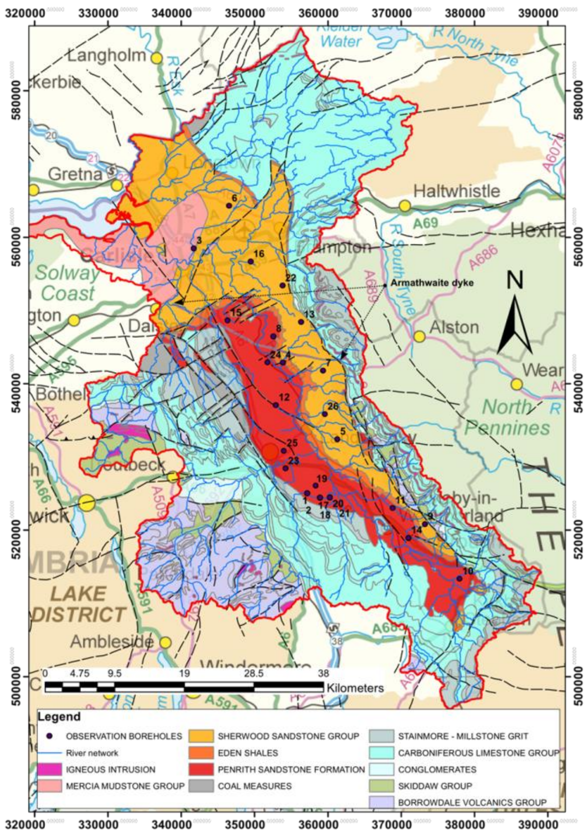
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Eden Valley observation boreholes: Hydrogeological framework and groundwater level time series analysis

Groundwater Directorate

Open Report OR/14/041



BRITISH GEOLOGICAL SURVEY

GROUNDWATER DIRECTORATE

OPEN REPORT OR/14/041

Eden Valley observation boreholes: Hydrogeological framework and groundwater level time series analysis

A E A Lafare, A G Hughes and D W Peach

Keywords

Geology, hydrogeology, time series analysis, Eden Valley.

Front cover

Geographical and geological setting of the Eden Valley catchment. BGS © NERC. River network data from CEH, © NERC. Contains OS data © Crown Copyright.

Bibliographical reference

LAFARE, A E A, HUGHES, A G, PEACH, D W. 2014. Eden Valley observation boreholes: Hydrogeological framework and groundwater level time series analysis. *British Geological Survey Open Report*, OR/14/041. 21pp.

Keyworth, Nottingham British Geological Survey 2014

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Acknowledgements

The Environment Agency are acknowledged for their supply of data and Simon Gebbet in particular for his insight into the hydrogeology.

Contents

FIGURES

Summary

This report summarises the analysis of groundwater level data from 26 boreholes in the Eden Valley, Cumbria. By undertaking a statistical analysis on 18 of these boreholes greater insight into the hydrogeology has been obtained. The work is presented to build a foundation on which greater analysis can be undertaken.

1 Introduction

This report has been prepared as part of the Hydrological Extremes and Feedbacks (HyDEF) project, which is funded by the Natural Environment Research Council (NERC) Changing Water Cycle programme. This project (see http://www.bgs.ac.uk/changingwatercycle/hydef.html) is led by Imperial College (ICL) and is a collaboration between ICL, University College (UCL), Reading University and the British Geological Survey (BGS). The project is investigating how extreme weather events (floods and droughts) will impact on the hydrology and in particular groundwater flow in the Thames Basin and the River Eden catchment in Cumbria under climate change. BGS' role is to ensure that the sub-surface processes are characterized, understood and simulated appropriately.

This report summarises the work undertaken in the Permo-Triassic sandstones in the Eden Valley and is based on the analysis of decade long daily time series of groundwater head data and an examination of the hydrogeology of the Vale of Eden. These head data, supplied by the Environment Agency, have allowed the development of an improved understanding of the groundwater behavior within the Permo-Triassic sandstone. The report consists of a short introductory section on the geology and hydrogeology of the Eden Valley, a description of the methodology employed to analyse the data, including how the time series decomposition was undertaken, and presents the main conclusions of the work. A detailed description of the boreholes, their geological and hydrogeological setting and the groundwater hydrographs are provided in an appendix.

2 Geology and hydrogeology of the Eden Valley

2.1 GEOGRAPHICAL AND GEOLOGICAL SETTING

The Permo-Triassic rocks of the Eden Valley lie in a fault-bounded basin (approximately 50 km long and 5-15 km wide) that is bounded to the southwest by the Lake District and to the northeast by the North Pennines (figure 1). This basin contains Permian and Triassic strata which dip gently to the north east (figure 2 and cross section, figure 3). The Pennine Fault and associated North Pennine escarpment form the eastern boundary of what appears to be a half-graben, throwing Permo-Triassic rocks against Carboniferous or Lower Palaeozoic rocks. To the west, the Permo-Triassic succession wedges out against Carboniferous strata (Allen et al. 1997).

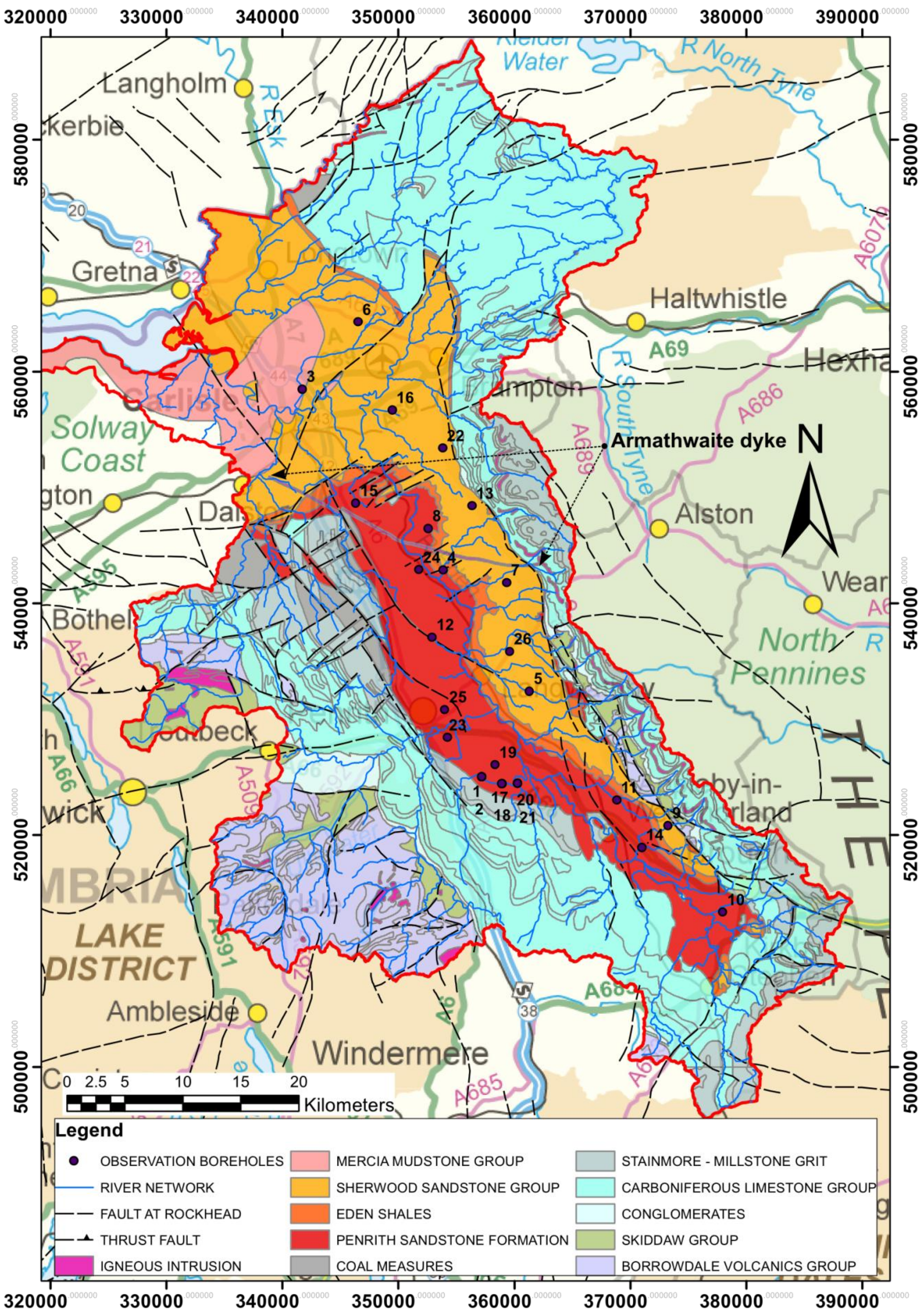


Figure 1 Geographical and geological setting of the Eden Valley catchment. BGS © NERC. River network data from CEH, © NERC. Contains OS data © Crown Copyright

The main features of the geology of the Eden catchment are summarized below.

- Ordovician and Silurian strata form the uplands of the Lake District and also occur outcropping in a fault bounded inlier adjacent to the Pennine Fault in the southeast part of the catchment (figure 1). These rocks are highly faulted and fractured, and include turbiditic sandstones, shales, lavas, volcaniclastic rocks, calcareous mudstones and siliciclastics.
- Devonian rocks are mostly represented by conglomerate formations which form conical hills. These conglomerates contain clasts mostly derived from the adjacent Borrowdale Volcanic Group (figure 1). They may act as localized minor aquifers dominated by fissure flow.
- The Carboniferous formations are composed of a layered succession of limestones, sandstones, mudstones and coals which fringes much of the Eden Catchment. The lower part of the Carboniferous succession is characterized by thickly-bedded limestones, including the Great Scar Limestone, which create elevated, karstic watersheds. These pass upwards into thinner limestones which are cyclically interbedded with sandstones, mudstones and thin coals of the Yoredale Group. In the northern half of the Eden catchment Upper Carboniferous Millstone Grit Group succeeds the Yoredale and there are outcrops of Coal Measures to the west of Armathwaite and further north.
- The Permian Penrith Sandstone lies unconformably over the Carboniferous (see geological cross-sections in figure 3), overstepping onto progressively older rocks from the Coal Measures in the north then over, Millstone Grit, Yoredales and onto the Great Scar limestone Group in the South north of Kirkby Stephen. This overstep is complicated by faulting.
- In the Great Scar Group hydraulic conductivity may be very high due to karst development but storage is likely to be quite low. In the Yoredales the limestones are often karstic, with lines of swallow holes found along outcrop. Storage and hydraulic conductivity rely almost entirely on fissure size, extent and degree of interconnection (Allen et al. 2010). It is likely that the Millstone Grit Group rocks (and similarly the Coal Measures) form an aquitard where they occur and form relatively impermeable base beneath the Penrith Sanstone.
- The Penrith Sandstone formation (early Permian) was deposited in a structurally-controlled intermontane basin broadly coincident with the present Vale of Eden. These largely Aeolian sandstones reach a thickness of about 900m in the center of the basin. The basal breccias and conglomerates locally known as Brockram become progressively more dominant southwards. It is composed of angular fragments of dolomitised limestone embedded in a strongly cemented calcareous sandstone matrix. The Penrith sandstone itself consists of well-rounded and well-sorted, medium to coarse grains. Less well-sorted finer grained sandstone beds with thin mudstone intercalations are common, mainly at the top of the sequence and at the margins of the basin, indicating episodes of fluvial deposition. In the northern part of the basin, parts of the top 100m of the formation have been secondarily cemented by silica. Where such cement is abundant, the relief is stronger. These cemented sandstones are very indurated and have a very low hydraulic conductivity (Butcher et al. 2003; Waugh 1970), while beneath this zone the Penrith sandstones are moderately cemented and form some of the most permeable strata of the Permo-Triassic sandstones of the Vale of Eden (Allen et al. 1997).

- The Eden Shale Formation overlies the Penrith Sandstone and consists mainly of mudstone and siltstone; sandstone, breccias and conglomerate intercalations being subordinate. Gypsum and anhydrite are present as beds, nodules, cements and veins (dissolved in places and likely to be responsible for localized high groundwater salinities). This formation is poorly permeable and acts as a confining layer capping the Penrith Sandstone.
- The St Bees Sandstone formation conformably overlies the Eden Shale Formation. The outcrop occupies the axial part of the Vale of Eden syncline. The formation consists mainly of very fine to fine-grained, indurated sandstone. Mudstone beds are generally subordinate, though increase in abundance towards the boundary with the underlying Eden Shale formation.
- The Mercia Mudstone Group is largely restricted to the Solway Basin north-west of Carlisle. Locally designed as the Stanwix Shales Formation, they typically comprise mudstone with minor sands and halite.
- The Cleveland-Armathwaite Dyke is a major Tertiary vertical igneous intrusion which cuts southeast across the Vale of Eden (figure 1). The dyke is up to 30m wide and has a significant influence on the catchment topography (low linear hills, and natural weir on the River Eden near Armathwaite). It is likely to have an impact on groundwater movement (Allen et al. 2010) and this assertion is discussed by Younger and Milne (1997).
- More than 75% of the Eden catchment bedrock geology is covered by Quaternary superficial deposits (see figure 2). Extensive areas of exposed bedrock are mainly restricted to the Lake District, the Northern Pennine escarpment and the Great Asby Scar Limestones. Nevertheless, exposed areas of sandstone (‘drift windows’) are present, mainly in the southern part of the catchment. The stratigraphy of these deposits is complex, with interdigitations of sand, gravel, silt and clay that may each develop their own piezometric level, resulting in complex perched water tables above the bedrock formations (Allen et al. 1997).

2.2 SUMMARY OF THE HYDROGEOLOGY

The Penrith and St Bees Sandstones are considered as the major aquifers in the Eden Valley. They are characterized by moderate-high permeability and porosity. While the Penrith Sandstone is characterized by both vertical and horizontal heterogeneity (in terms of cementation and grain size), the St Bees Sandstone tends to act as one aquifer. Regional groundwater flow generally appears to be dominated by intergranular flow whilst flow into boreholes is predominantly contributed by fractures (regionally, the fracture networks are not necessarily well connected) (Allen et al. 1997).

Large areas of the sandstone aquifers are covered by superficial deposits of variable lithology (from clay to gravel) and thickness (up to 30m in the northern part of the Eden catchment). These must have a significant impact on recharge and its distribution (Butcher et al. 2006).

The limestones within the Yoredale Group and the Great Scar Limestone Group have undoubted fracture permeability as evidenced by the surface karstic features such as swallow holes, clints and grykes limestone pavements at Great Asby and Orton.

The principal aquifer types within the Eden catchment are:

- Unconfined sandstone with no, or little, drift cover.

- Unconfined sandstone with drift more than 5m thick and an unsaturated zone within the sandstone.
- Confined sandstone, showing a groundwater level that fluctuates within the overlying superficial deposits.
- Limestone exhibiting significant fracture flow, with potentially solution enlarged fractures.

The River flow in the Eden catchment is derived from surface water flowing from adjacent uplands (Carboniferous Limestone and older formations), direct runoff within the Vale of Eden and base flow contribution from the Permo-Triassic sandstones and other aquifers.

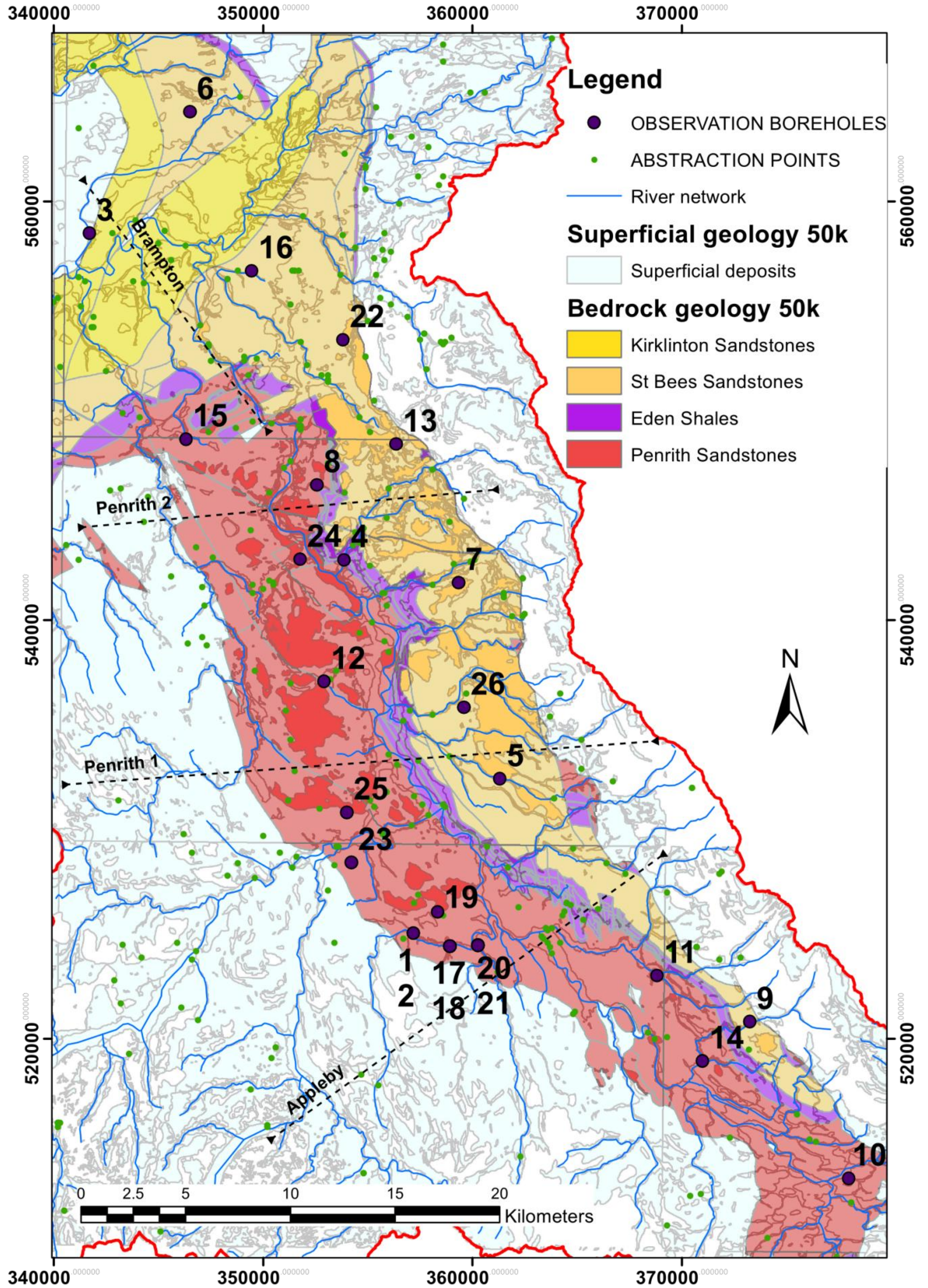


Figure 2 Simplified bedrock geology and occurrence of superficial deposits surrounding the boreholes; position of the cross sections presented in Figure 3. BGS © NERC. River network data from CEH, © NERC. © Crown Copyright

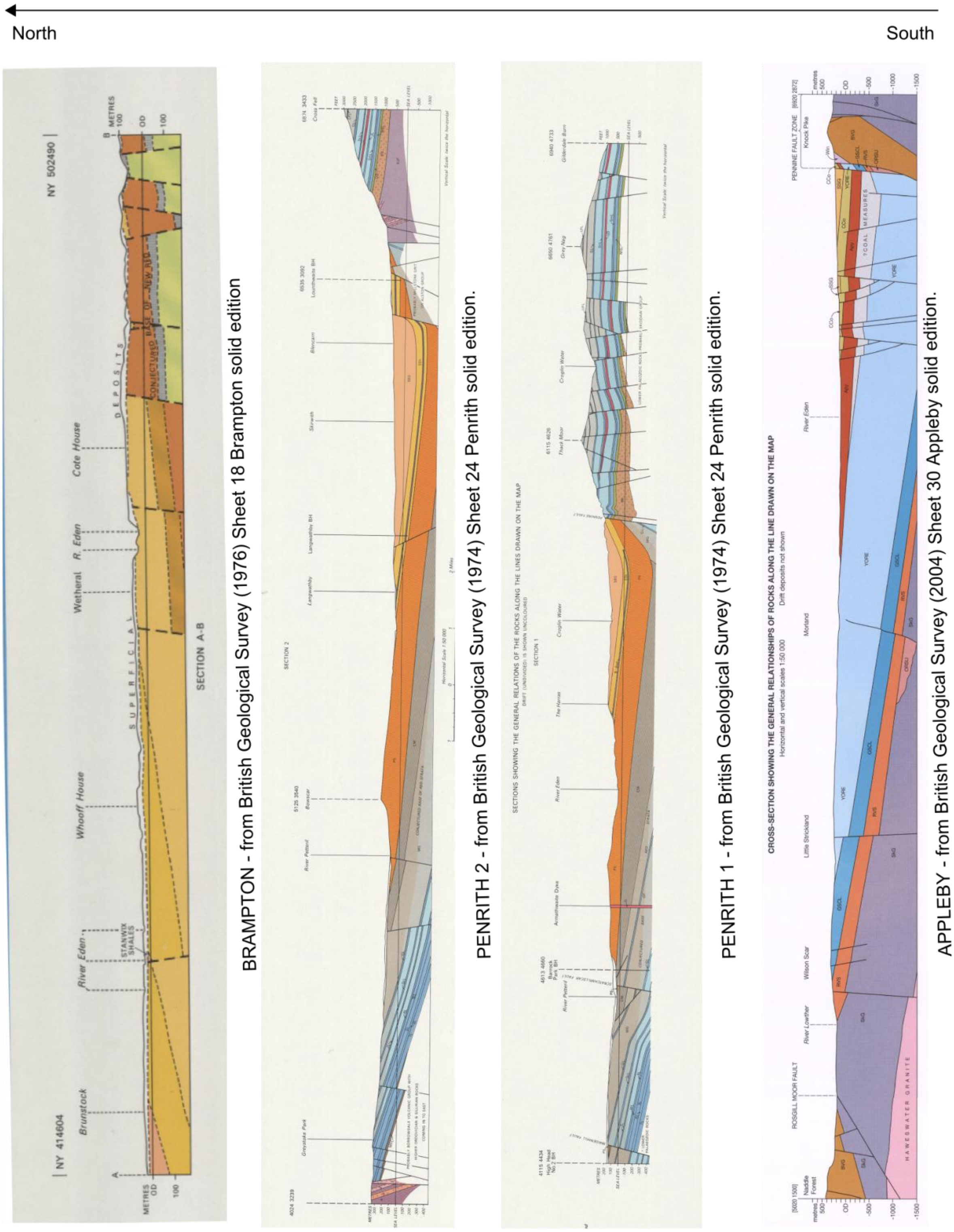


Figure 3 Geological cross sections in the Eden Valley catchment (from the South to the North); the position and orientation of each cross section (Appleby, Penrith 1, Penrith 2 and Brampton) is indicated in Figure 2. BGS © NERC

3 Data and methodology

A summary description of the geological and hydrogeological setting of each borehole along with the groundwater hydrograph and its decomposition are provided in Appendix 1. Data from 26 observation boreholes (see figure 2) obtained from the Environment Agency were used for this study. The purpose for the analysis was to improve the hydrological/hydrogeological conceptual model of the Eden Valley by better understanding the groundwater level responses and the causes of these responses. Since there are very limited data concerning the hydrogeology of the Carboniferous limestones and no time series of groundwater level measurements, the analysis was restricted to the Permo-Trias aquifers.

A standard set of diagrams were produced for each borehole (see the key provided at the beginning of Appendix 1):

- General location map
- Geological map (bedrock, quaternary deposits)
- Hydrogeological domain (map, and histograms showing the characteristics of the superficial deposits 1000m and 2000m from the borehole: no superficial, High permeability or Low permeability, thin 1 to thick 3)
- Geological log

It has to be noted that inconsistencies occasionally occur between the hydrogeological domain class and the information associated to the boreholes. For example the Scaleby borehole (number 6) lies within a cell of the domain map with the code 211 denoting relatively thin superficial deposits (less than 6m), which is not consistent with the geological log indicating a till layer 13m thick. The cell size (100m x 100m) of the domain map and the uncertainties associated to data such as superficial thickness maps can be cited as potential explanations.

This information was used to provide a descriptive interpretation of the area surrounding each borehole (see the boreholes summary sheets in the Appendix 1).

