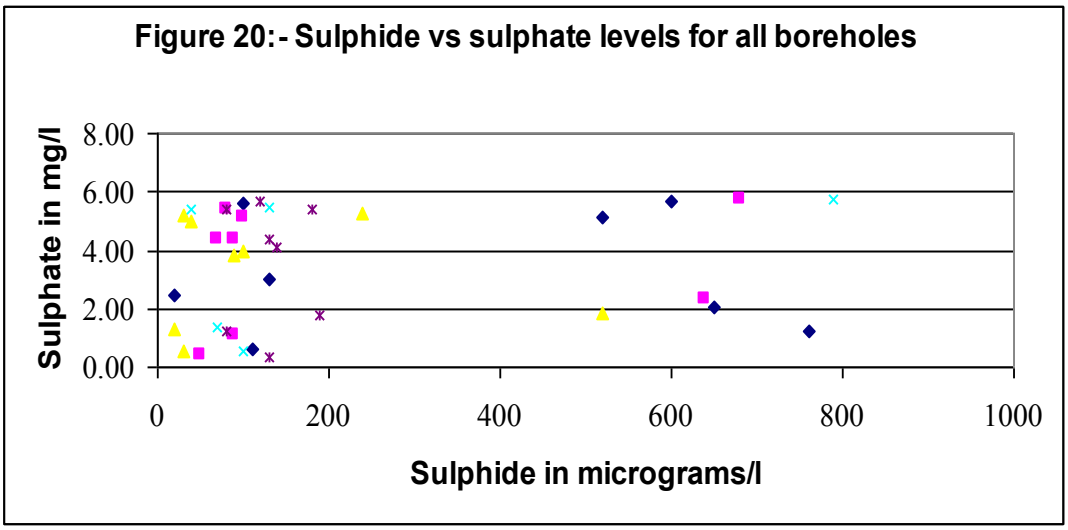


Figure 20:- Sulphide vs sulphate levels for all boreholes
Sulphate in mg/l
8.00
6.00
4.00
2.00
0.00
0
200
400
600
800
1000
Sulphide in micrograms/l

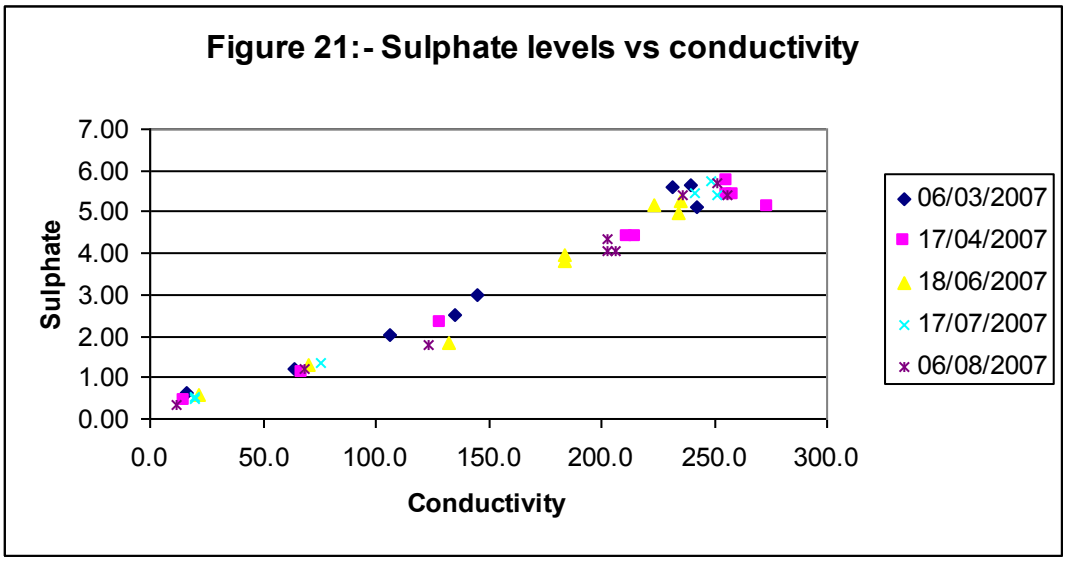


Figure 21:- Sulphate levels vs conductivity
Sulphate
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Conductivity
06/03/2007
17/04/2007
18/06/2007
17/07/2007
06/08/2007

Appendix – Results of Severn Trent Laboratories chemical analysis

Report number LL/348847/2006
Date reported 06/06/2006

Comments Unstabilised sulphide, sulphate form probably SO_3^{2-}.