Daily groundwater level time series are available from 18 boreholes for a time period between 2000 and 2012. For the remaining 6, only manual measurements (4-6 per year) are available. These hydrographs (groundwater level related to m AOD) are plotted alongside with the time series of the rainfall and an estimate of recharge (mm/day) obtained using the Eden Valley recharge model which used the BGS ZOODRM code (Mansour and Hughes, 2004). The time series from the nearest model node to the borehole location have been plotted (see Appendix 1).

In order to better assess the groundwater level responses, a time series decomposition was performed for the daily groundwater level data using the Seasonal Trend decomposition by Loess (STL) method (Cleveland et al. 1990; Shamsudduha et al. 2009). Each time series, previously processed (extraction of the longest continuous period recorded, correction and filling of short gaps using interpolation, creation of time series characterized by a period of 365 days), was decomposed using the STL decomposition method in the R statistical language as:

$$Y_t = T_t + S_t + R_t$$

Where Y_t is the groundwater level at time t, T_t is the trend component, S_t is the seasonal component representing for example the annual cycles, and R_t is an irregular (remainder) component that can be related to short term variations (an example is provided in figure 4).

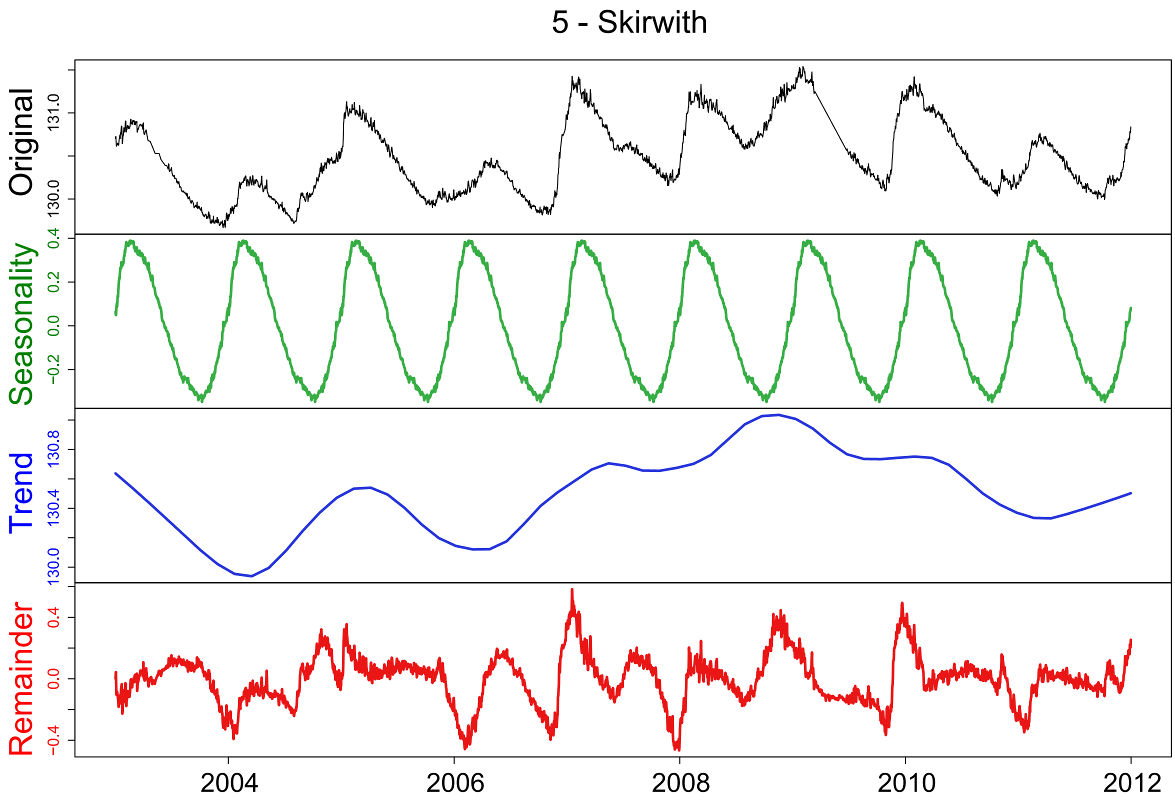


Figure 4 Example of daily groundwater level time series decomposition using the stl algorithm. The time series corresponds to the Skirwith borehole (no. 5) in the St Bees Sandstone formation.

The STL method consists of a series of smoothing operations with different moving window widths chosen to extract different frequencies within a time series, and can be regarded as an extension of classical methods for decomposing a series into its individual components. STL uses the locally weighted regression (LOESS) technique that was first proposed by Cleveland (1979) and later modified by Cleveland and Devlin (1988). The regression can be a line or a higher polynomial. The weighting reduces the influence of outlying points and is an example of robust regression. The nonparametric nature of the STL decomposition technique enables detection of nonlinear patterns in long-term trends that cannot be assessed through linear trend analyses (Shamsudduha et al. 2009).

Based on the statistical dispersion of each of the components obtained after decomposition (trend, seasonality, remainder/short term variations) compared to the statistical dispersion of the original signal (as a percentage), relationships between the hydrogeological setting and the characteristics of the hydrographs are investigated. The variance of each time series component is calculated, as well as the ratio of this variance with the variance of the original signal. For example in the case of the trend:

$$Ratio_{trend} = \frac{Variance_{trend}}{Variance_{original}}$$

The variance of each component and these ratios are provided for each continuously measured boreholes in Appendix 1.

4 Summary and conclusions

The results of the time series decomposition, relationships between the hydrogeological setting and the characteristics of the hydrographs can be summarized as:

- The boreholes situated within the St Bees Sandstone generally display hydrographs characterized by a well identified seasonality.
- The hydrographs from the boreholes in the Penrith Sandstone are in general rather more influenced by the long term trend found in the data.
- Therefore, the hydrogeological differences between the Penrith and the St Bees sandstones aquifers are reflected in the differing responses (inferred porosity, storage, hydraulic conductivity and heterogeneity) (Allen et al. 2010; Allen et al. 1997; Seymour et al. 2008; Younger and Milne 1997).

As described in section 2, the Penrith Sandstone is characterized by potentially important vertical and/or horizontal heterogeneities. The differences in groundwater level response emphasized by the results of the decomposition could be explained by such heterogeneities.

- A group of boreholes is, for example, characterized by a strong trend component (boreholes 8, 12, 19 and 24). They are located in the northern part of the Penrith Sandstone that is more likely to contain silicified beds that could prevent the aquifer to respond efficiently to localized recharge.
- The borehole at Great Musgrave (10) has an anomalous response not typical of the Penrith Sandstone, which could be explained by the presence of Brockram (see section 2). These carbonate breccias and conglomerates, containing mainly carbonate clasts and calcite cement may function like other other carbonate rocks (Ford and Williams 2007) and could have been locally dissolved and respond rapidly to local recharge events.
- The influence of stream stage via river-aquifer interaction on the hydrograph response is clearly demonstrated by the great importance of the signal remainder after removal of seasonality and long term trends. The best examples are the boreholes situated in the region of Cliburn, near to river Leith (1,2,17,18,20,21).
- The depth of the borehole has a distinct influence on the response (paired boreholes 1-2, 17-18 and 20-21) suggesting potential vertical heterogeneity mainly within the Penrith Sandstone (Seymour et al. 2008), which is consistent with presence of beds characterized by different grain size and sorting, as well a secondary cemented beds.

Other potential factors, such as the characteristics of the superficial deposits or the influence of important geological features (faults, Armathwaite dykes, relationships with the carboniferous limestone) require further investigation. Indeed a significant degree of structural control on groundwater flow has for example already been demonstrated within the Permo-Triassic sandstone aquifers of North-West England (Seymour et al. 2006). The dominant faulting appears to be able in this case to divide the aquifers into a series of interconnected blocks.

References

ALLEN DJ, BLOOMFIELD JP, ROBINSON VK, ET AL. (1997) THE PHYSICAL PROPERTIES OF MAJOR AQUIFERS IN ENGLAND AND WALES. 312.

ALLEN DJ, NEWELL AJ, BUTCHER AS (2010) PRELIMINARY REVIEW OF THE GEOLOGY AND HYDROGEOLOGY OF THE EDEN DTC SUB-CATCHMENTS. 45.

BUTCHER A, LAWRENCE A, JACKSON C, ET AL. (2006) INVESTIGATING RISING NITRATE CONCENTRATIONS IN GROUNDWATER IN THE PERMO-TRIASSIC AQUIFER, EDEN VALLEY, CUMBRIA, UK. GEOL SOC LOND SPEC PUBL 263:285–296. DOI: 10.1144/GSL.SP.2006.263.01.16

BUTCHER AS, LAWRENCE AR, JACKSON C, ET AL. (2003) INVESTIGATION OF RISING NITRATE CONCENTRATIONS IN GROUNDWATER IN THE EDEN VALLEY, CUMBRIA: SCOPING STUDY. ENVIRONMENT AGENCY NATIONAL GROUNDWATER AND CONTAMINED LAND CENTRE

CLEVELAND RB, CLEVELAND WS, MCRAE JE, TERPENNING I (1990) STL: A SEASONAL-TREND DECOMPOSITION PROCEDURE BASED ON LOESS. J OFF STAT 6:3–73.

CLEVELAND WS (1979) ROBUST LOCALLY WEIGHTED REGRESSION AND SMOOTHING SCATTERPLOTS. J AM STAT ASSOC 74:829–836. DOI: 10.1080/01621459.1979.10481038

CLEVELAND WS, DEVLIN SJ (1988) LOCALLY WEIGHTED REGRESSION: AN APPROACH TO REGRESSION ANALYSIS BY LOCAL FITTING. J AM STAT ASSOC 83:596–610. DOI: 10.1080/01621459.1988.10478639

FORD DC, WILLIAMS PW (2007) KARST HYDROGEOLOGY AND GEOMORPHOLOGY. JOHN WILEY & SONS, CHICHESTER

MANSOUR M.M. AND HUGHES A.G. 2004. USER'S MANUAL FOR THE RECHARGE MODEL ZOODRM. BGS INTERNAL REPORT.

SEYMOUR KJ, INGRAM JA, GEBBETT SJ (2006) STRUCTURAL CONTROLS ON GROUNDWATER FLOW IN THE PERMO-TRIASSIC SANDSTONES OF NW ENGLAND. GEOLOGICAL SOCIETY, LONDON, SPECIAL PUBLICATIONS 263:169–185. DOI: 10.1144/GSL.SP.2006.263.01.09

SEYMOUR K, ATKINS J, HANDOO A, ET AL. (2008) INVESTIGATION INTO GROUNDWATER-SURFACE WATER INTERACTIONS AND THE HYDRO-ECOLOGICAL IMPLICATIONS OF TWO GROUNDWATER ABSTRACTIONS IN THE RIVER LEITH CATCHMENT, A SANDSTONE DOMINATED SYSTEM IN THE EDEN VALLEY, CUMBRIA. A STUDY UNDERTAKEN FOR THE REVIEW OF CONSENTS UNDER THE HABITATS DIRECTIVE. ENVIRONMENT AGENCY

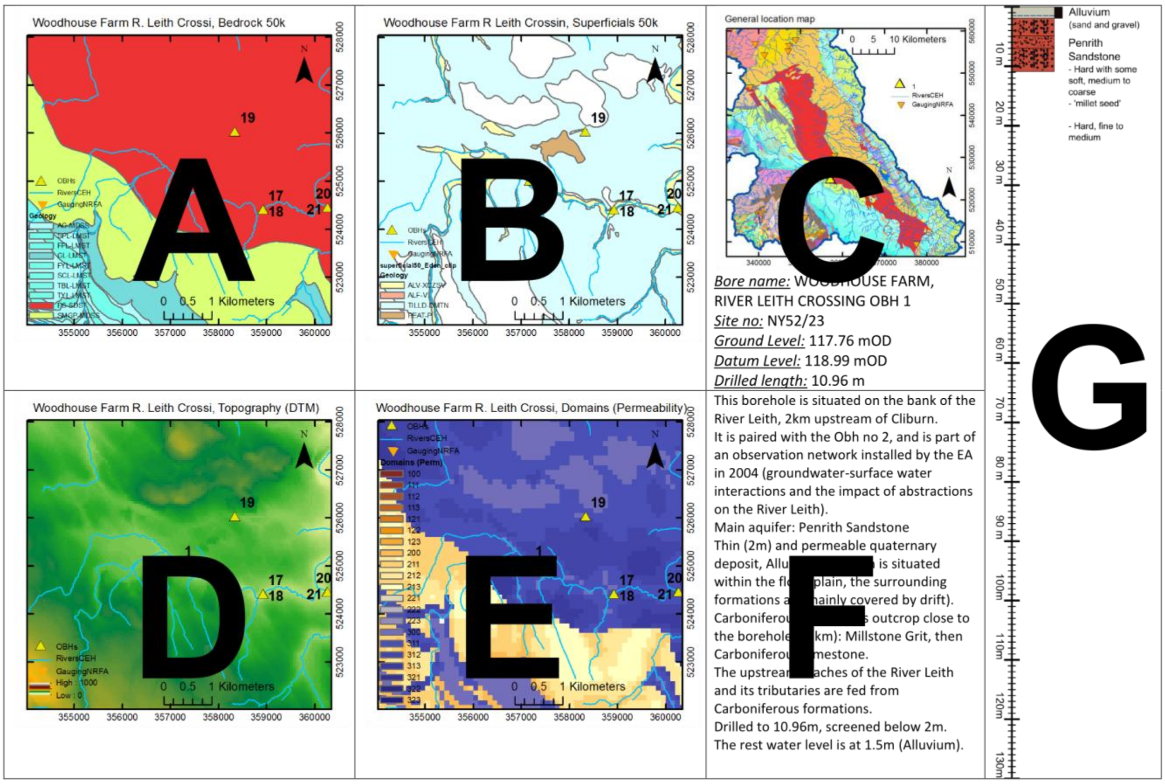
SHAMSUDDUHA M, CHANDLER RE, TAYLOR RG, AHMED KM (2009) RECENT TRENDS IN GROUNDWATER LEVELS IN A HIGHLY SEASONAL HYDROLOGICAL SYSTEM: THE GANGES-BRAHMAPUTRA-MEGHNA DELTA. HYDROL EARTH SYST SCI 13:2373–2385. DOI: 10.5194/HESS-13-2373-2009

WAUGH B (1970) PETROLOGY, PROVENANCE AND SILICA DIAGENESIS OF THE PENRITH SANDSTONE (LOWER PERMIAN) OF NORTHWEST ENGLAND. J. SEDIMENT. RES. 40:

YOUNGER PL, MILNE CA (1997) HYDROSTRATIGRAPHY AND HYDROGEOCHEMISTRY OF THE VALE OF EDEN, CUMBRIA, UK. PROC YORKS GEOL POLYTECH SOC 51:349–366. DOI: 10.1144/PYGS.51.4.349

Appendix 1 – Summary of the geology and hydrogeology of each borehole

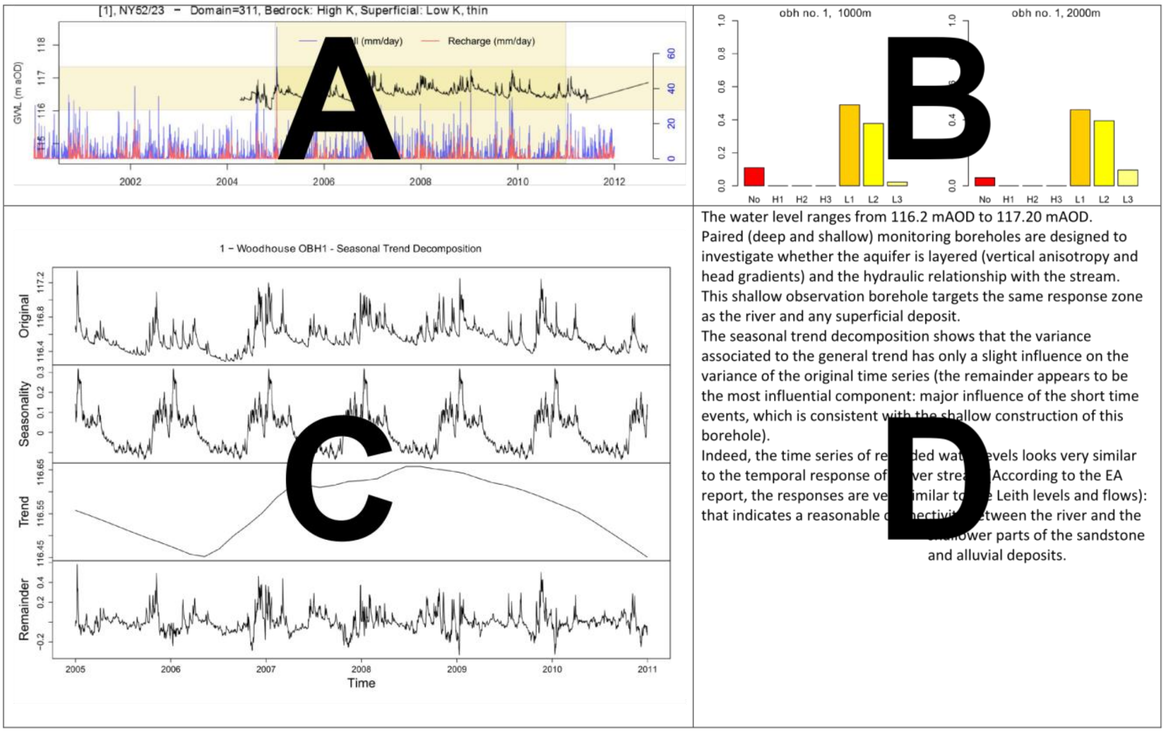
Each borehole is described using a same layout composed of two pages. The composition of the pages is described in the key provided below.



Page 1:

A. Solid geology. BGS © NERC. River network data from CEH, © NERC. © Crown Copyright
B. Superficial geology. BGS © NERC
C. General location map and geographical information. BGS © NERC
D. Topography. BGS © NERC
E. Domains map : each domain class is represented by a 3-digits code : x y z
    - x representing the relative permeability of the bedrock :
      1 : Low permeability, 2 : Intermediate permeability, 3 : High permeability
    - y representing the occurrence and permeability of the superficial deposits :
      0 : No deposits, 1 : Low permeability, 2 : High permeability
    - z representing the relative thickness of the superficial deposits
      1 : 0 – 6.3m, 2 : 6.3 – 19m, 3 : > 19m

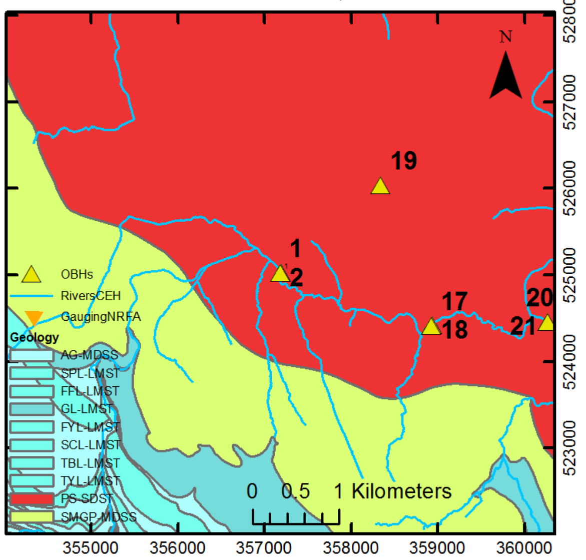
F. Text : description of the general geographical and geological setting
G. Geological log



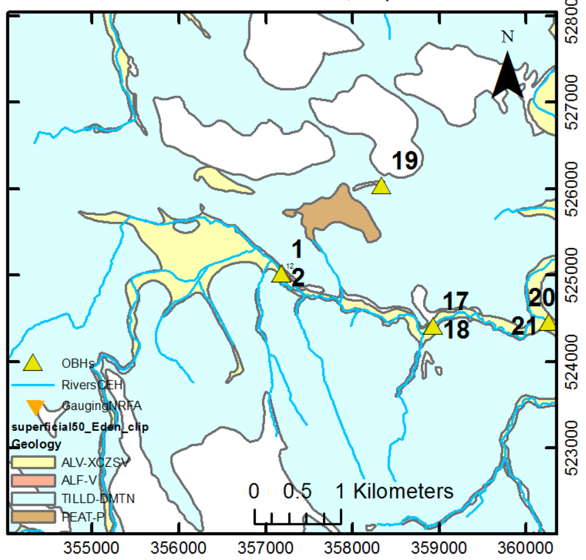
Page 2:

A. Groundwater level hydrograph, alongside with rainfall and recharge time series associated to the area containing the borehole
B. Histogram showing the characteristics of the superficial deposits 1000m and 2000m from the borehole
    - No : no superficial deposit
    - H : high permeability superficial deposits, with increasing thickness (1-3)
    - L : low permeability superficial deposits, with increasing thickness (1-3)
C. Time series decomposition between Seasonality, trend and remainder (only daily time series)
D. Text : interpretation of the hydrograph and the results of the decomposition

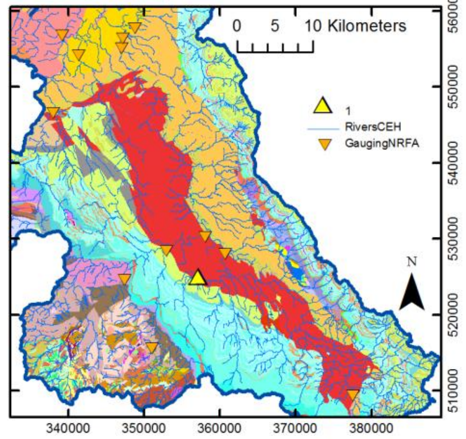
Woodhouse Farm R. Leith Crossi, Bedrock 50k

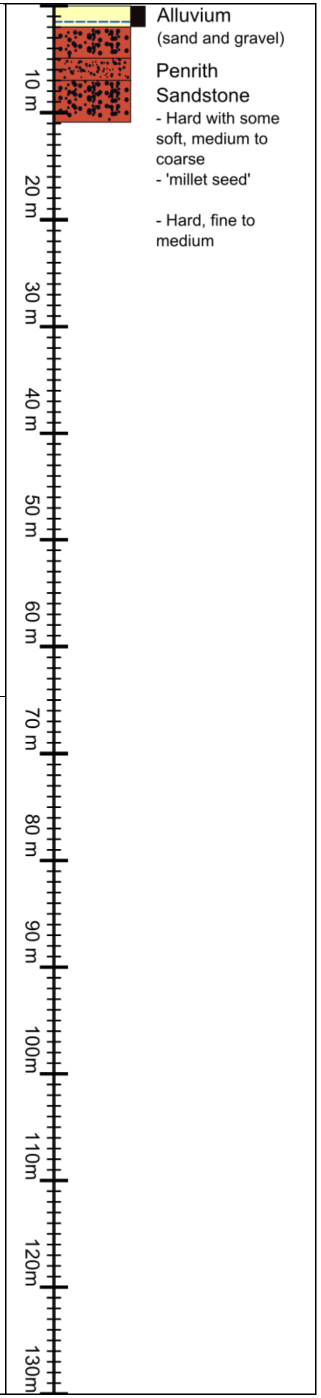


Woodhouse Farm R Leith Crossin, Superficials 50k



General location map





Bore name: WOODHOUSE FARM, RIVER LEITH CROSSING OBH 1

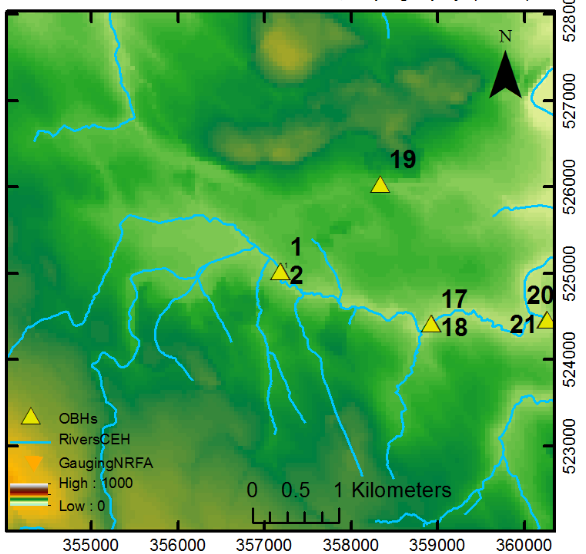
Site no: NY52/23

Ground Level: 117.76 m AOD

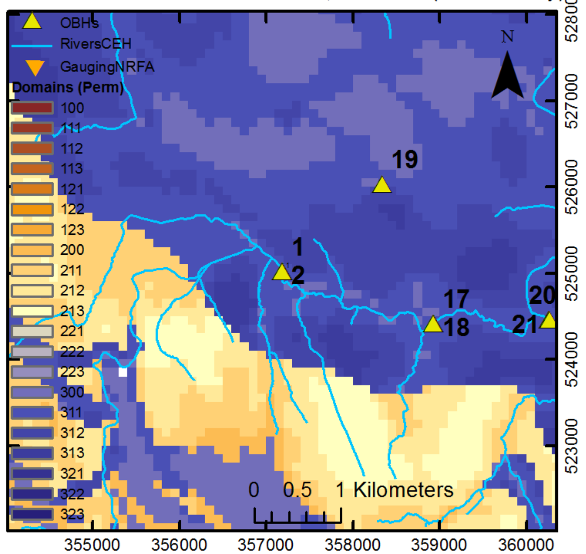
Datum Level: 118.99 m AOD

Drilled depth: 10.96 m

Woodhouse Farm R. Leith Crossi, Topography (DTM)



Woodhouse Farm R. Leith Crossi, Domains (Permeability)



This borehole is situated on the bank of the River Leith, 2km upstream of Cliburn. It is paired with the Obh no 2, and is part of an observation network installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith).

Main aquifer: Penrith Sandstone overlain by 2m of permeable sand and gravel Alluvium (the Obh is situated within the flood plain while the bedrock farer are mainly covered by till).

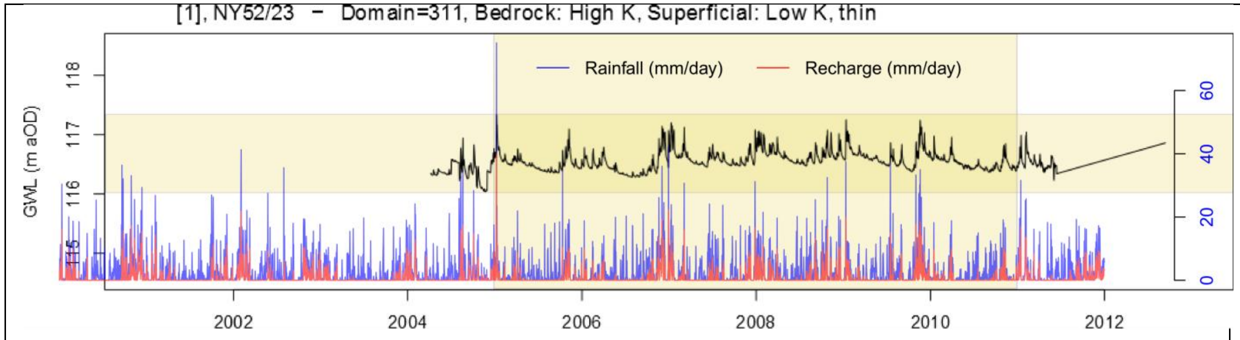
Carboniferous Millstone Grit outcrops less than 1 km from the borehole.

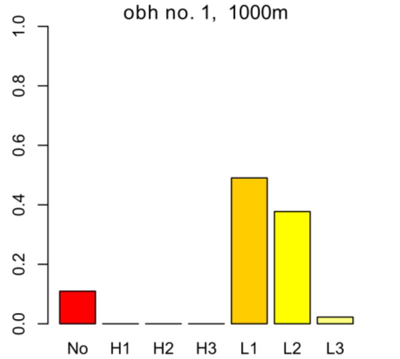
The upstream reaches of the River Leith and its tributaries are fed from Carboniferous formations.

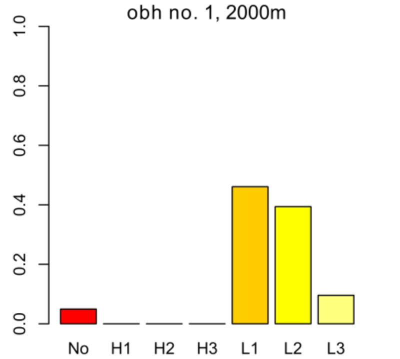
Drilled to 10.96m, screened below 2m.

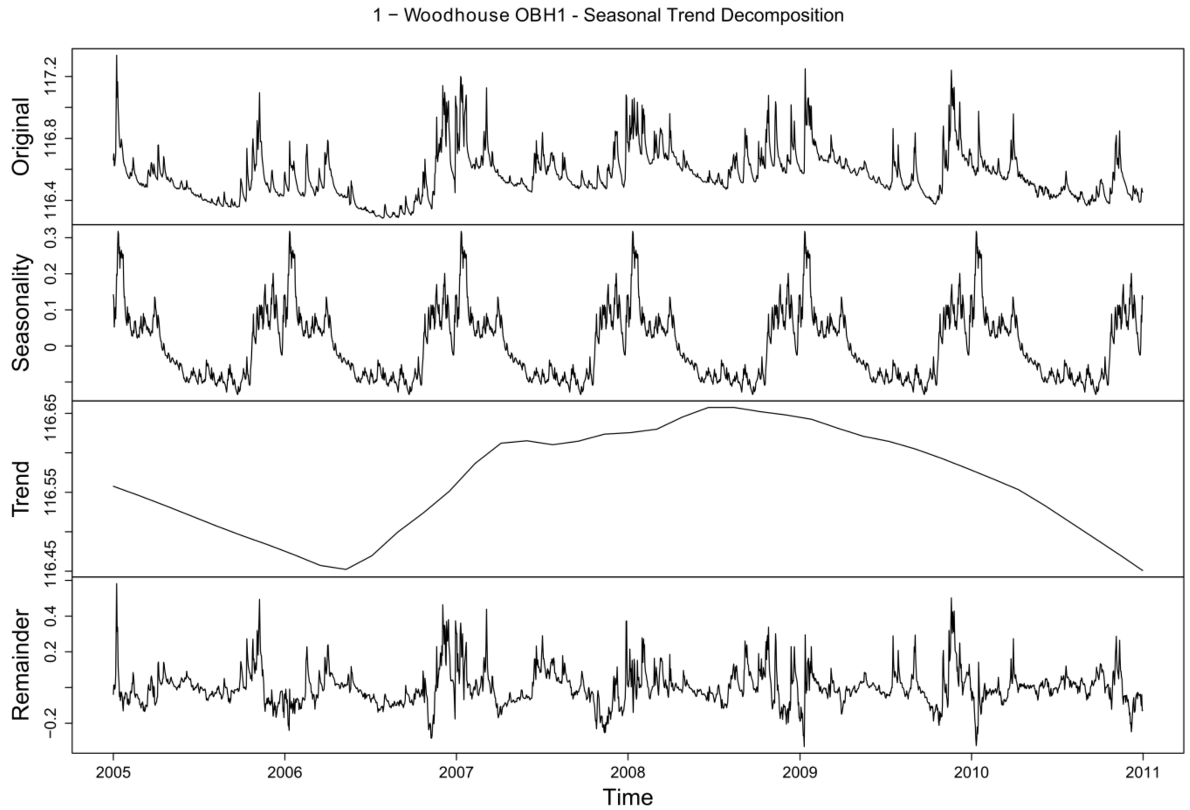
The rest water level is at 1.5m below the ground level (Alluvium).

1 – Cilburn Woodhouse farm (shallow) – Continuous recording









The water level ranges from 116.2 m AOD to 117.2 m AOD.

Paired (deep and shallow) monitoring boreholes are designed to investigate whether the aquifer is layered (vertical heterogeneity producing head gradients) and the hydraulic relationship with the stream.

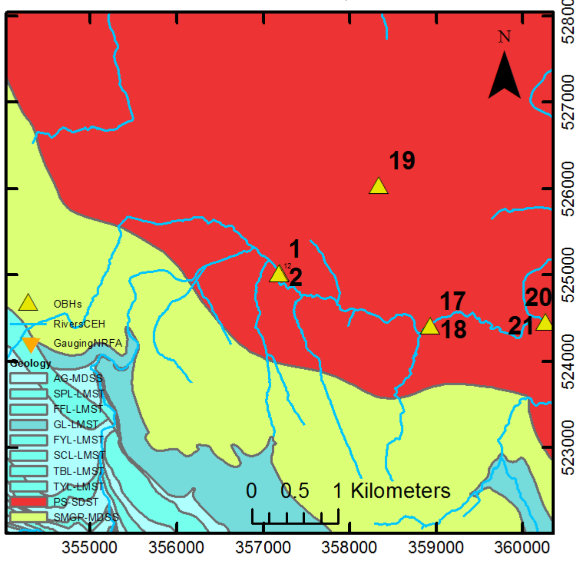
This shallow observation borehole targets the same response zone as the river and any superficial deposits.

The seasonal trend decomposition shows that the variance associated to the general trend (19.4% of the original variance) has only a slight influence on the variance of the original time series. The remainder (49.5%) appears to be the most influential component indicating that the river is likely to be the major control on the Obh heads. The water level record looks very similar to the river hydrograph (According to the EA report, the responses are very similar to the Leith levels and flows): that indicates a reasonable connectivity between the river and the shallower parts of the sandstone and alluvial deposits.

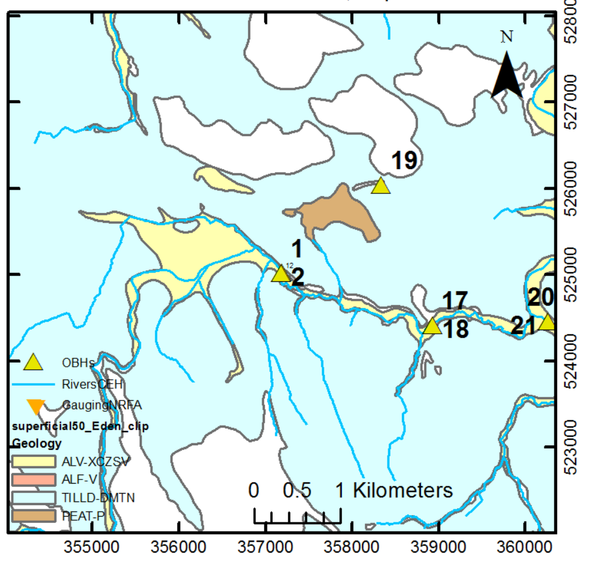
	Season.	Trend	Rem.	Original
Variance	0.0076	0.0052	0.0133	0.0270
Ratio (%)	28.1	19.4	49.5	100

1 – Cilburn Woodhouse farm (shallow) – Continuous recording

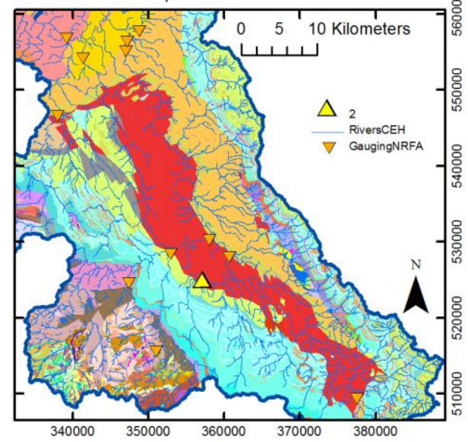
Woodhouse Farm R Leith Crossin, Bedrock 50k

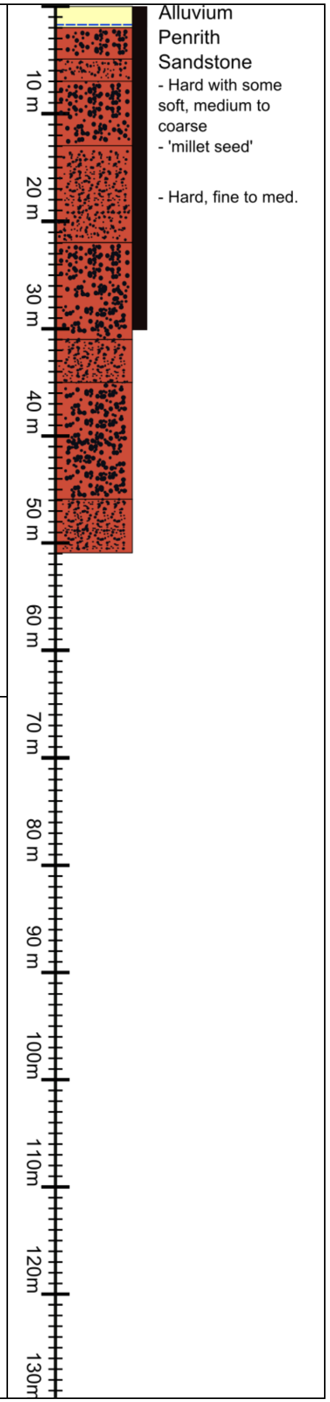


Woodhouse Farm R Leith Crossin, Superficials 50k



General location map





<u>*Bore name:*</u> WOODHOUSE FARM, RIVER LEITH CROSSING OBH 2

<u>*Site no:*</u> NY52/24

<u>*Ground Level:*</u> 117.72 m AOD

<u>*Datum Level:*</u> 119.03 m AOD

<u>*Drilled depth:*</u> 50.85 m

This borehole is situated on the bank of the River Leith, 2km upstream of Cliburn.

It is paired with the Obh no 1, and is part of a data collection framework installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith).

Main aquifer: Penrith Sandstone overlain by 2m of permeable sand and gravel Alluvium (the Obh is situated within the flood plain while the bedrock farer are mainly covered by till).

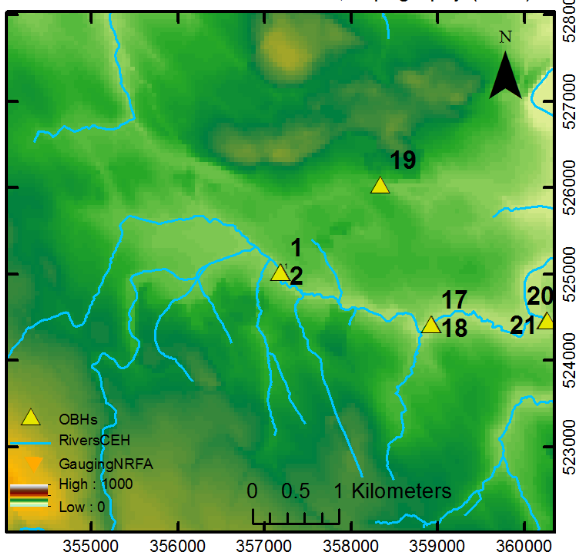
Carboniferous Millstone Grit outcrops less than 1 km from the borehole.

The upstream reaches of the River Leith and its tributaries are fed from Carboniferous formations.

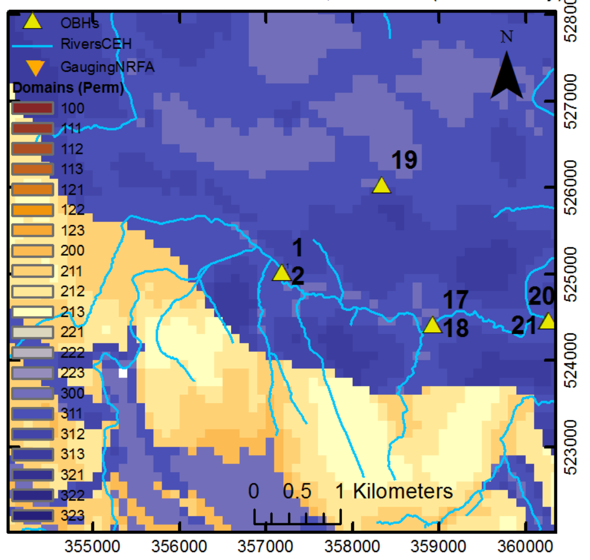
Drilled to 50.85m, screened below 30m.

The rest water level is at 2.0m below the ground level.

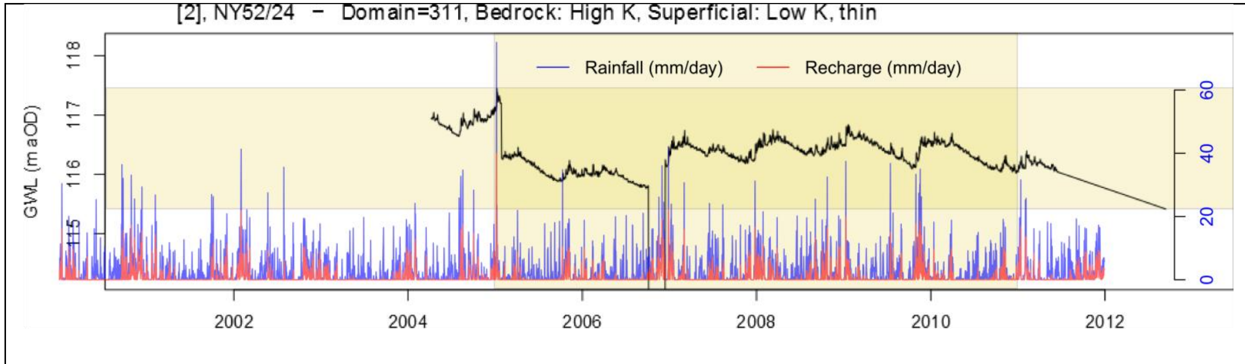
Woodhouse Farm R. Leith Crossi, Topography (DTM)

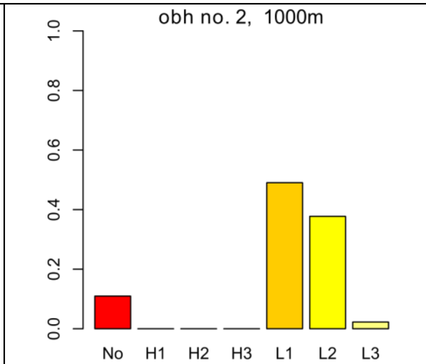


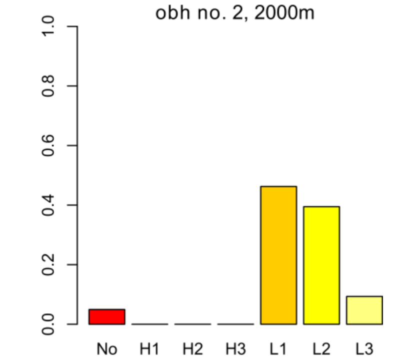
Woodhouse Farm R. Leith Crossi, Domains (Permeability)

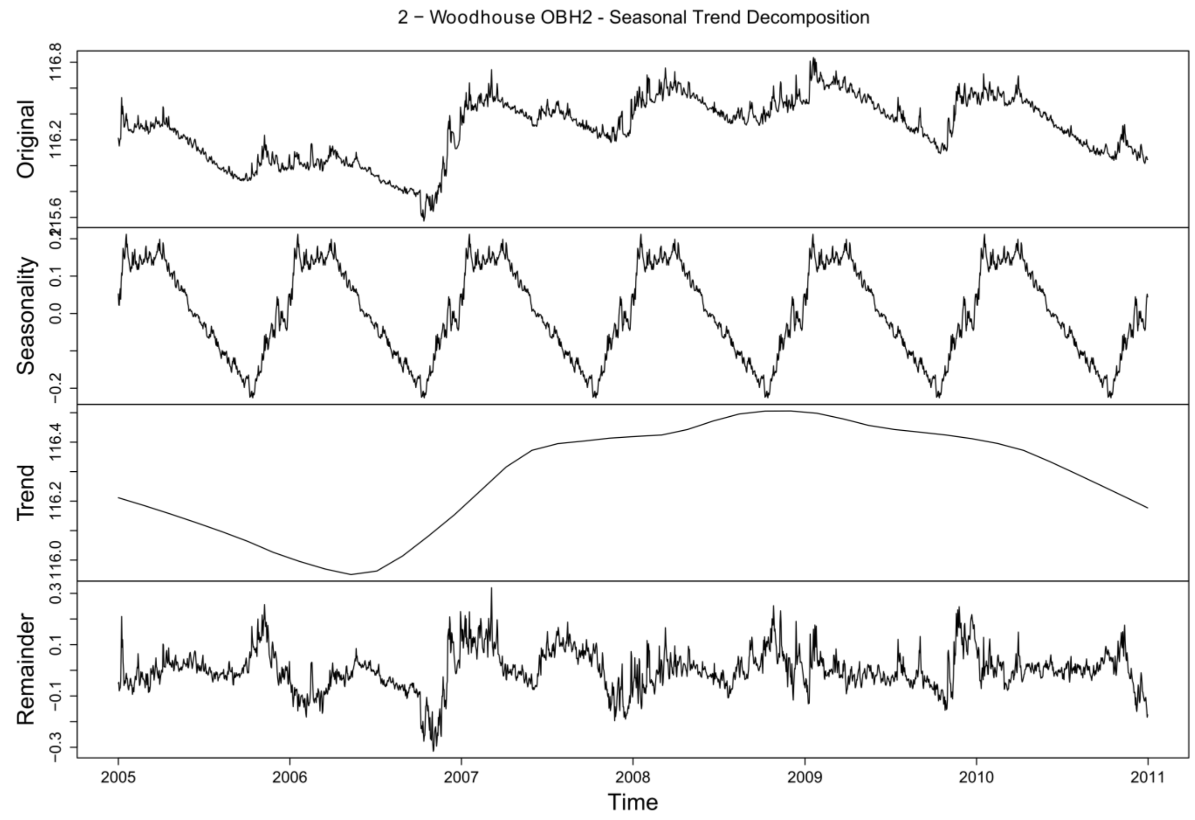


2 – Cilburn Woodhouse farm (deep) – Continuous recording









The water level ranges from 115.6 to 116.8 m AOD. which is lower than Obh 1. This indicates some degree of vertical heterogeneity within the Penrith Sandstone aquifer.

Paired (deep and shallow) monitoring boreholes are designed to investigate whether the aquifer is layered (vertical heterogeneity and head gradients) and the hydraulic relationship with the stream.

This shallow observation borehole targets the same response zone as the river and any superficial deposits, whereas, the deeper borehole is measuring heads deeper in the Penrith Sandstone.

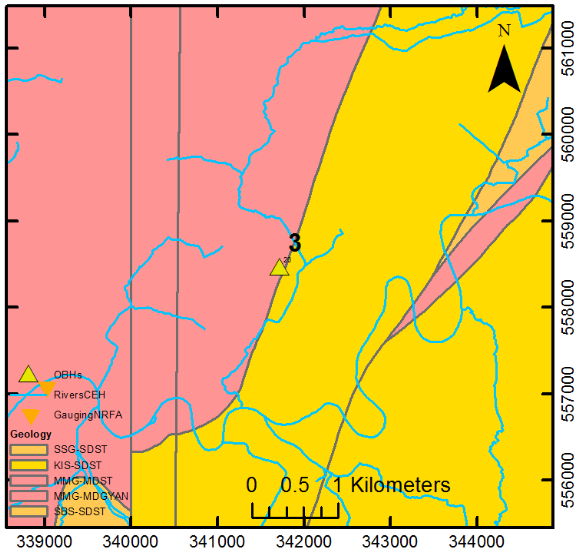
The variance associated with the general trend has the most influence on the hydrograph in this case (61.8%). According to the EA report, this piezometer responds to barometric pressure changes rather than rainfall or river events, which means that the deeper parts of the aquifer must be confined by lower permeability layers.

This vertical heterogeneity can be explained by the presence of low permeability siliceous layers and variations in grain size of the sandstone (observed in the related geological log). This is characteristic of the behaviour of the Penrith Sandstone recorded elsewhere in the Eden Valley (EA report 2008, Younger and Milne 1997, etc.)