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as form unknown mg/l	220	200	190	300	260	640	250	240	1400
Sulphate as form unknown g/l	*0.2*	*0.2*	*0.2*	*0.3*	*0.3*	*0.6*	*0.3*	*0.2*	*1.4*
Ammonia as N mg/l	4.1	4.8	2.0	5.3	7.8	<0.20	3.2	3.2	<0.20
Nitrate as NO_3 mg/l	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
Nitrite as NO_2 mg/l	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070
Sulphide as S ug/l	<10	<10	<10	<10	<10	<10	<10	<10	<10
pH	7.4	7.2	7.8	7.1	7.0	7.7	7.2	7.2	8.0

Report number LL/373896/2006
Date reported 25/09/2006

Comments Unstabilised sulphide, sulphate form probably SO_3^{2-}, pH unbelievable

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as form unknown mg/l	470	440	320	480	470	570	440	420	260
Sulphate as form unknown g/l	0.47	0.44	0.32	0.48	0.47	0.57	0.44	0.42	0.26
Ammonia as N mg/l	4.5	4.5	2.6	4.9	8.4	0.2	3.4	3.5	1.7
Nitrate as NO_3 mg/l	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
Nitrite as NO_2 mg/l	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
Sulphide as S ug/l	<10	<10	11	<10	<10	<10	15	16	<10
pH	11.3	11.3	11.7	11.4	7.4	8.0	7.3	7.3	7.9

Report number LL/382121/2006
Date reported26/10/2006

Comments Unstabilised sulphide, Sulphate as SO_4^{2-}.

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l	5.1	5.2	1.1	5.6	5.4	0.6	4.1	3.8	1.8
Ammonia as N mg/l	4.5	4.7	2.0	5.1	8.4	<0.2	3.5	3.2	0.9
Nitrate as NO_3 mg/l	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
Nitrite as NO_2 mg/l	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070
Sulphide as S ug/l	<10	<10	<10	<10	<10	<10	<10	<10	<10
pH	6.7	6.8	7.5	7.0	7.0	7.7	7.1	7.2	7.3

Report number LL/397503/2007
Date reported 09/01/2007

Comments Stabilised sulphide supplied, but not tested, Sulphate as SO_4^{2-}.

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l	5.4	5.3	1.1	5.7	5.7	0.5	3.9	3.6	1.4
Ammonia as N mg/l	4.2	4.3	2.4	5.1	8.0	<0.2	3.0	2.7	0.7
Nitrate as NO_3 mg/l	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
Nitrite as NO_2 mg/l	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070	<0.070
Sulphide as S ug/l	<10	<10	<10	<10	<10	<10	<10	<10	<10
pH	5.9	6.3	7.3	6.9	7.0	7.2	7.2	7.2	7.1

Report number LL/404414/2007
Date reported 16/02/2007
Date sampled 31/01/2007
Comments

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l	Not measured	Not measured	Not measured	0.06	0.028	0.035	3.7	0.038	1.7
Ammonia as N mg/l	<0.2	1.70	<0.2	11.00	<0.2	<0.2	6.40	0.31	0.25
Nitrate as NO_3 mg/l	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
Nitrite as NO_2 mg/l	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
Sulphide as S ug/l	<10	<10	<10	<10	<10	<10	<10	<10	<10
pH	6.9	6.9	7.4	6.9	6.9	7.4	7.1	7.2	7.1

Report number **LL/411942/2007**
Date reported **13/03/2007**
Date sampled **06/03/2007**
Comments First results with stabilised sulphide

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l	~	5.14	1.23	5.67	5.59	0.62	2.49	3.01	2.03
Ammonia as N mg/l	~	8.3	2.3	5.8	8.2	4.5	5.3	3.8	1.8
Nitrate as NO_3 mg/l	~	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Nitrite as NO_2 mg/l	~	0.03	0.94	<0.01	<0.01	0.04	<0.01	<0.01	<0.01
Sulphide as S ug/l	~	520	760	600	100	110	20	130	650
pH	~	7.1	7.7	7.2	7.2	7.6	7.5	7.5	7.4

Report number **LL/421757/2007**
Date reported **11/05/2007**
Date sampled **17/04/2007**
Comments Sulphide tested on arrival, rest after some weeks. Do not put any store by other than sulphide.

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l	~	5.13	1.11	5.73	5.40	0.44	4.39	4.39	2.33
Ammonia as N mg/l	~	7.6	0.5	5.7	8.2	<0.3	3.1	2.9	0.6
Nitrate as NO_3 mg/l	~	3.1	10.6	3.1	3.1	5.8	3.1	3.1	2.7
Nitrite as NO_2 mg/l	~	<0.1	4.9	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphide as S ug/l	~	100	90	680	80	50	90	70	640
pH	~	5.6	7.2	6.6	6.9	7.8	7.1	7.1	7.2

	BH101 Pz 6.7 split sample
in g/l	5.42
in ug/l	4.9
	3.1
Dubious results, see comments	<0.1
	670
	6.9

Report number LL/435377/2007
Date reported 04/07/2007
Date sampled 18/06/2007
Comments

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l		4.980	1.280	5.280	5.180	0.575	3.830	3.940	1.840
Ammonia as N mg/l		7.9	3.4	6.1	9.2	0.7	3.6	3.5	1.1
Nitrate as NO_3 mg/l		<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Nitrite as NO_2 mg/l		<0.01	1.64	<0.01	<0.01	0.02	<0.01	<0.01	<0.01
Sulphide as S ug/l		40	20	240	30	30	90	100	520
pH		4.9	7.4	5.3	5.8	7.3	7.0	7.2	6.6

Report number L442127
Date reported 25/07/2007
Date sampled 17/07/2007
Comments

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz 2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l		5.390	1.360	5.760	5.460	0.538			
Ammonia as N mg/l		5.8	3.0	5.5	8.6	<0.3			
Nitrate as NO_3 mg/l		<2.5	<2.5	<2.5	<2.5	<2.5			
Nitrite as NO_2 mg/l		<0.01	0.3	<0.01	<0.01	0.1			
Sulphide as S ug/l		40	70	790	130	100			
pH		7.00	7.50	7.10	7.00	7.40			

	Pz 2.0	Second sample from borehole
in g/l	0.505	Sulphate as SO_4^{2-} g/l
in ug/l	<0.3	Ammonia as N mg/l
Second sample collected sequentially	<2.5	Nitrate as NO_3 mg/l
	0.14	Nitrite as NO_2 mg/l
	60	Sulphide as S ug/l
	7.3	pH

Report number **LL/446900/2007**

Date reported **20/08/2007**

Date sampled **06/08/2007**

Comments

Determinand	BH100 Pz 8.6	BH100 Pz 6.0	BH100 Pz 3.5	BH101 Pz 6.7	BH101 Pz 4.0	BH101 Pz 2.0	BH102 Pz 4.6	BH102 Pz2.8	BH102 Pz 1.7
Sulphate as SO_4^{2-} g/l		5.43	1.20	5.70	5.43	0.34	4.36	4.07	1.79
Ammonia as N mg/l		6.0	2.8	5.5	7.9	<0.3	3.3	3.3	1.1
Nitrate as NO_3 mg/l		<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Nitrite as NO_2 mg/l		<0.01	0.5	<0.01	<0.01	0.1	<0.01	<0.01	<0.01
Sulphide as S ug/l		180	80	120	80	130	130	140	190
pH		6.8	7.4	7.0	6.9	7.4	6.8	7.0	6.9

	Pz 4.6	Duplicate
in g/l	4.07	Sulphate as SO_4^{2-} g/l
in ug/l	3.3	Ammonia as N mg/l
Second sample collected sequentially	<2.5	Nitrate as NO_3 mg/l
	<0.01	Nitrite as NO_2 mg/l
	40	Sulphide as S ug/l
	6.9	pH