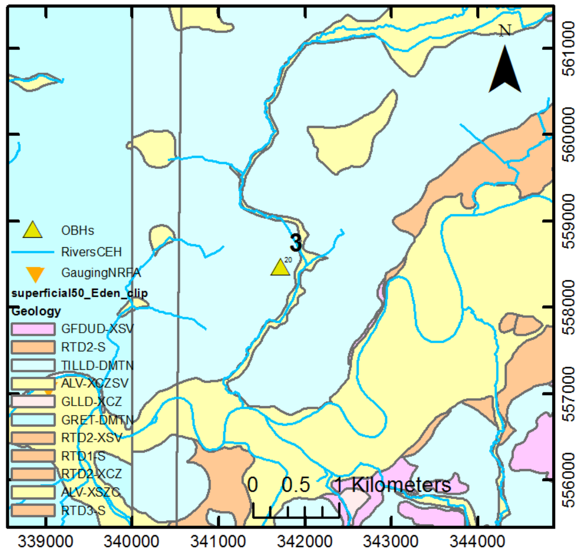
	Season.	Trend	Rem.	Original
Variance	0.0129	0.0366	0.0065	0.0592
Ratio (%)	21.7	61.8	11.0	100

2 – Cilburn Woodhouse farm (deep) – Continuous recording

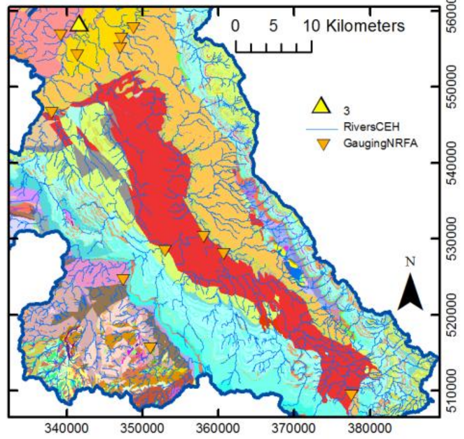
TARRABY NORTH CUMBRI, Bedrock 50k



TARRABY NORTH CUMBRI, Superficials 50k



General location map



Bore name: TARRABY, CARLISLE, BORE NO 14

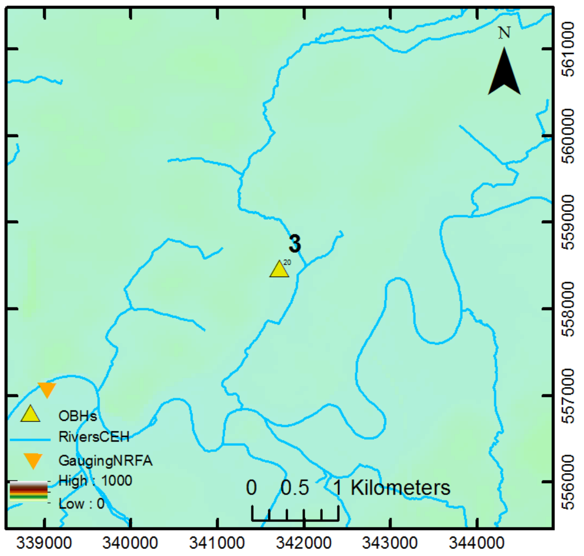
Site no: NY45/17

Ground Level (DTMnextmap): 16.8 m AOD

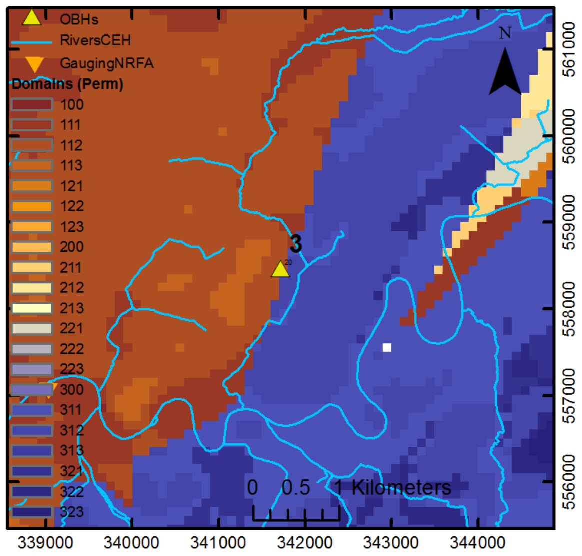
Datum Level:

Drilled depth: 110.34 m

TARRABY NORTH CUMBRI, Topography (DTM)



TARRABY NORTH CUMBRI, Domains (Permeability)

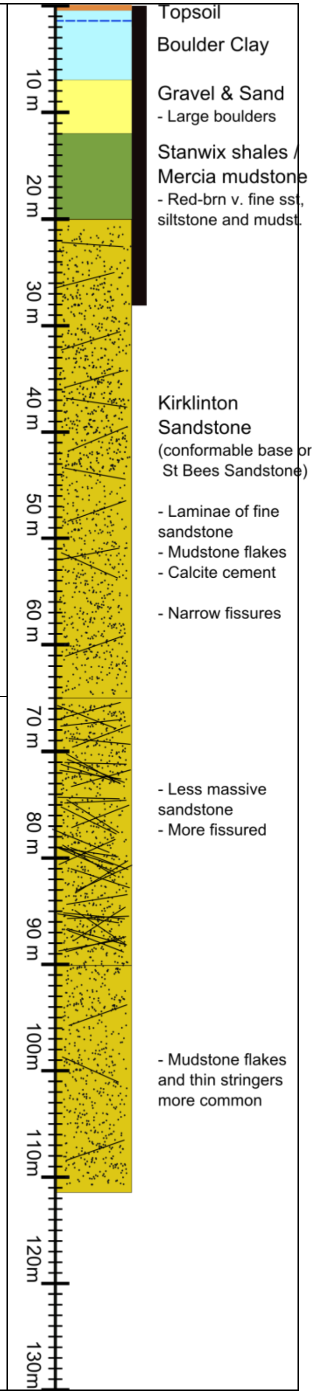


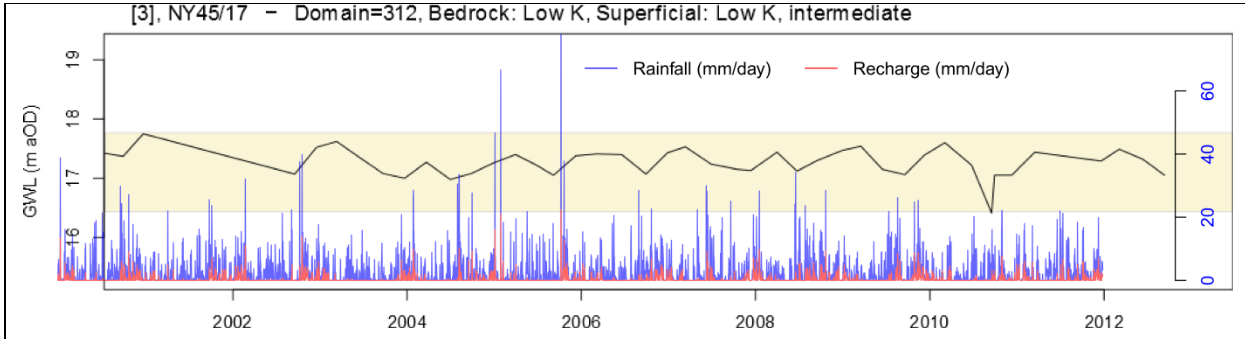
This borehole is situated North East of Carlisle, close to the Brunstock Beck.

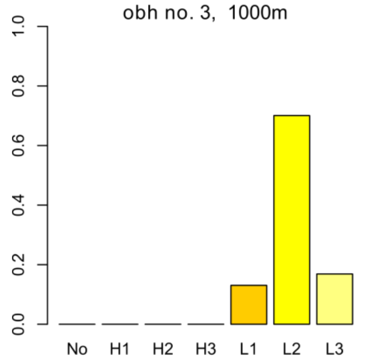
The main aquifer unit is the Kirklinton Sandstone Formation (parent unit: Sherwood Sandstone group, as is the underlying St Bees Sandstone).

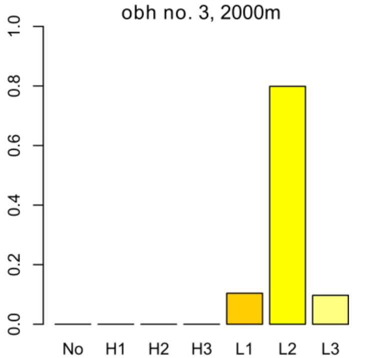
The sandstone is covered by 8m of Stanwix Shale / Mercia Mudstone and the borehole is situated approximately at the boundary between Kirklinton sst and younger Mercia mudstone.

12 m of superficial deposits are present, including sandy boulder clay at the top and gravel and sand. Boulder clay cover found over much of the area around the borehole.





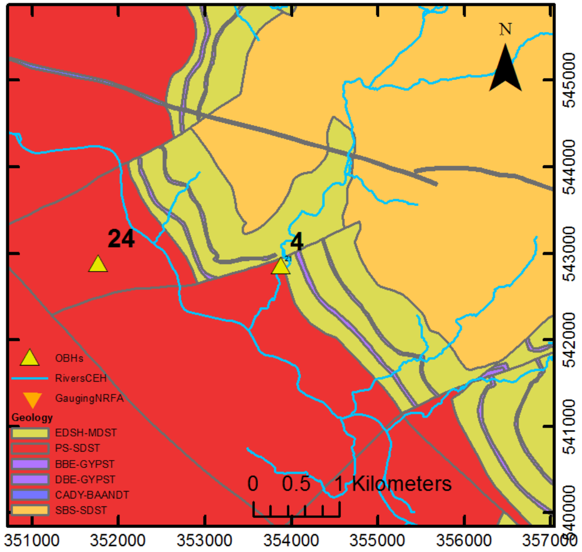




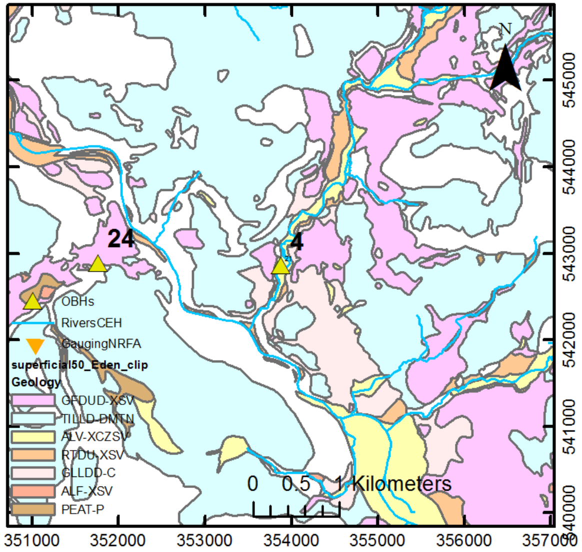
The water level ranges from 16.4 to 17.8 m AOD.
The measurements were taken approximately three or four times a year.
The areas of radius 1km and 2km around the borehole are mainly covered by relatively thick and low permeable superficial deposits (boulder clay).
The rest water level lies at 1.5m below datum at the level of the boulder clay.
The amplitude of the water level variations is generally less than 1m, except for a particularly low recorded level in 2010.

3 – Carlisle Tarraby – manually read

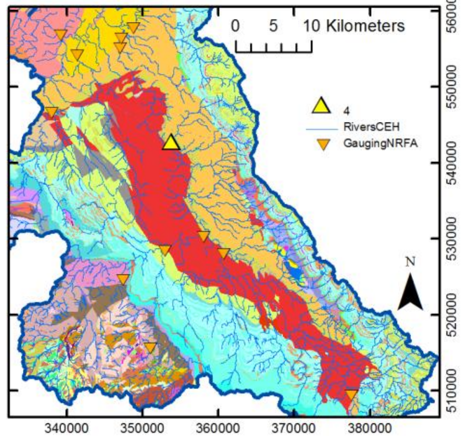
STAFFIELD NORTH CUMB, Bedrock 50k

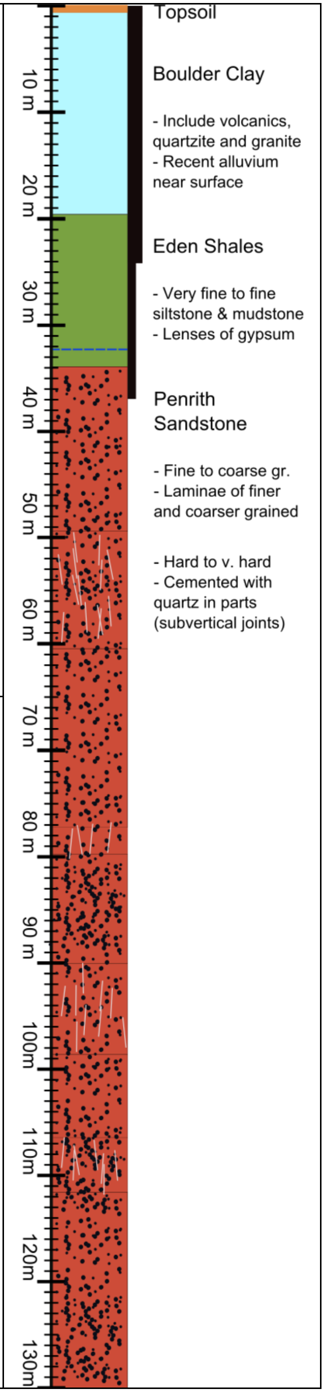


STAFFIELD NORTH CUMB, Superficials 50k



General location map





__Bore name:__ CROGLIN BRIDGE, STAFFIELD, NORTH CUMBRIA OBH. 6

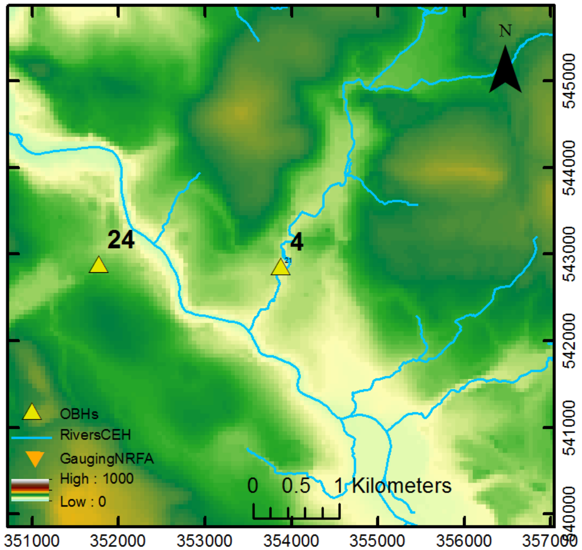
__Site no:__ NY54/11

__Ground Level:__ 96.35 m AOD

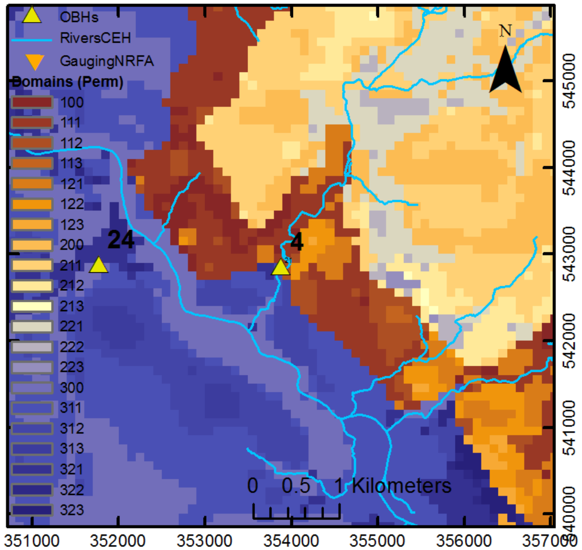
__Datum Level:__

__Drilled depth:__ 131.04 m

STAFFIELD NORTH CUMB, Topography (DTM)



STAFFIELD NORTH CUMB, Domains (Permeability)



This borehole is situated west of Staffield, near to the Croglin Low Bridge crossing Croglin Water that flows into the River Eden 1km to the south.

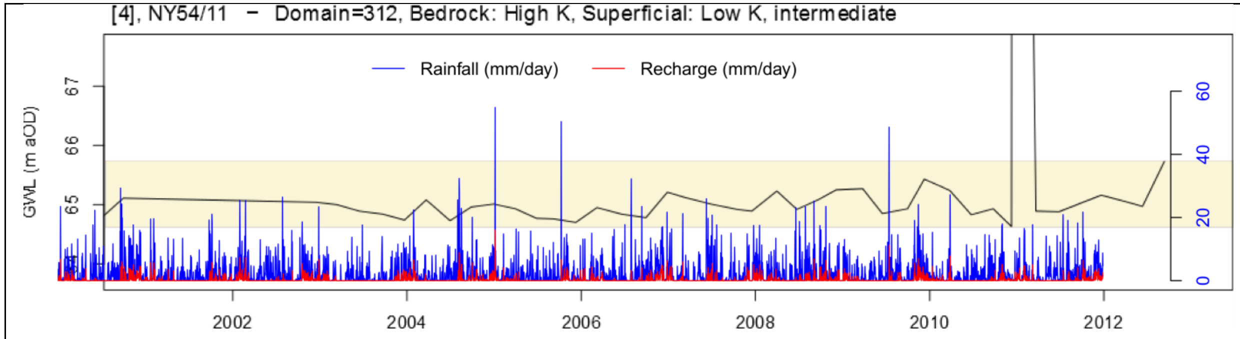
The main aquifer is the Upper Penrith Sandstone, but the borehole is cased down to 37m below datum. The sandstone is covered by 14m of Eden Shales (very fine siltstone and mudstone) and 20m of Quaternary Boulder Clay.

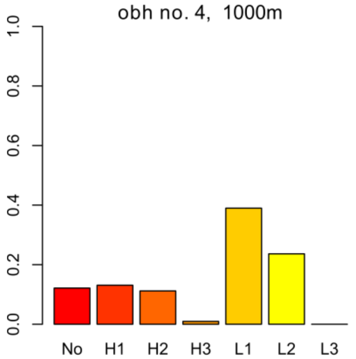
The borehole is situated close to the boundary of the Penrith Sst/Eden Shales, and 1km south of the Armathwaite Dyke.

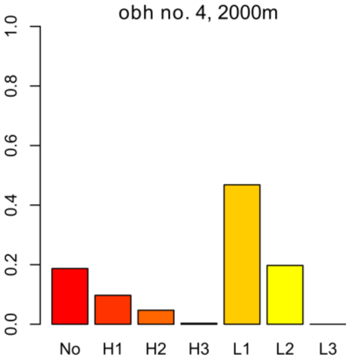
The Penrith sandstone is vertically variable with hard parts cemented with quartz.

The superficial deposits are highly variable in terms of permeability and thickness in the area around the borehole (till, alluvium, glaciofluvial).During drilling artesian flows were encountered when hole reached approximately 13m deep).

4 – Staffield, Croglin bridge – manually read



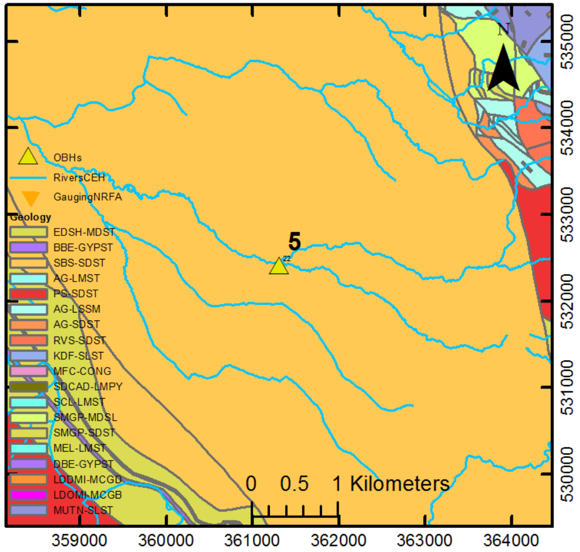




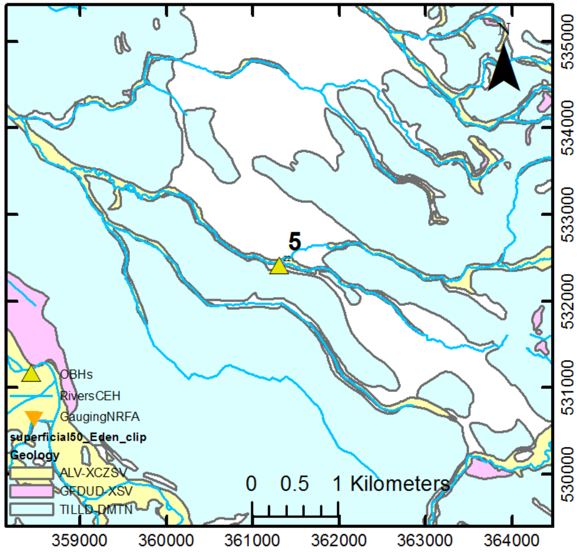
The water level ranges from 64.6 to 65.8 m AOD.
The measurements were taken approximately three or four times a year.
The areas of radius 1km and 2km around the borehole are mainly covered by superficial deposits with highly variable permeability and thickness.
The rest water level is at 32 m below datum within the basal beds of the Eden Shales.
The amplitude of the water level variations is low.

4 – Staffield, Croglin bridge – manually read

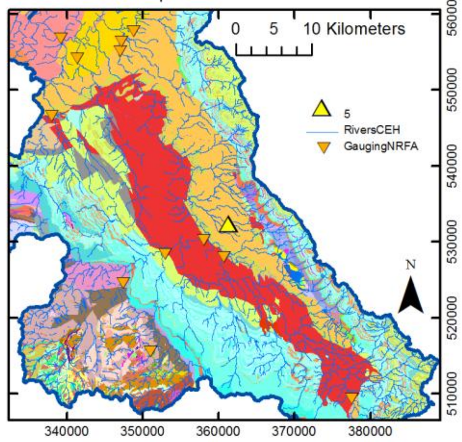
SKIRWITH, Bedrock 50k



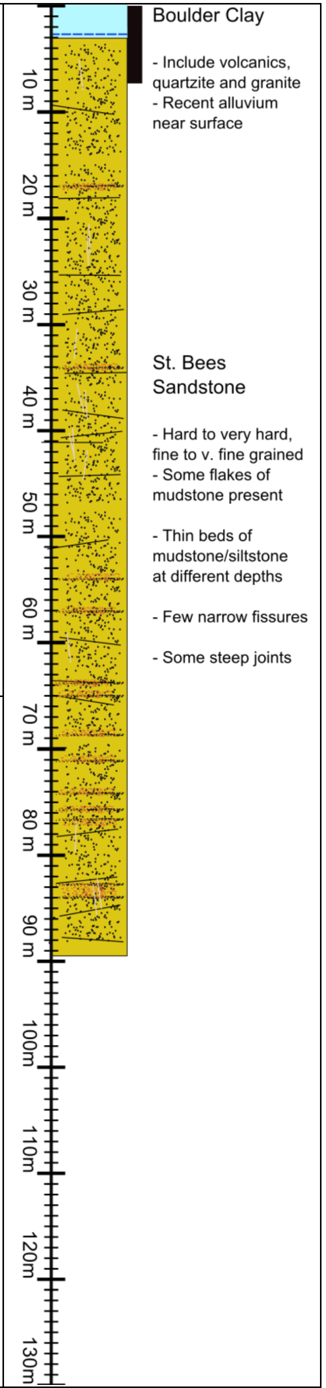
SKIRWITH, Superficials 50k



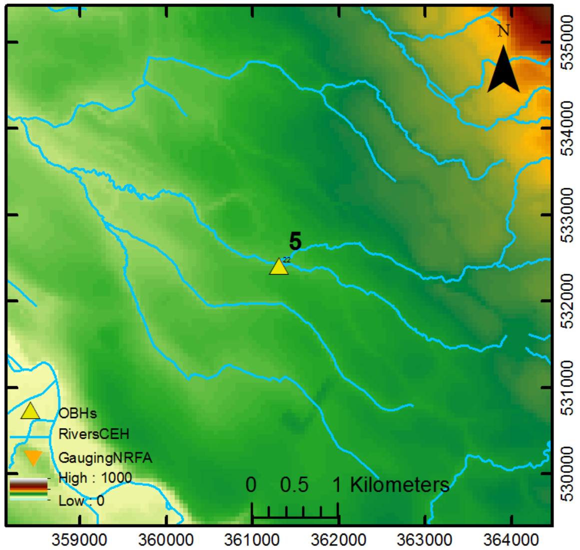
General location map



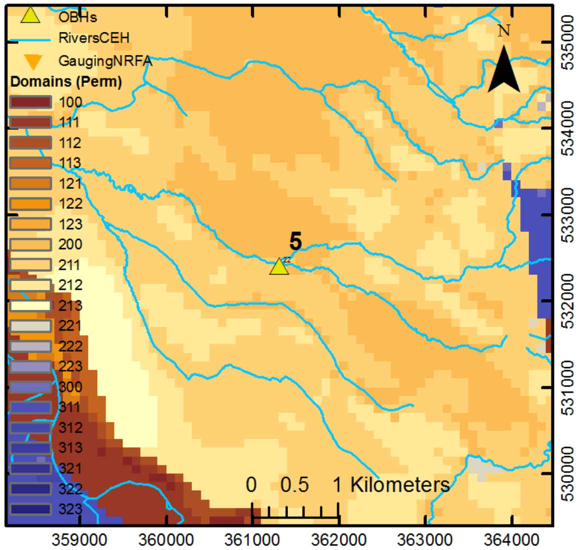
Bore name: SKIRWITH ABBEY
Site no: NY63/2
Ground Level: 133.25 m AOD
Datum Level:
Drilled depth: 89.62 m



SKIRWITH, Topography (DTM)

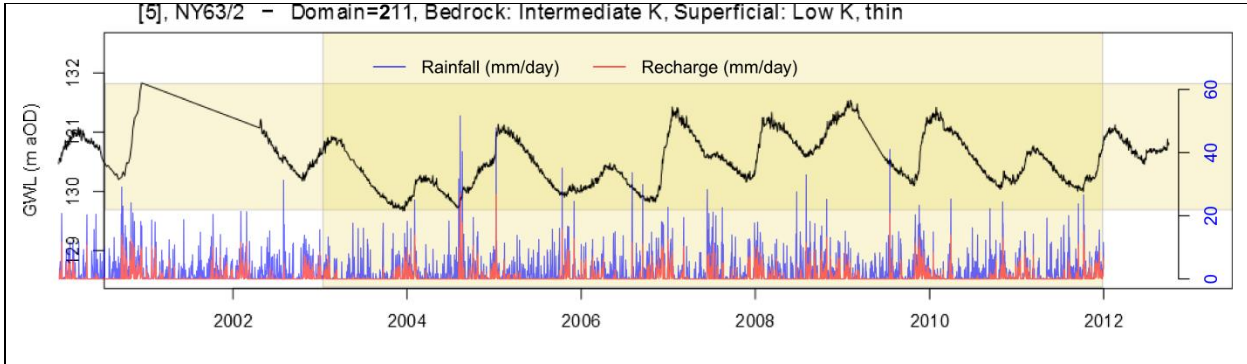


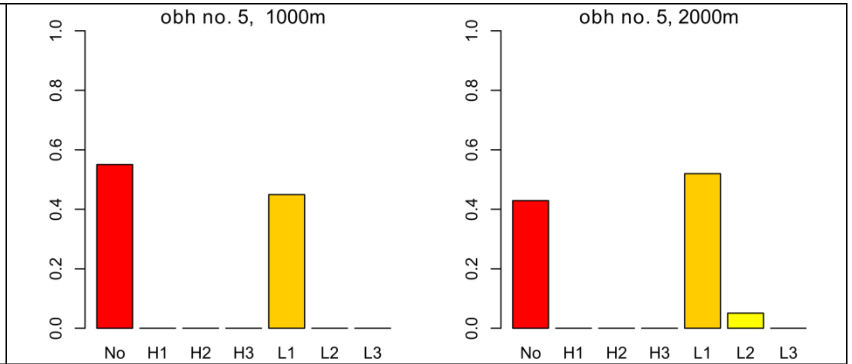
SKIRWITH, Domains (Permeability)

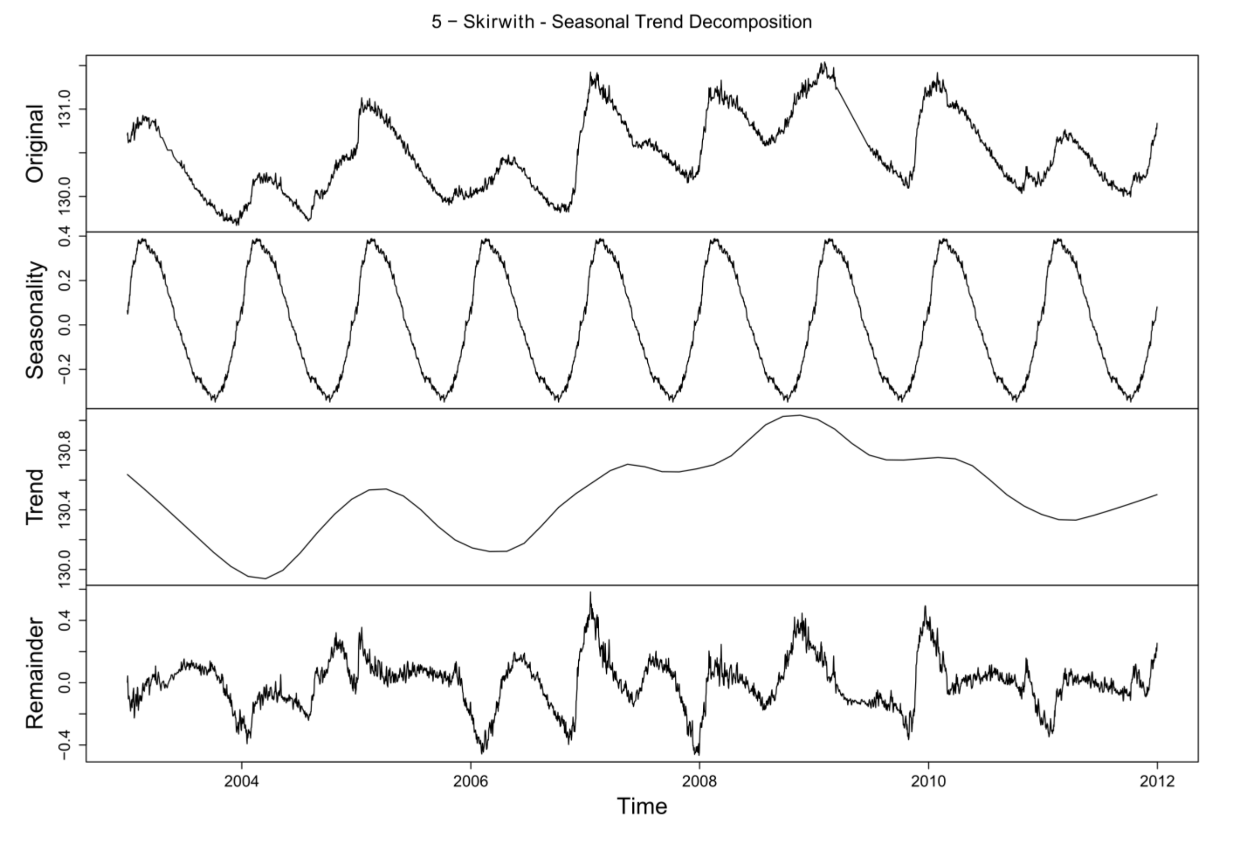


The borehole is situated west of Skirwith village, at the confluence of the Blencarn Beck with the Skirwith beck which flows from the Pennine Fells at the eastern boundary of the Eden Valley. These are underlain by Carboniferous Limestones). The main aquifer is within the St Bees Sandstone which constitutes the bedrock for an extensive area around the borehole. 3m of glacial drift (boulder clay including igneous material) are present.
The rest water level is at 2.9m, approximately coincident with the sandstone/boulder clay boundary. Approximately 50 % of the area around the borehole is made up of outcropping bedrock while the remaining 50 % is covered by a thin layer of low permeability boulder clay.

5 – Skirwith – continuous recording





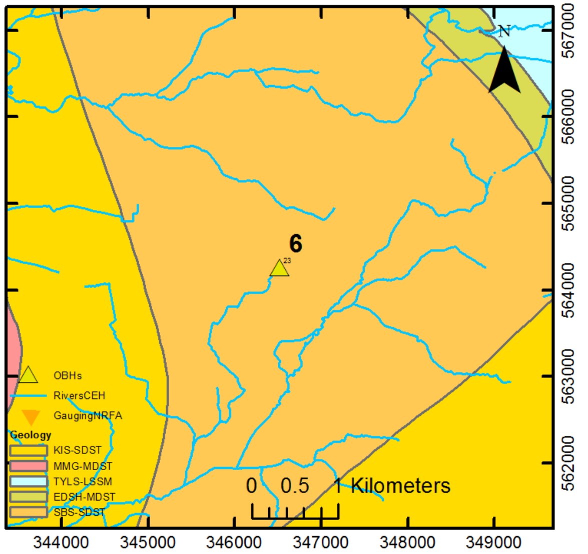


The water level ranges from 129.7 to 131.5 m AOD.
The variance associated with the general trend (41.9%) and the seasonality (34.0%) control the variance of the original signal. The short time scale events have only a small influence (13.2% of the original variance) on the overall signal.
The variation of the groundwater level is mainly seasonal with a relatively high amplitude (nearly 2m) and is only a little perturbed by small scale events. This could reflect the the greater homogeneity of the St Bees Sandstone aquifer in comparison with the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability) but the frequent fine grained mudstone laminations and beds may limit vertical hydraulic conductivity.

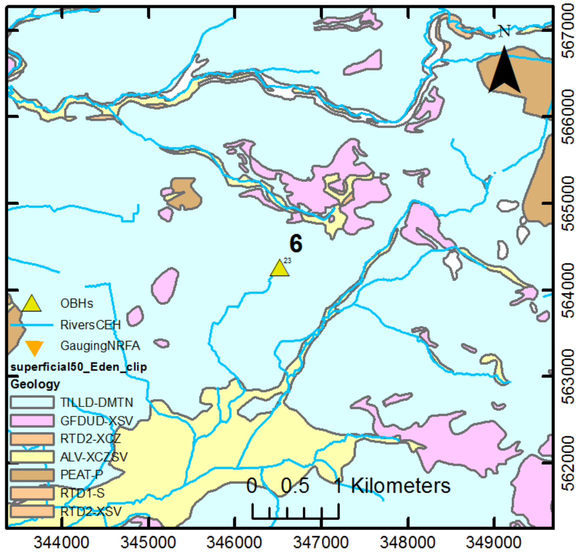
	Season.	Trend	Rem.	Original
Variance	0.0604	0.0744	0.0234	0.1775
Ratio (%)	34.0	41.9	13.2	100

5 – Skirwith – continuous recording

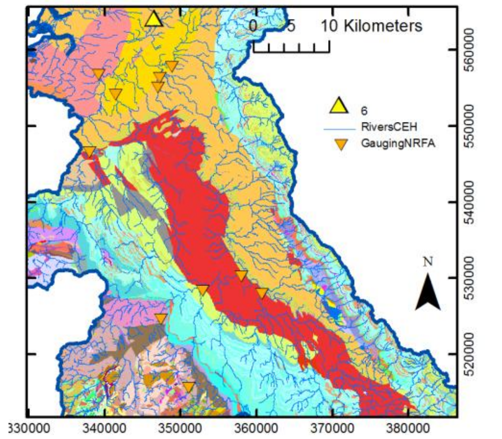
SCALEBY NORTH CUMBRI, Bedrock 50k



SCALEBY NORTH CUMBRI, Superficials 50k



General location map



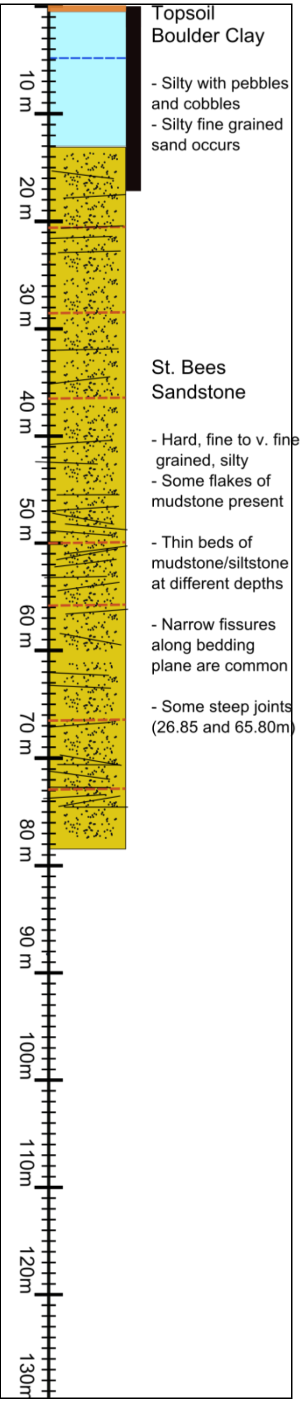
<u>Bore name:</u> HALFWAY HOUSE FARM, SCALEBY

<u>Site no:</u> NY46/3

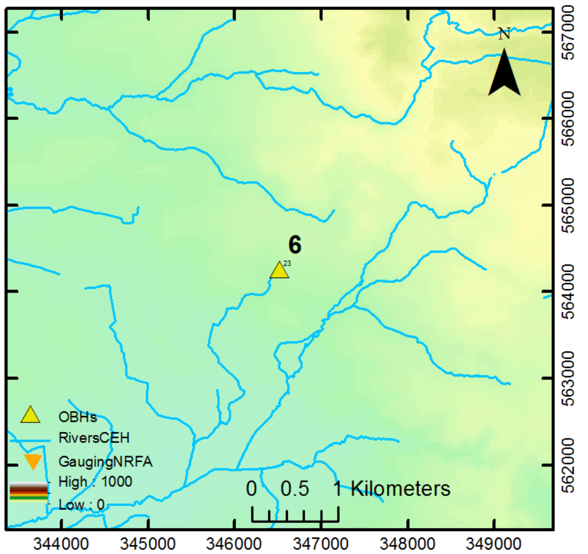
<u>Ground Level (DTMNextmap):</u> 44.8m AOD

<u>Datum Level:</u>

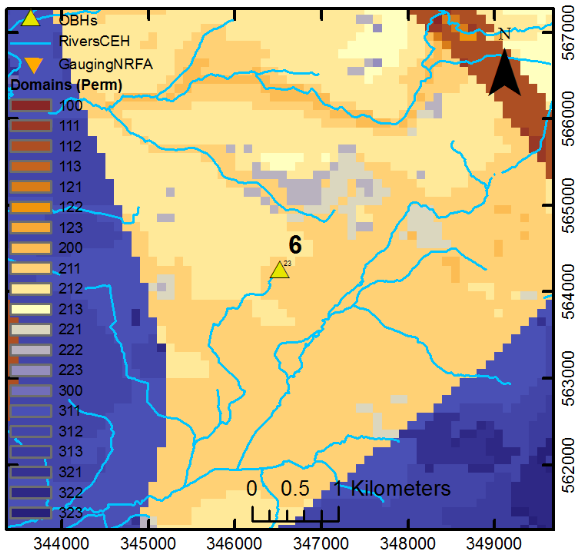
<u>Drilled length:</u> 78.33 m



SCALEBY NORTH CUMBRI, Topography (DTM)

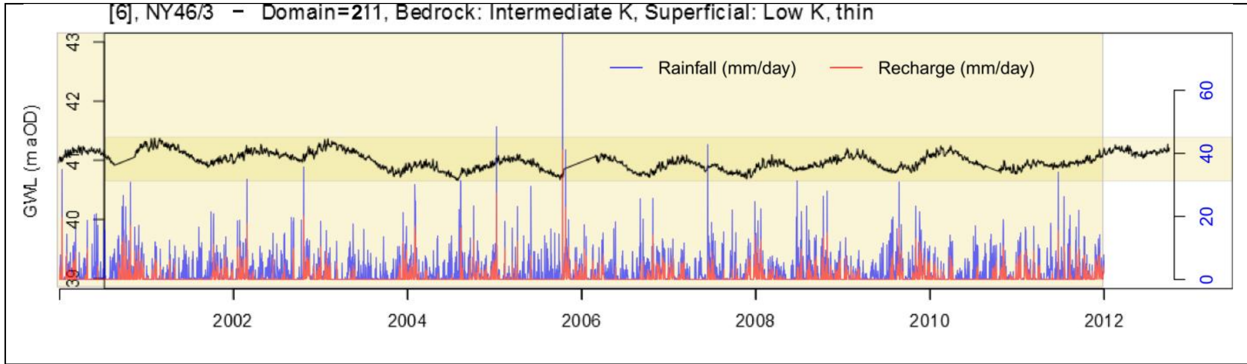


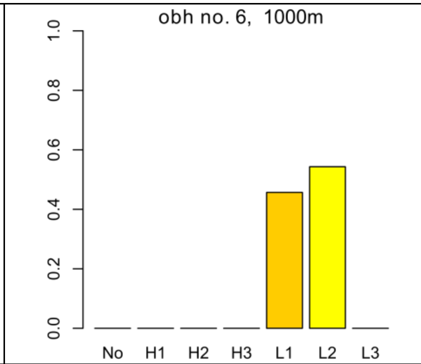
SCALEBY NORTH CUMBRI, Domains (Permeability)

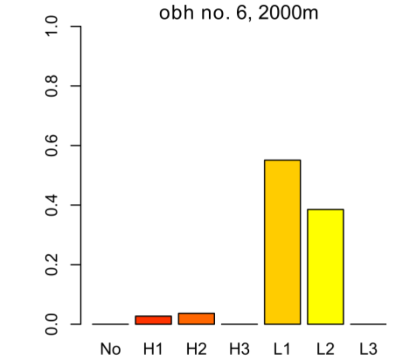


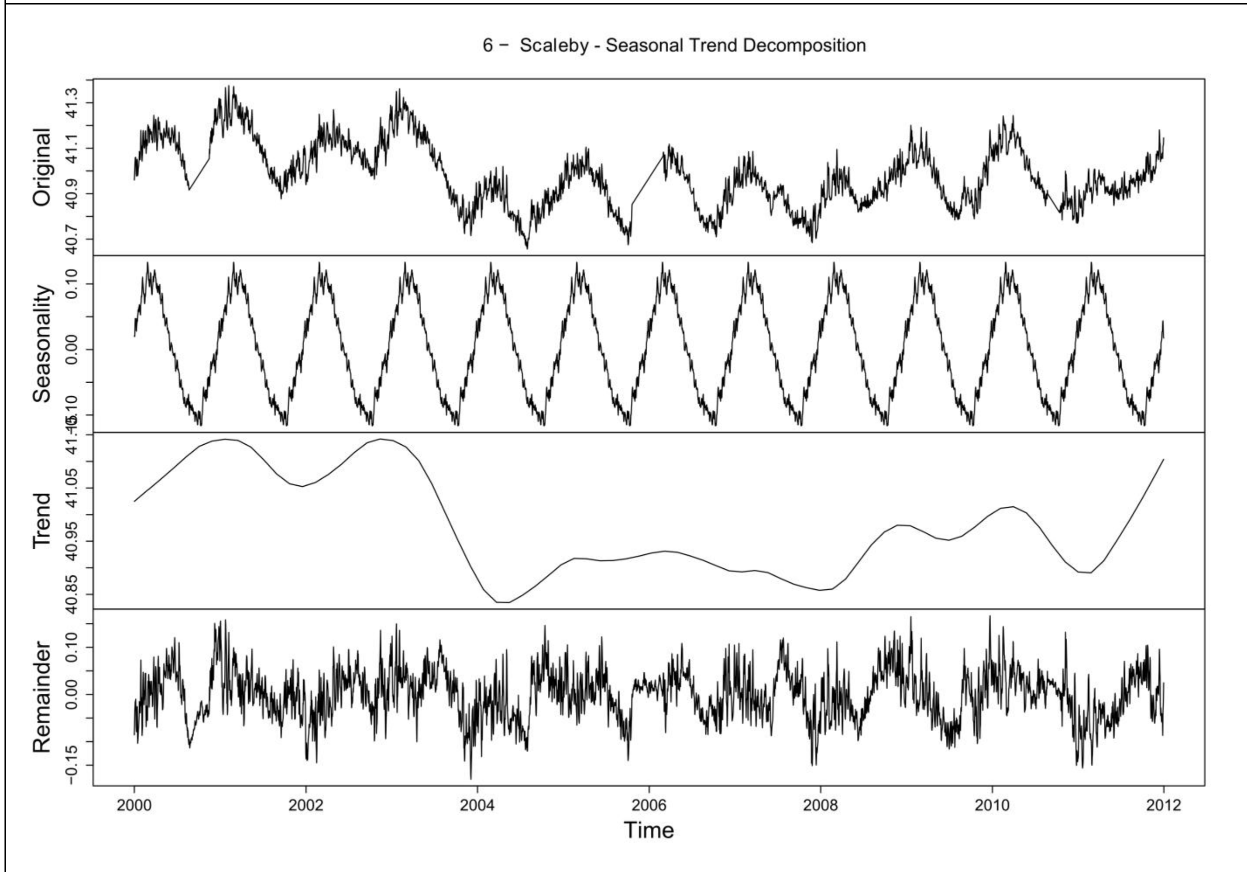
This borehole is situated 7km North East of Carlisle, close to the Scaleby village.
The main aquifer is within the St Bees Sandstone Formation (casing down to 19m below datum so below the superficial cover).
The sandstone is overlain by 13m of boulder clay.
A significant part of the area surrounding the borehole is covered with relatively thick till deposits. It has to be noted that the domain class associated to this borehole 211 denotes relatively thin superficial deposits (less than 6m), which is not consistent with the geological log. The cell size (100m) of the domain map and the uncertainties associated to data such as superficial thickness can be cited as potential explanations.
The rest water level is at 5m below datum.

6 – Scaleby – continuous recording







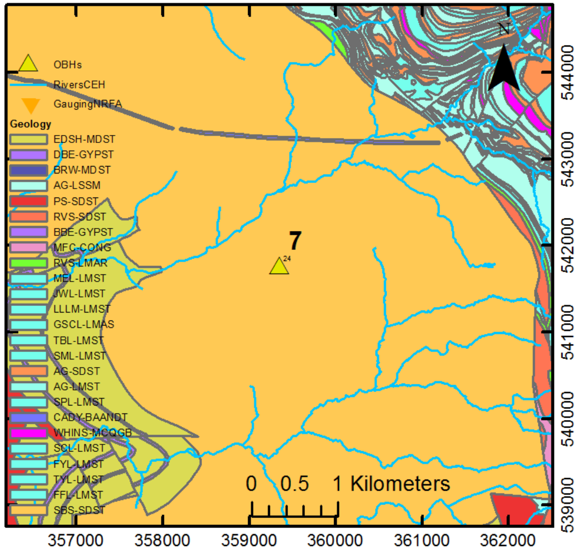


The water level ranges from 40.7 to 41.3 m AOD.
The variance associated to the general trend (45.9%) and the seasonality (29.1%) control the variance of the original signal. The influence of short time scale events has a smaller importance on the overall signal though they can be observed (more noticeable compared to the overall variance than for example the Skirwith borehole, no. 5, but could be caused by the lower seasonal amplitude). This relatively weak reaction to short time events could be related to the presence of the low permeability superficial layer that confines the underlying sandstone aquifer.
The variations of the groundwater level are mainly seasonal with a relatively small amplitude (~ 0.5m). The frequent perturbations related to small scale events can be observed but do not influence greatly the overall variation. This could reflect the great homogeneity of the St Bees Sandstone aquifer compared to the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability) and the differences in porosity and storage between both sandstone aquifers. But the frequent mud laminations and beds may limit vertical hydraulic conductivity.
However, the amplitude is clearly lower than for borehole no 5 for example (borehole located at the extreme north of the catchment).

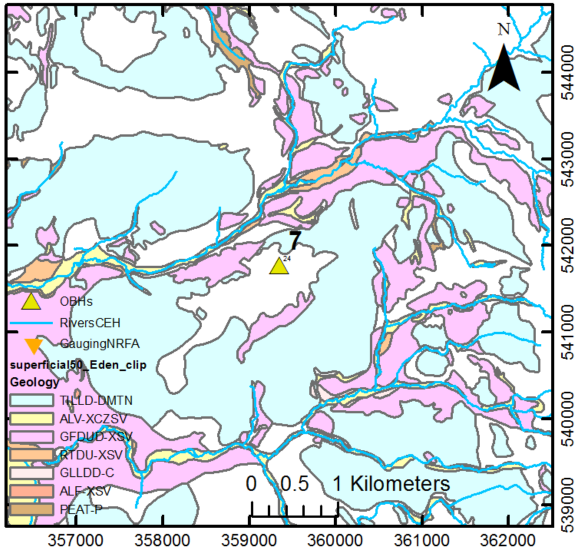
	Season.	Trend	Rem.	Original
Variance	0.0053	0.0084	0.0027	0.0183
Ratio (%)	29.1	45.9	14.9	100

6 – Scaleby – continuous recording

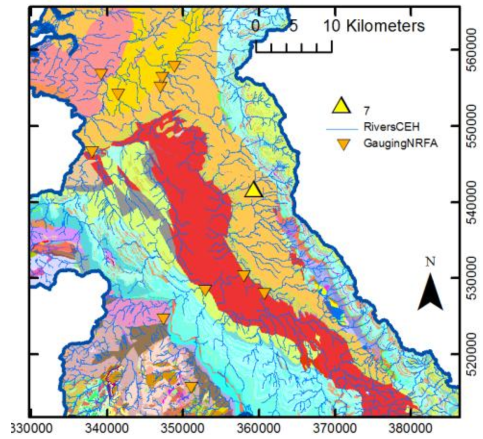
Renwick BH, Bedrock 50k



Renwick BH, Superficials 50k



General location map



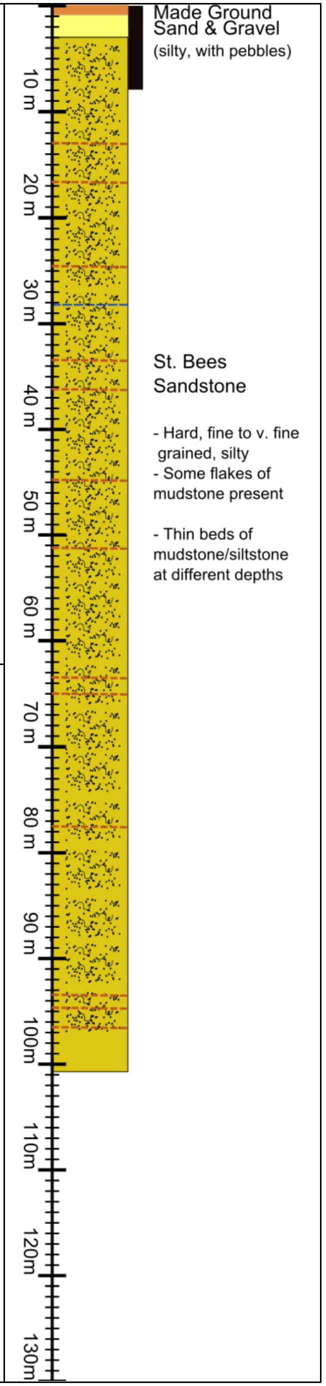
Bore name: RENWICK OBH

Site no: NY54/55

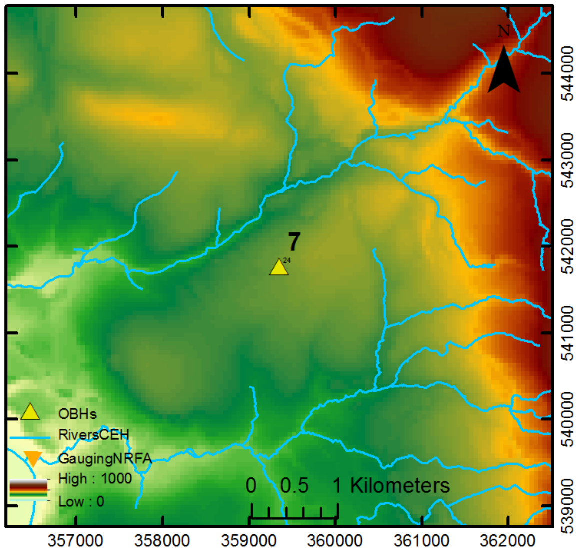
Gr. Level (DTMNextmap): 203.3m AOD

Datum Level:

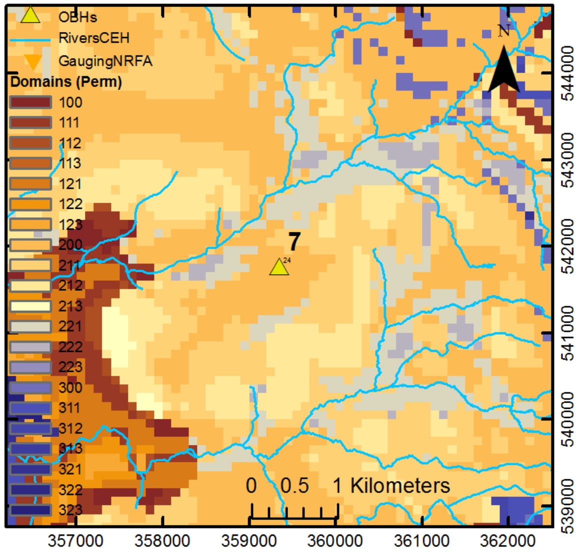
Drilled depth: 100.9 m



Renwick BH, Topography (DTM)



Renwick BH, Domains (Permeability)



The borehole is situated south to the Renwick village, 600m southeast of the Raven Beck which flows from the Pennine Fells (Eastern boundary of the Eden Valley catchment underlain by Carboniferous Limestone Formations).

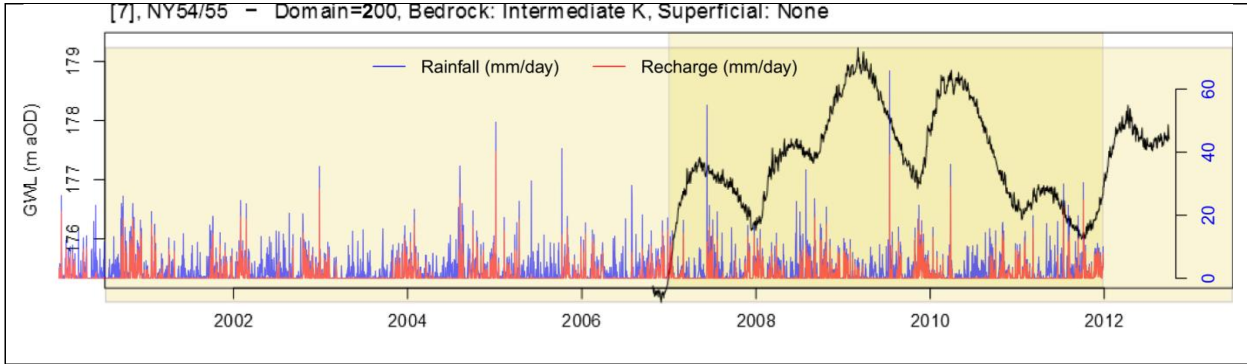
The Armathwaite Dyke lies 1.5km northward.

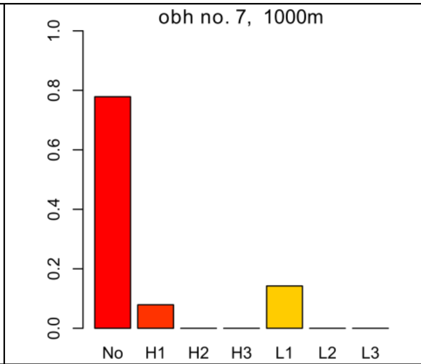
The main aquifer is within the St Bees Sandstone (which is the bedrock for a significant area around the borehole).

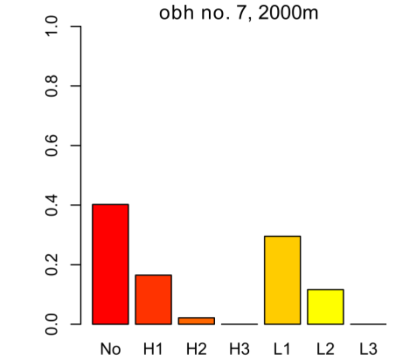
3m of unconsolidated sand and gravel are present on top of the sandstone.

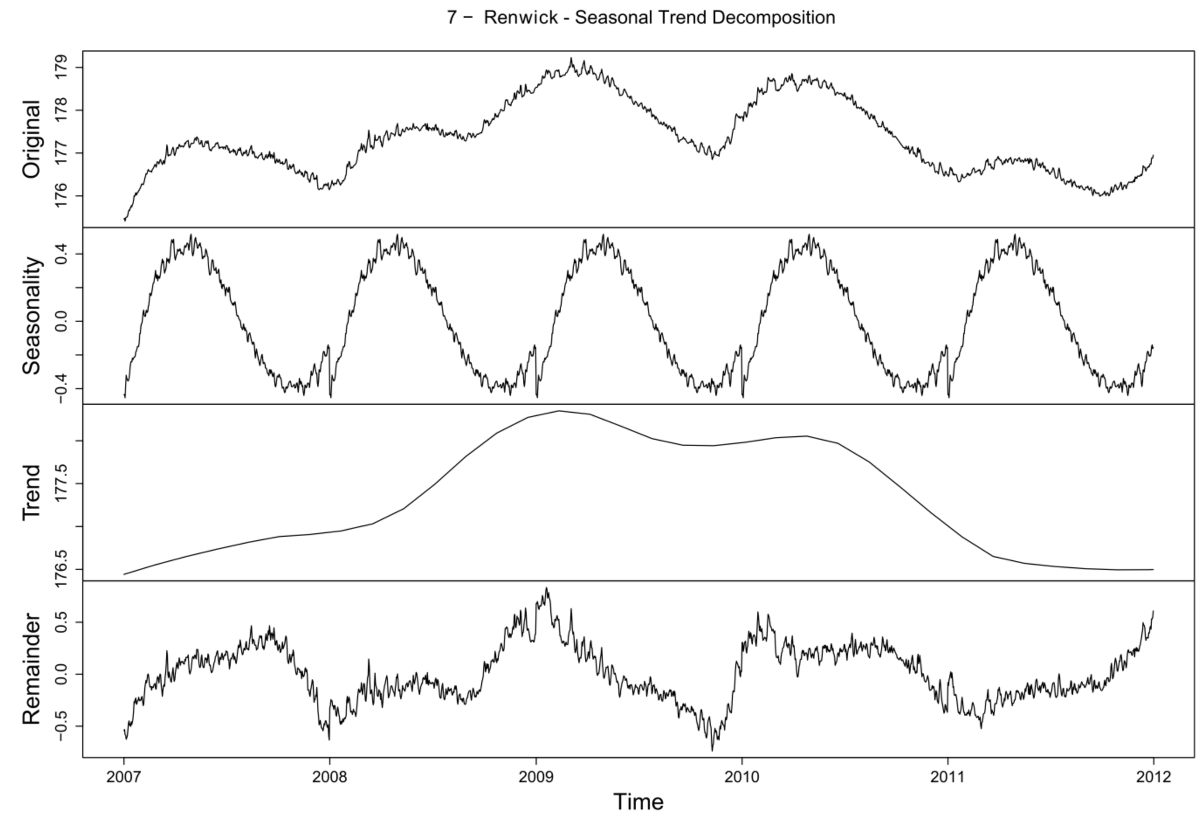
The rest water level is at 28.2m below datum, with perched water encountered at 16m (beds of mudstone/siltstone are present at different depths and could create perched water levels). Close to the borehole, a significant area of the bedrock is uncovered while the remaining 50 % are covered by relatively thin layer of low permeability boulder clay.

7 – Renwick – continuous recording







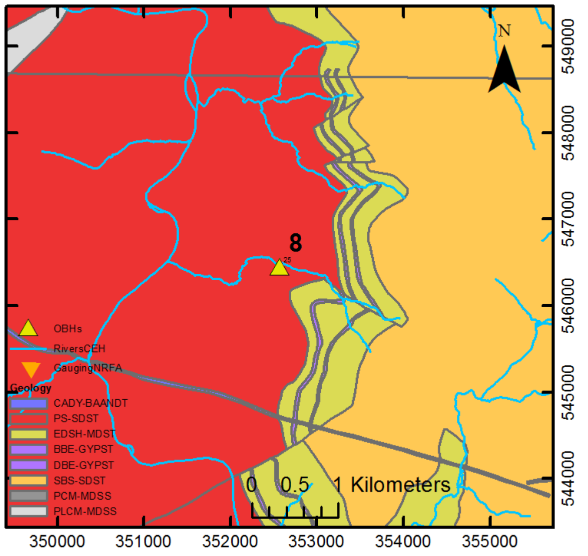


The water level ranges from 175 to 179 m AOD.
The variance associated to the general trend (61.3%) mainly controls the variance of the original signal. The influence of the short time scale events has only a small effect on the overall signal though they can be observed.
The variations of the groundwater level are dominated by the seasonality and the general trend with a relatively high amplitude (nearly 4m) and only a little perturbed by small scale events. This could reflect the greater homogeneity of the St Bees Sandstone aquifer compared with the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability). But the frequent mud laminations and beds may limit vertical hydraulic conductivity.
The amplitude is particularly high (almost 4m), and highly controlled by the trend. The relative proximity to the potential barrier constituted by the Armathwaite Dyke could provide a part of explanation of such a behavior (though the intensive jointing of this dyke can be expected to yield an overall considerable permeability, Younger et al 1997), as well as the proximity of the Pennines and a potentially highly variable amount of recharge. Besides, the recharge could be influenced by the absence of superficial deposits near to the borehole.

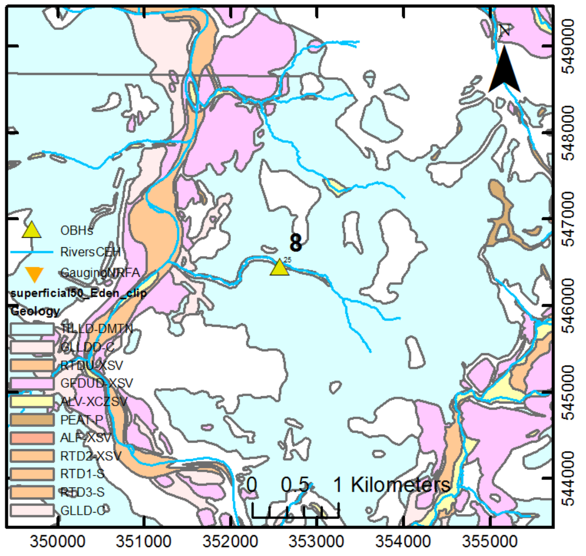
	Season.	Trend	Rem.	Original
Variance	0.1212	0.5219	0.0761	0.8511
Ratio (%)	14.2	61.3	8.9	100

7 – Renwick – continuous recording

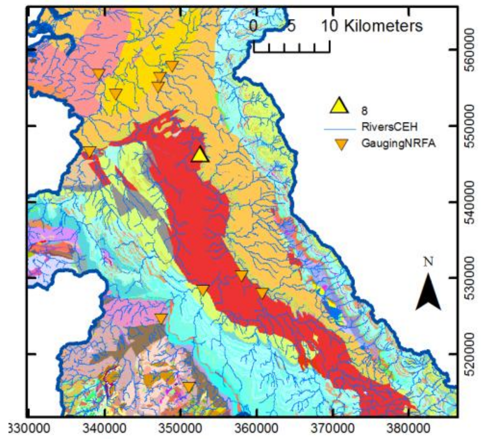
AINSTABLE NORTH CUMB, Bedrock 50k



AINSTABLE NORTH CUMB, Superficials 50k



General location map



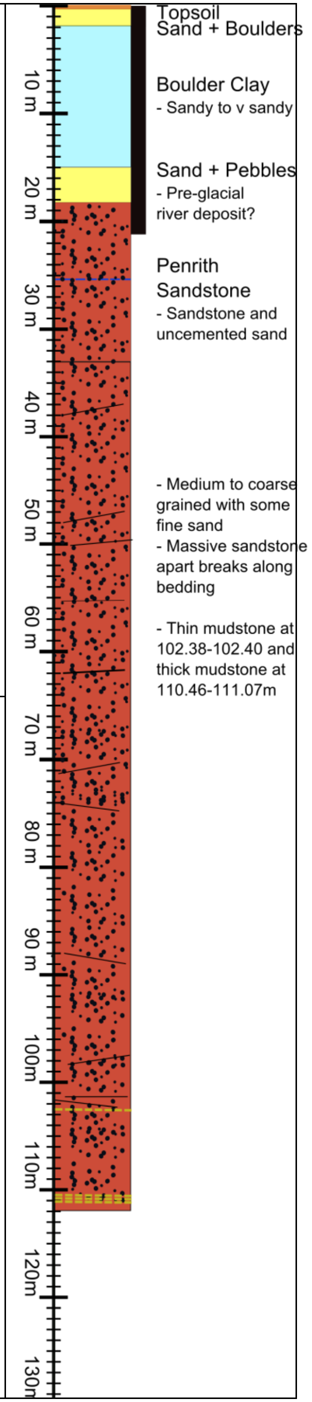
<u>*Bore name:*</u> AINSTABLE HALL, NORTH CUMBRIA OBH 7

<u>*Site no:*</u> NY54/10

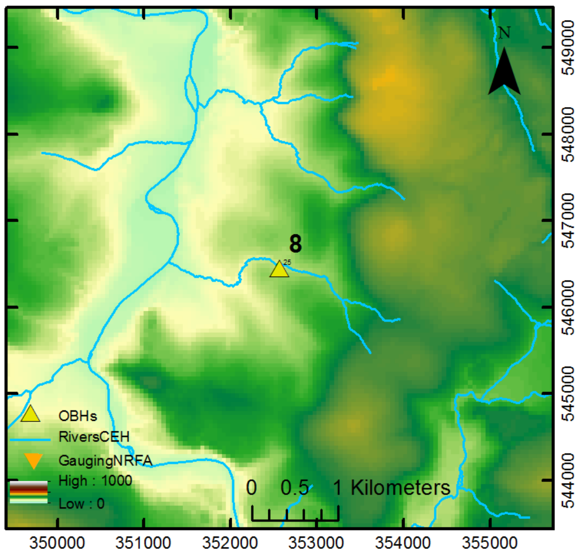
<u>*Ground Level (DTMNextmap):*</u> 107 m AOD

<u>*Datum Level:*</u>

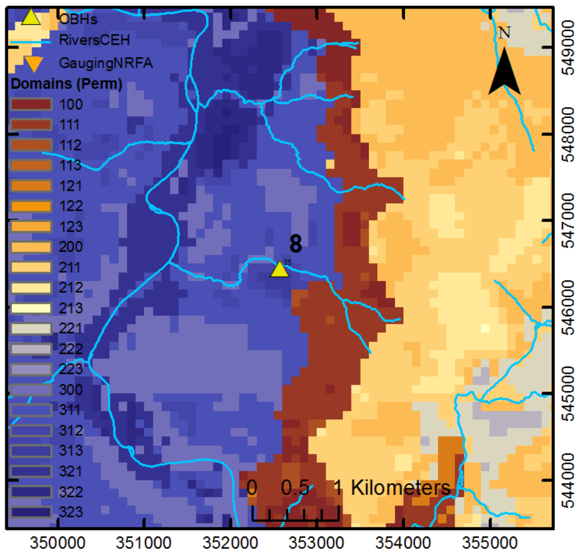
<u>*Drilled depth:*</u> 112 m



AINSTABLE NORTH CUMB, Topography (DTM)



AINSTABLE NORTH CUMB, Domains (Permeability)



This borehole is situated between the villages of Armathwaite and Ainstable, beside the Hall Beck that flows to the R. Eden 1km westward. The boundary between the Penrith Sandstones and the Eden Shales lies 500m to the east.

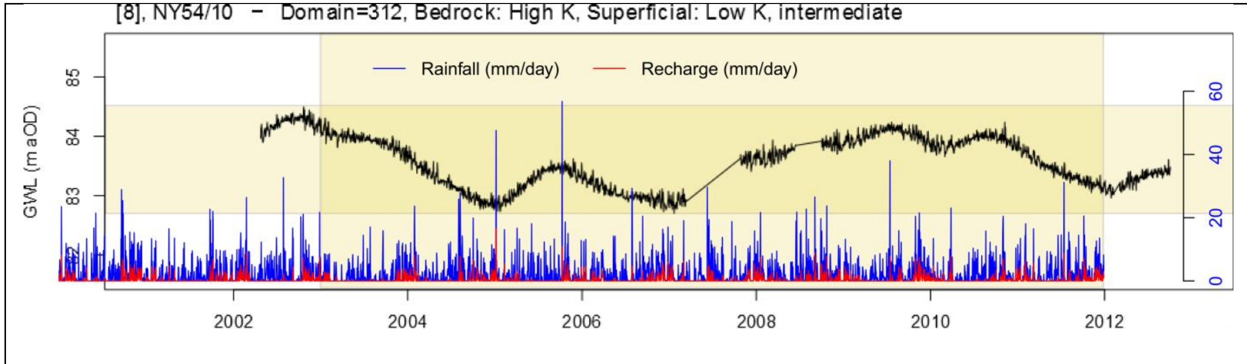
The main aquifer is the Penrith Sandstone (the borehole is cased down to 21m below datum).

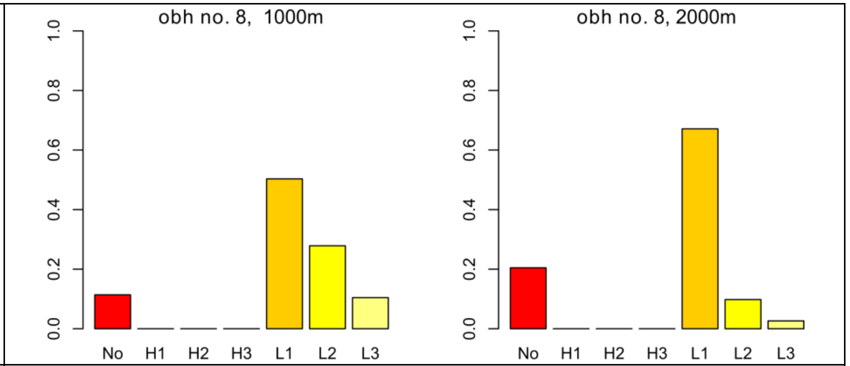
Overlying the Penrith Sst there is a 3m thick layer of sand and pebbles (pre-glacial river deposit) itself covered by 15m of boulder clay.

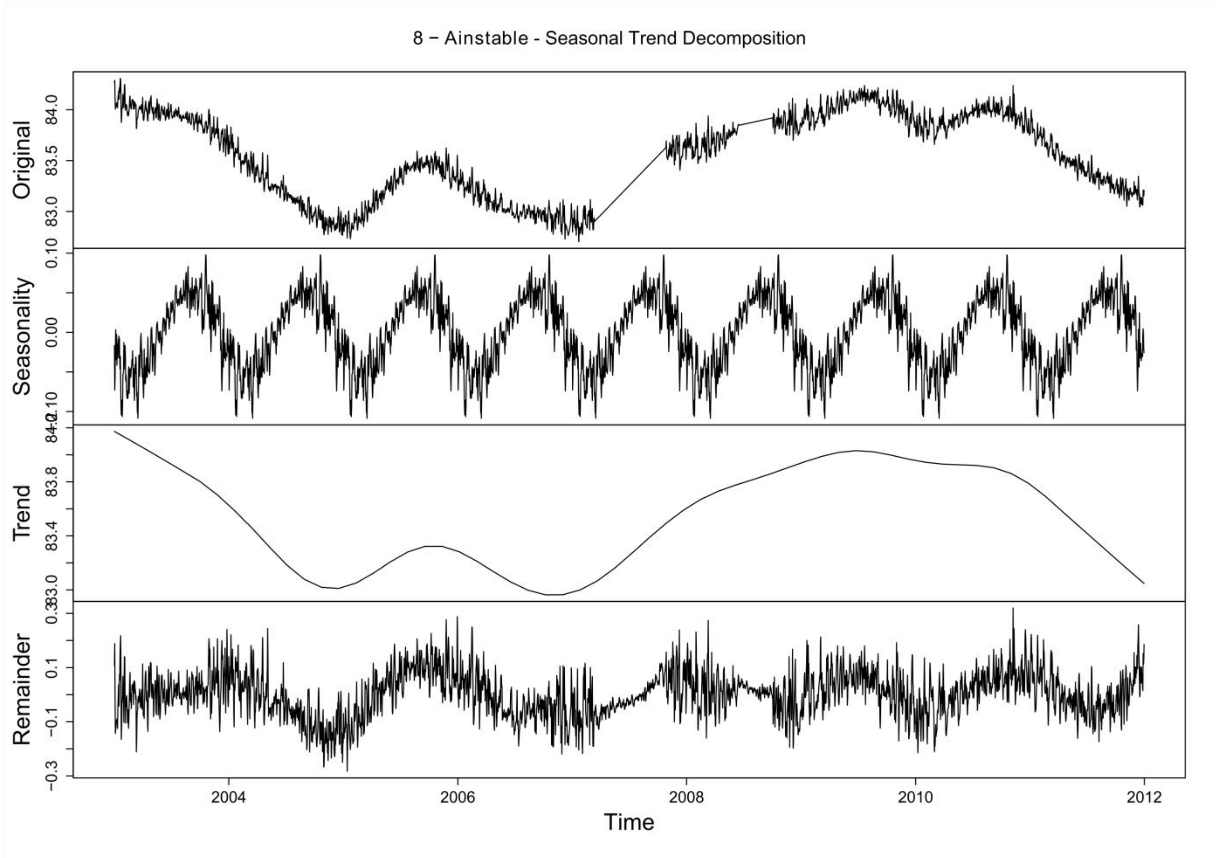
The rest water level is at 25m below the datum.

Most of the area around the borehole is covered by a relatively thin layer of superficial deposits.

8 – Ainstable – continuous recording





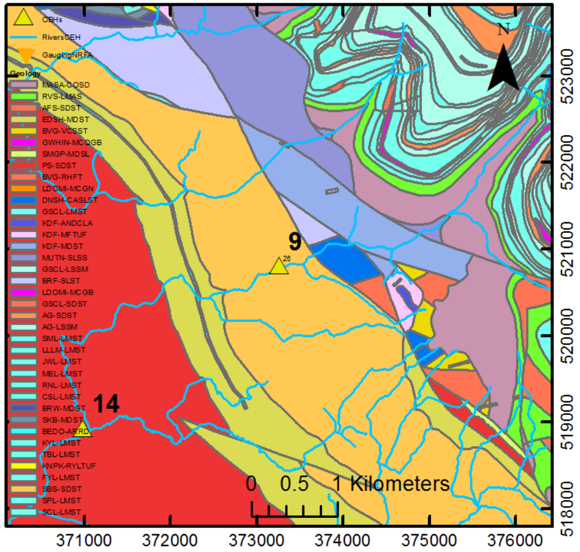


The water level ranges from 82.8 to 84.5 m AOD.
The variance associated to the general trend (85.2%) explains most of the variance associated with the original signal. The influence of the short time scale events is less important than in the case of the shallow piezometer and the seasonality is attenuated. The location of this borehole might provide an explanation for this behavior: the Armathwaite Dyke is situated very close to the south, as well as outcrop of the Eden Shales. Thus connection with the rest of the Penrith aquifer may be affected, as well as the response to the recharge.
The low permeable superficial cover might prevent the water level within the underlying sandstone to respond significantly to the short time scale events.
The relative proximity of the River Eden may also have an influence.
Also the location of the borehole in this northerly part of the Penrith Sandstone outcrop could mean that that the sandstone is silicified in part, which would lead to this kind of behavior.

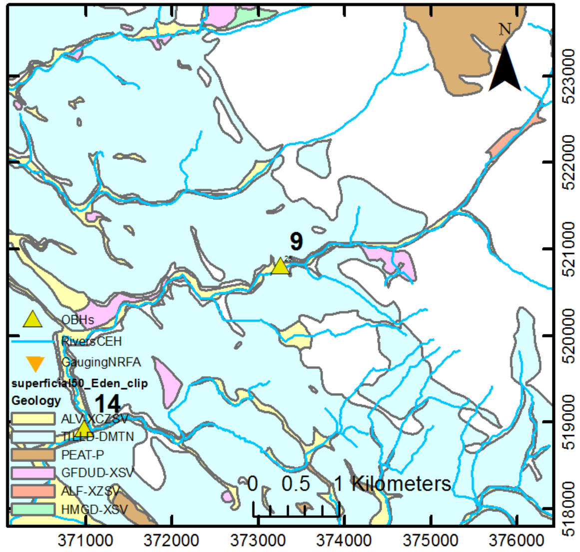
	Season.	Trend	Rem.	Original
Variance	0.0025	0.1548	0.0070	0.1817
Ratio (%)	1.4	85.2	3.9	100

8 – Ainstable – continuous recording

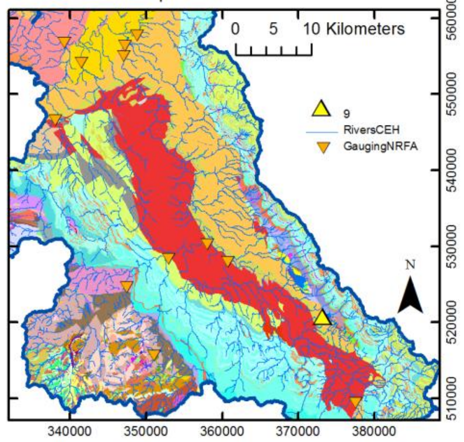
Hilton, Bedrock 50k



Hilton, Superficials 50k



General location map



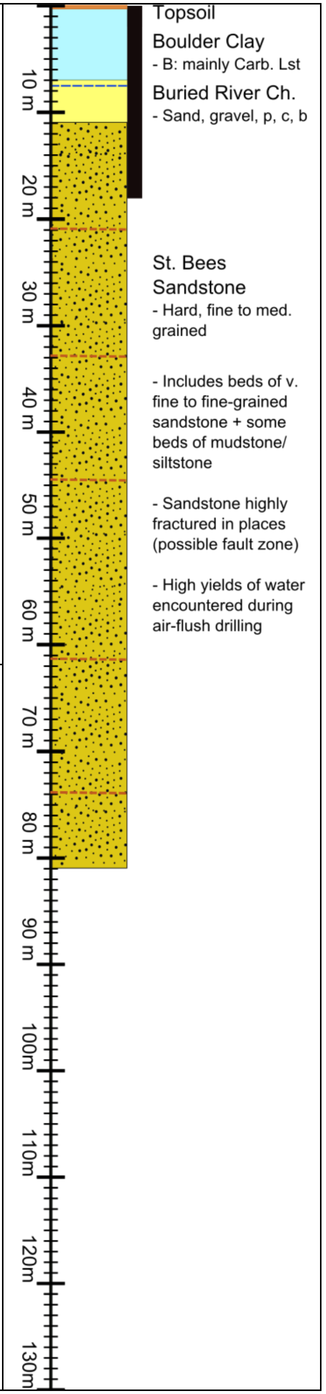
Bore name: HILTON OBH

Site no: NY72/9

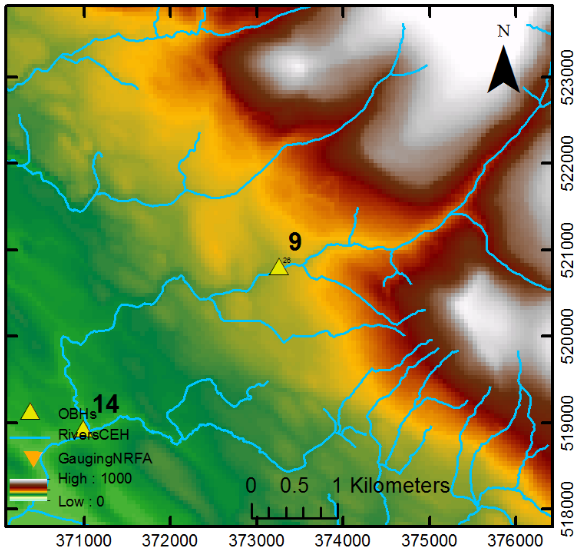
Gr. Level (DTMNextmap): 220.5m AOD

Datum Level:

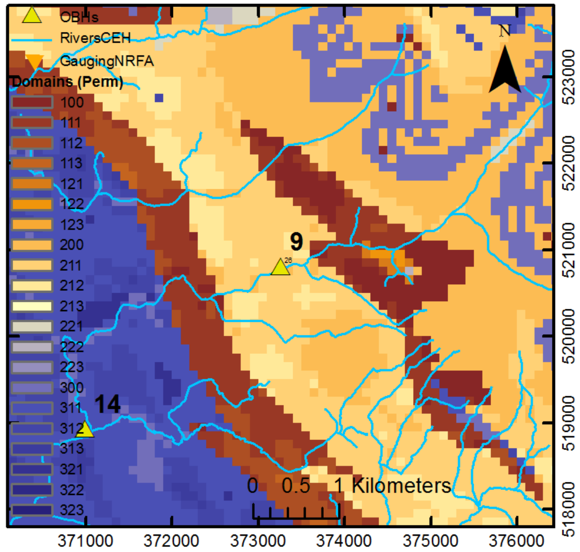
Drilled depth: 81.53 m



Hilton, Topography (DTM)



Hilton, Domains (Permeability)



The borehole is situated in Hilton village, close to the Hilton beck which flows from the Pennine Fells (Eastern boundary of the Eden valley, underlain by Carboniferous Limestone Formations). The Hilton beck flows on the Carboniferous limestone in the Pennine fells and then onto low permeability Ordovician/Silurian rocks before arriving at the St Bees Sandstone close to Hilton.

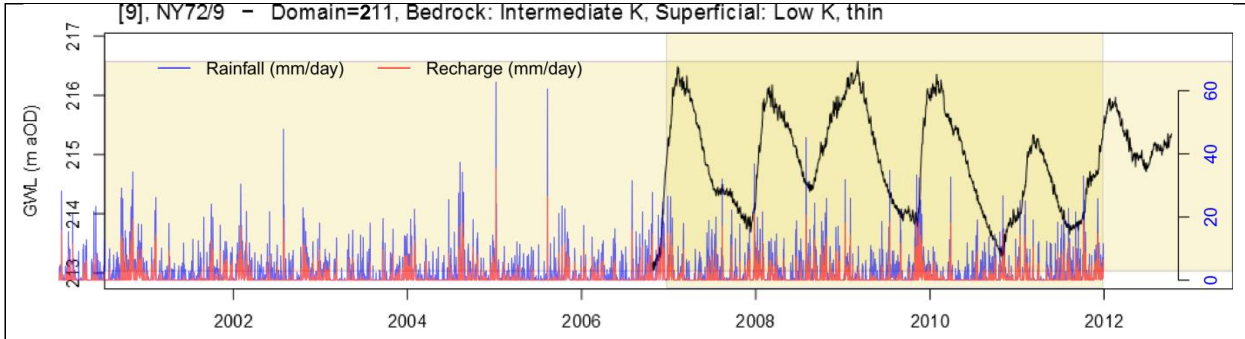
The main aquifer is within the St Bees Sandstone.

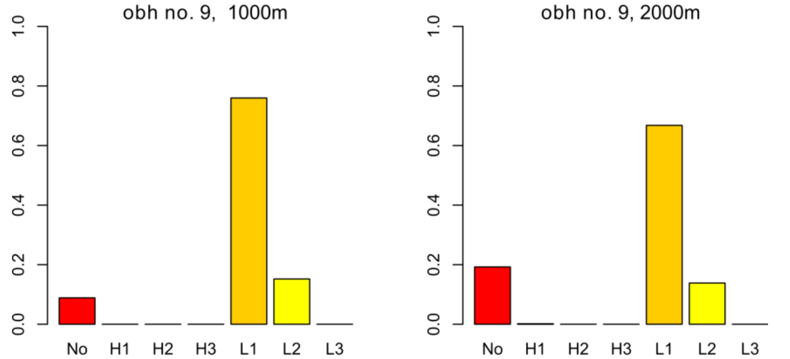
4m of sand and gravel (buried river channel) are present on top of the sandstone, and covered by 7m of drift (boulder clay, with mainly Carboniferous Limestone boulders).

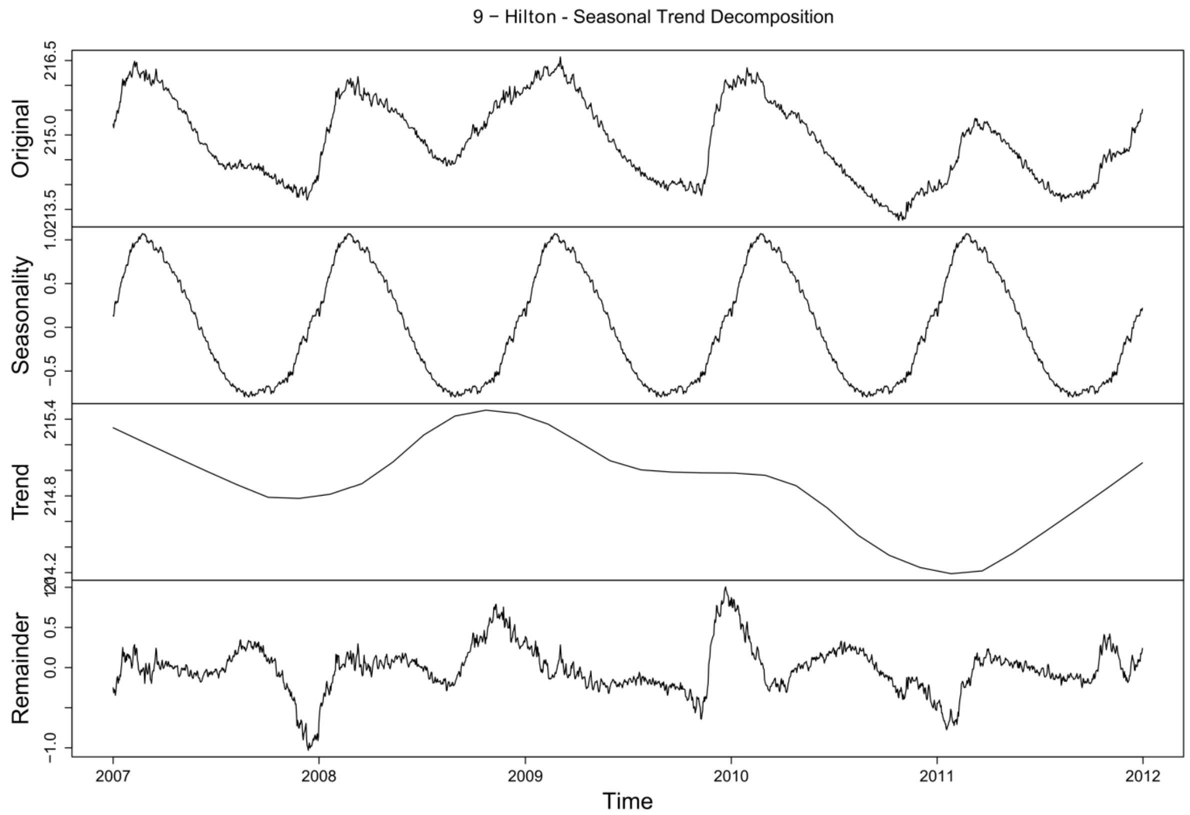
The rest water level is at 7.5m below datum.

Most of the area around the borehole is boulder clay covered.

9 – Hilton – continuous recording







The water level ranges from 213 to 216.6 m AOD.

The variance associated to the seasonality (63.4%) mainly controls the variance of the original signal. Short time scale events have very little influence on the overall signal though they can be observed. The trend is less evidently observed than for other boreholes drilled in the St Bees Sandstone.

The variations of the groundwater level have a particularly high amplitude of nearly 3.5m. This could reflect the greater homogeneityof the St Bees Sandstone aquifer in compared to the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability). But the frequent mud laminations and parting may limit vertical hydraulic conductivity.

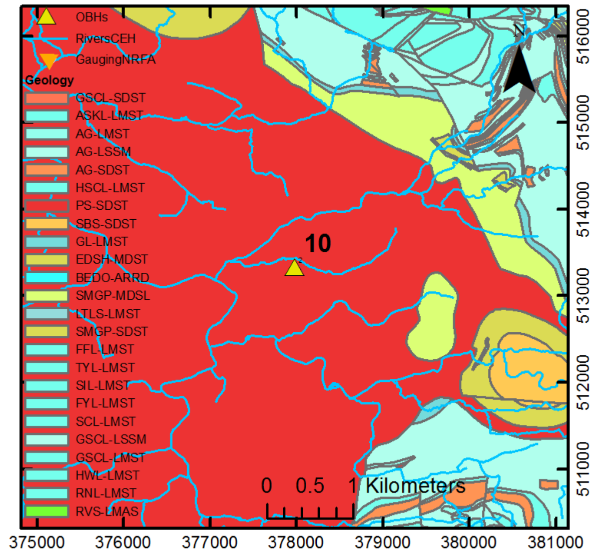
The high seasonal amplitude may be explained by higher recharge in this area because the borehole is situated very close to the area receiving the highest amount of rainfall).

A rapid response to the recharge during winter, and then a somewhat slower recession through the summer, has been observed.

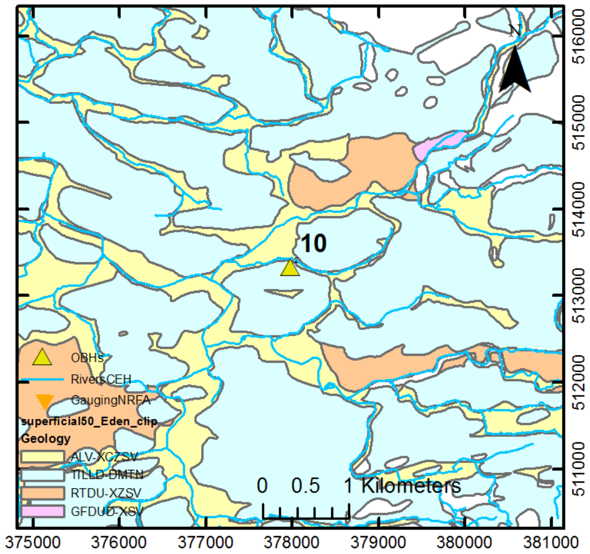
	Season.	Trend	Rem.	Original
Variance	0.4490	0.1116	0.1086	0.7084
Ratio (%)	63.4	15.8	15.3	100

9 – Hilton – continuous recording

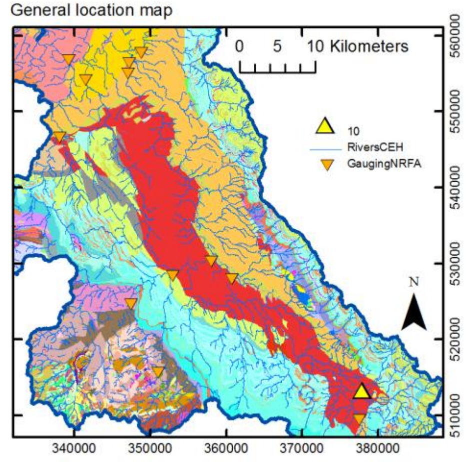
GREAT MUSGRAVE N CUM, Bedrock 50k



GREAT MUSGRAVE N CUM, Superficials 50k



General location map



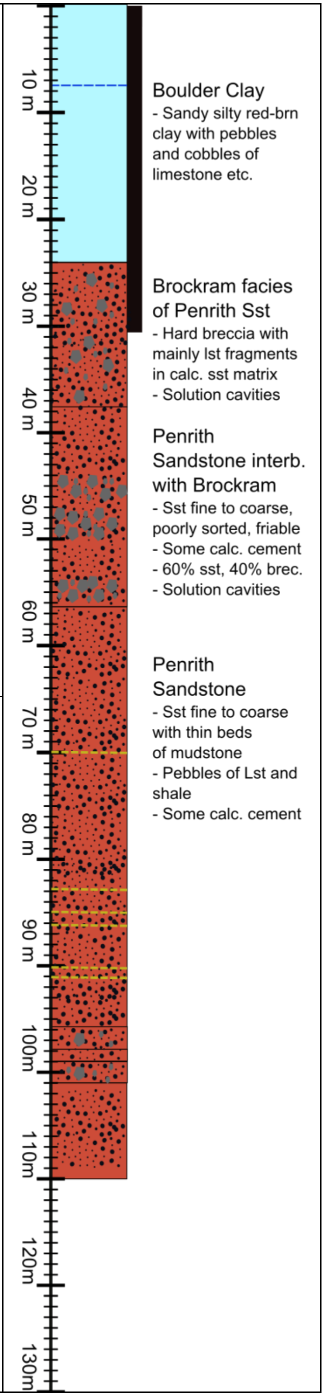
<u>*Bore name:*</u> NORTH CUMBRIA OBH 1, HEANINGS FARM, GREAT MUSGRAVE

<u>*Site no:*</u> NY71/3

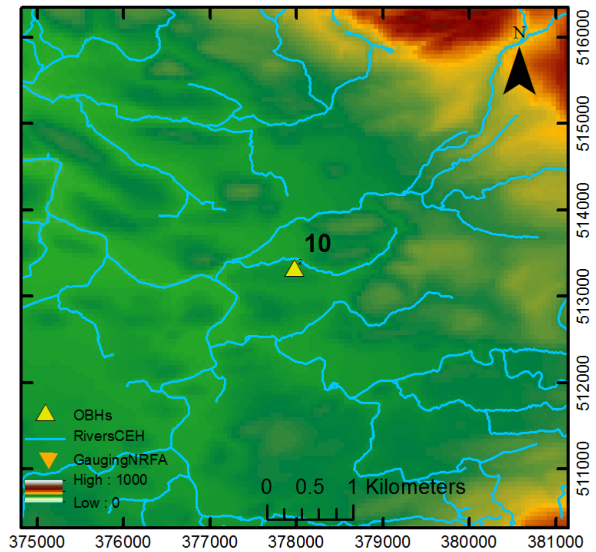
<u>*Ground Level:*</u> 160 m AOD

<u>*Datum Level:*</u>

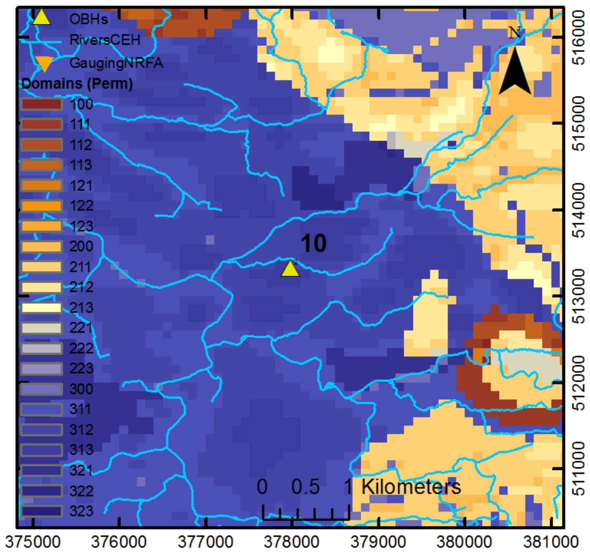
<u>*Drilled depth:*</u> 110.42 m



GREAT MUSGRAVE N CUM, Topography (DTM)



GREAT MUSGRAVE N CUM, Domains (Permeability)



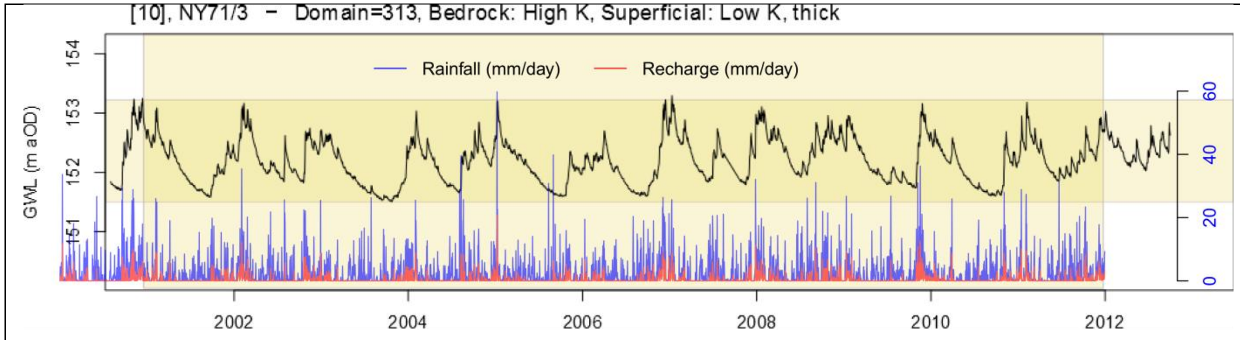
This obh is situated in the far south of the Eden Valley, on a small hill (probably a drumlin) less than 1km east the Great Musgrave village (situated at the confluence of the Swindale beck within the River Eden). The Swindale Beck drains Carboniferous Limestone fells tothe south east of the catchment.

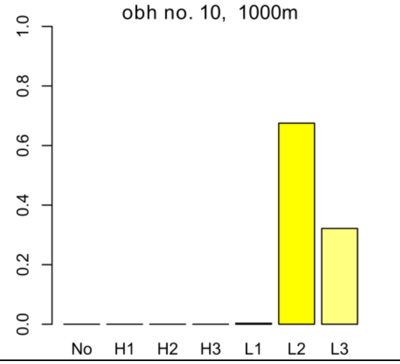
The main aquifer is the Penrith Sandstone formation, including both sandstone and Brockram (Hard breccias with mainly Limestone fragments in a calcareous sandstone matrix). Dissolution occurs within limestone clasts.

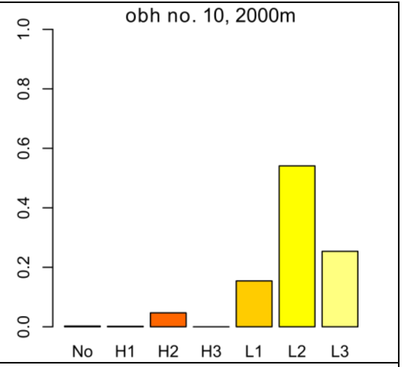
24m of superficial deposits are present above the Penrith Sst. The rest water level is at 7.5m below datum.

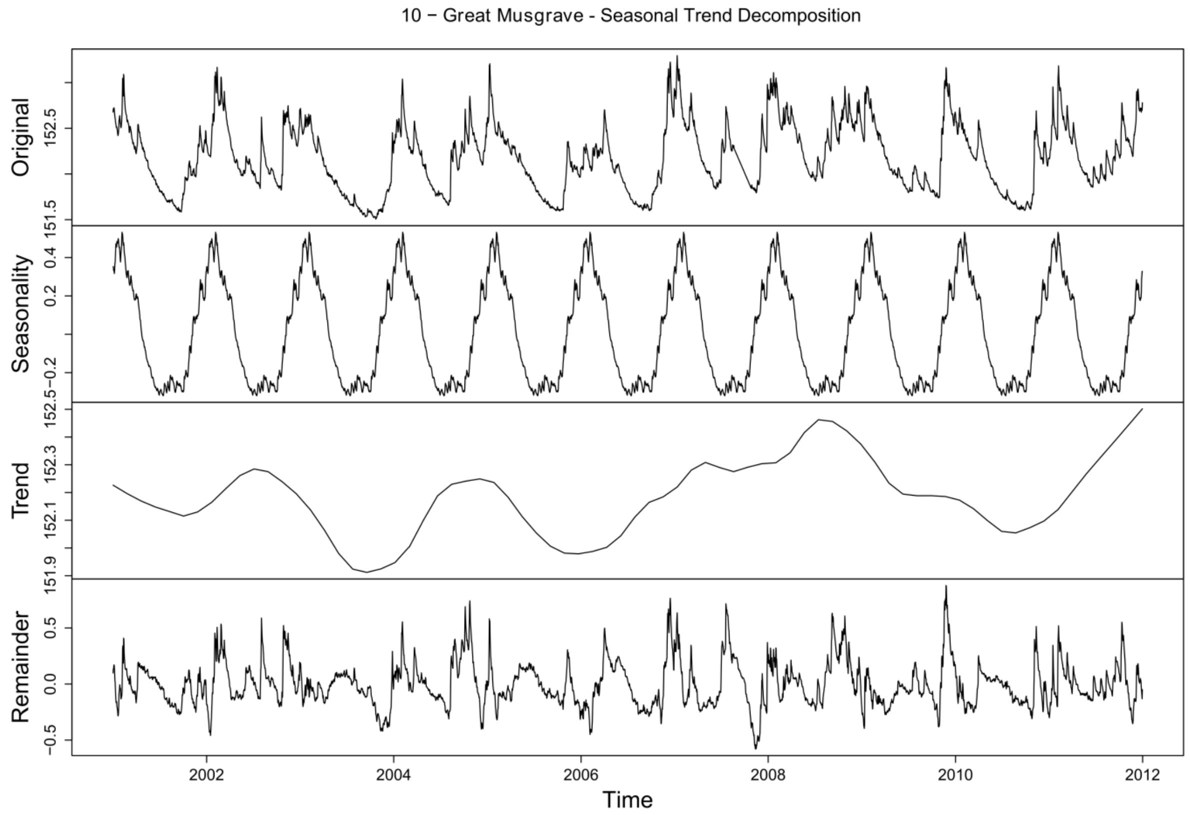
The superficial deposits around the borehole are mainly boulder clay on the hills (drumlins) and alluvium in the streams flood plains.

10 – Great Musgrave – continuous recording





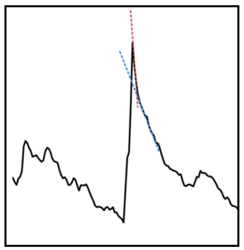




The water level ranges from 151.5 to 153.2 m AOD.
The maximum amplitude reaches 1.7m. A m AODerately well-defined seasonality is observed, though some summer events appear (e.g.2002, 2004). Generally, the shape of the curve is spiky.

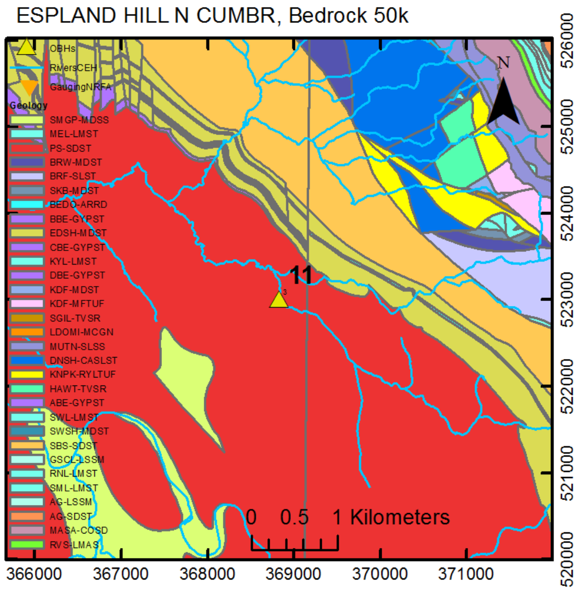
The variances associated with the seasonality (51.4%) and the remainder (31.4%) explain most of the variance associated to the original time series.
The water level seems to respond very quickly to short term events, even if the bedrock is covered by a relatively thick layer of boulder clay.
This borehole is one of the most southerly of the group, situated relatively close to the potentially karstified Carboniferous formations which could result in fast flow processes.

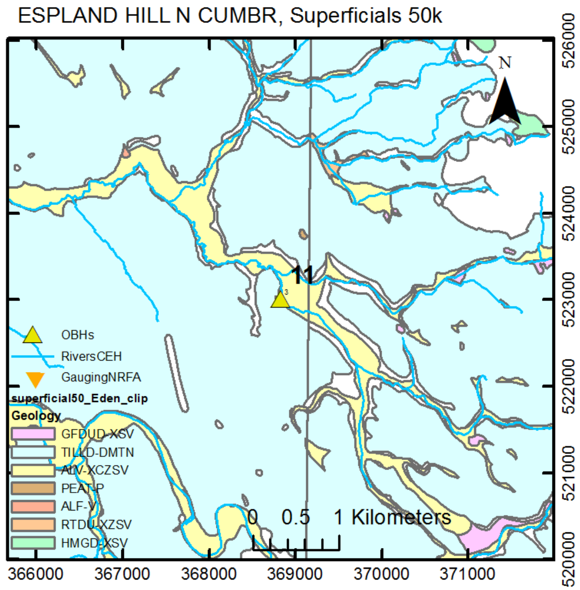
The Brockram can be significantly fractured, with possible enlargement of fractures by dissolution of limestone clasts (solution cavities were recorded on the log): thus there could be different flow paths, fast through enlarged fractures and slower within the sandstone matrix. The presence of potentially fast flow paths together with slower flow may provide an explanation for the shape of the water level hydrograph:
Rapid increase of the water level in response to the event, then fast recession (red) associated to the rapid drainage using the enlarged fractures followed by the slower recession (blue) due to flow in the sandstone matrix.

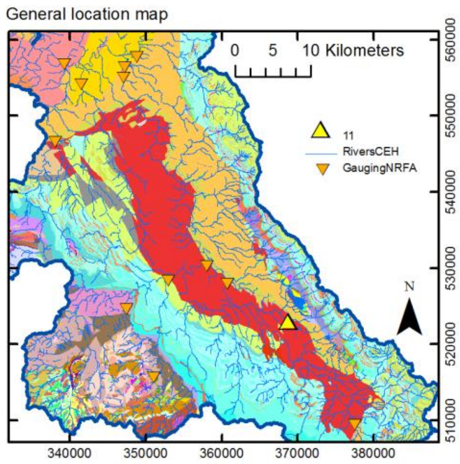


	Season.	Trend	Rem.	Original
Variance	0.0716	0.0194	0.0438	0.1394
Ratio (%)	51.4	13.9	31.4	100

10 – Great Musgrave – continuous recording







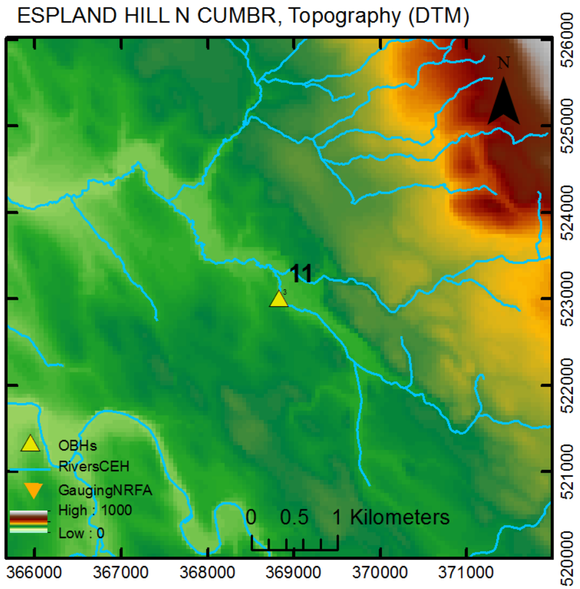
Bore name: NORTH CUMB. OBH2, ESPLAND HILL, BRAMPTON, APPLEBY

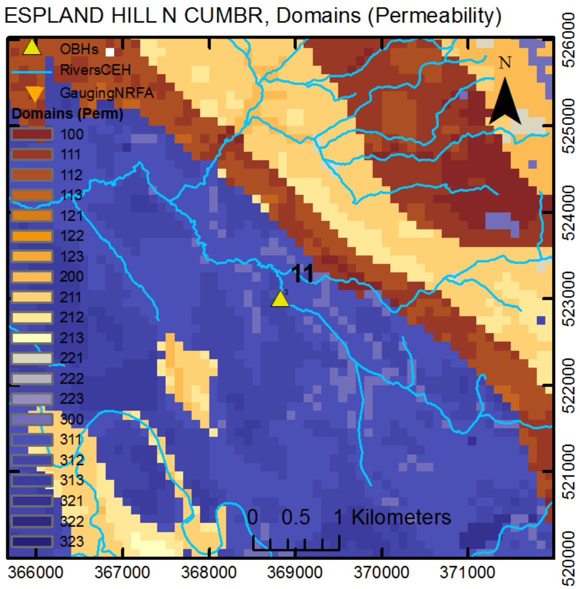
Site no: NY62/4

Ground Level: 137.69 m AOD

Datum Level:

Drilled depth: 101.56 m





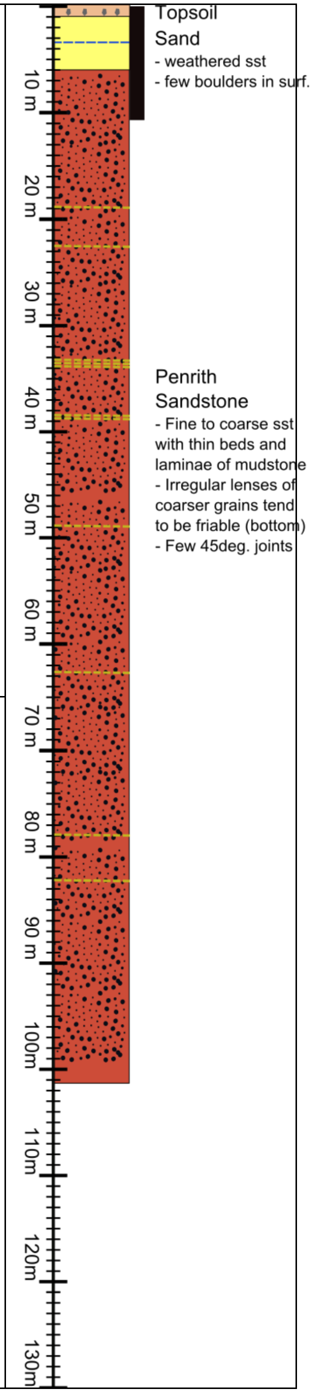
This borehole is situated south east of Brampton, on Espland Hill, near to the confluence of the Frith Beck within the Burthwaite Beck. Both becks flow from Pennine Fells, over St Bees Sandstone and Eden Shales.

These becks flow within ancient glacial melt-water channels, with outcrops of Penrith Sandstone on the sides of the channel.

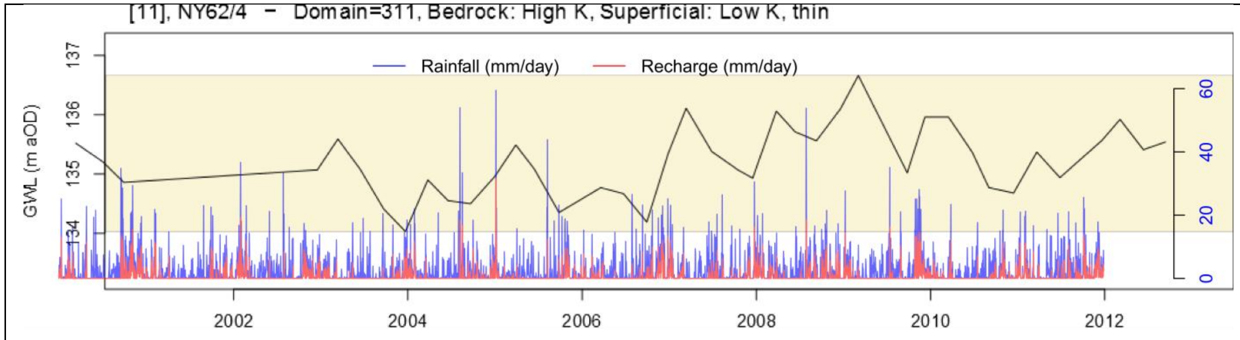
The entire borehole depth is within the Penrith Sandstone, with weathered sandstone and some boulders in the first seven meters.

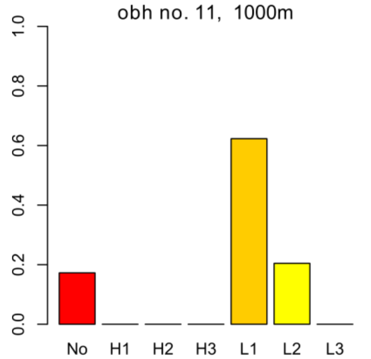
Around the borehole, some areas are free of superficials, while there is silty clay rich alluvium in the glacial meltwater channel and and to the south.

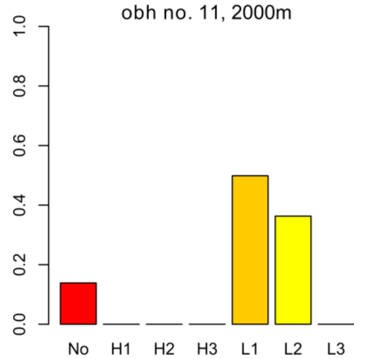
The rest water level is at 3.2m below the datum.



11 – Espland Hill, Appleby – manually read



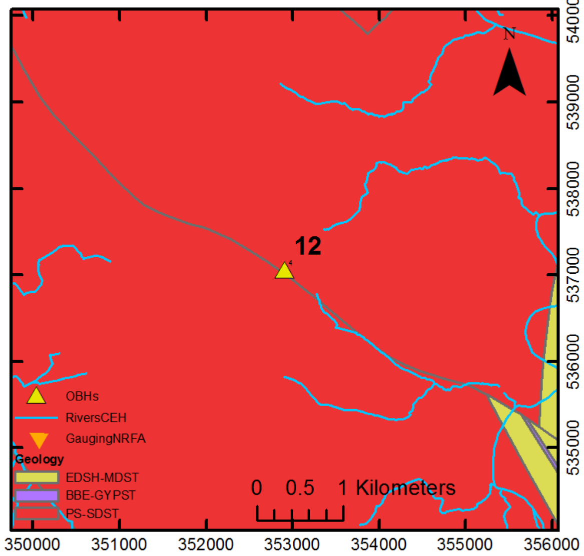




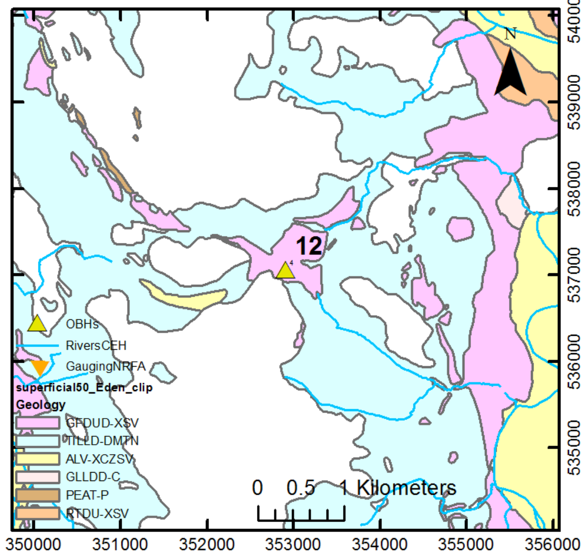
The water level ranges from 134 m AOD to 137.7m AOD.
The variation of the water level appears to be relatively wide, with an easily identifiable seasonality (generally lower than 135m AOD in summer, and often higher than 136m aOD during the winter).
These variations could be related to the presence of superficial “windows” on the Penrith Sandstone and possibly a good connection to the surface flow that drains high Carboniferous Limestone.

11 – Espland Hill, Appleby – manually read

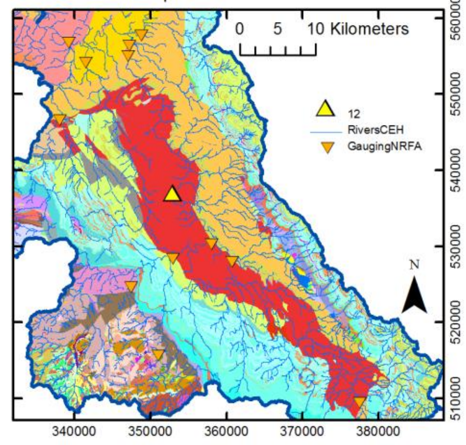
E BROWNRIGG N CUMBRI, Bedrock 50k

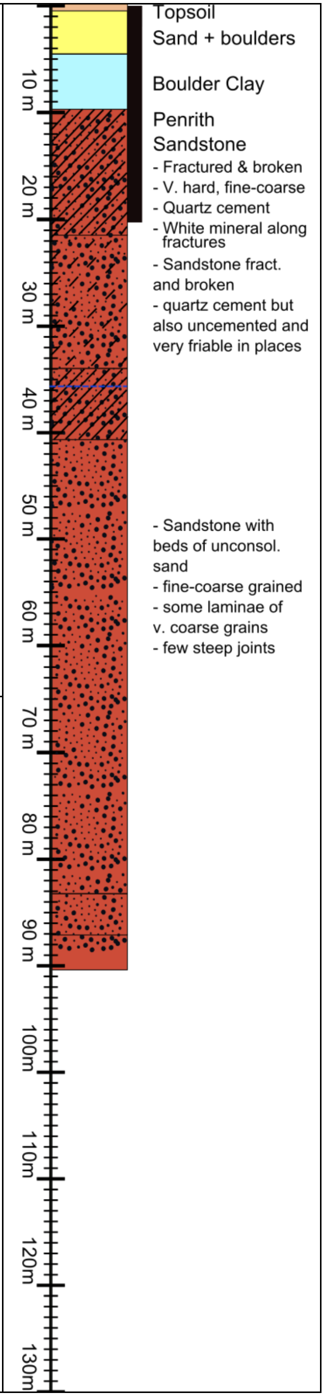


E BROWNRIGG N CUMBRI, Superficials 50k



General location map





__Bore name:__ NORTH CUMB. OBS. WELL 5, EAST BROWNRIGG

__Site no:__ NY53/9

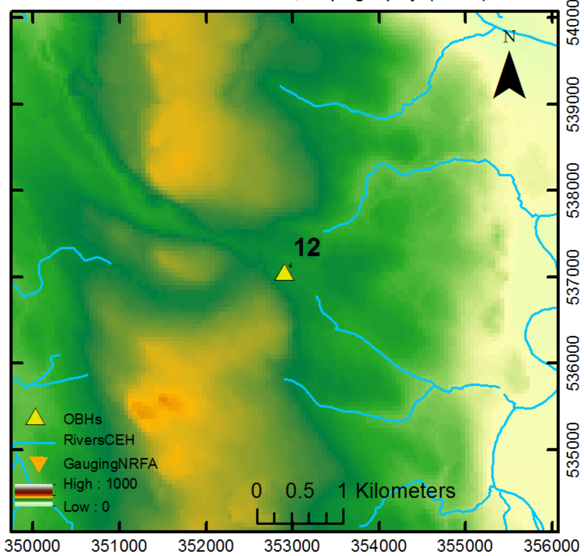
__Ground Level:__ 159.50 m AOD

__Datum Level:__

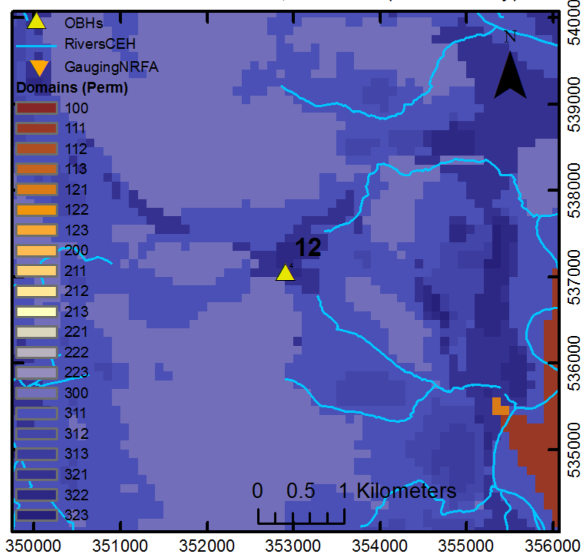
__Drilled depth:__ 90.30 m

This borehole is situated at East Brownrigg, between two hills of well cemented and silicified sandstone outcrop (Lazonby Fell and Wan Fell) close to a major fault.
The aquifer is the Penrith Sandstone, with 30m of fractured and broken silicified sandstone, possibly associated to the fault.
The Penrith Sst is covered by 5.5m of drift and 4.5m of sand and boulders (glaciofluvial deposits).
The rest water level is at 36m below the datum (relatively deep in comparison with the other boreholes).

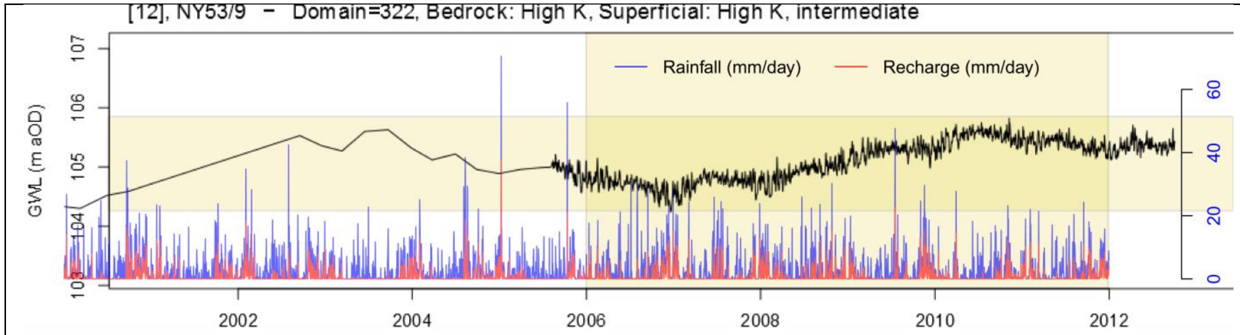
E BROWNRIGG N CUMBRI, Topography (DTM)

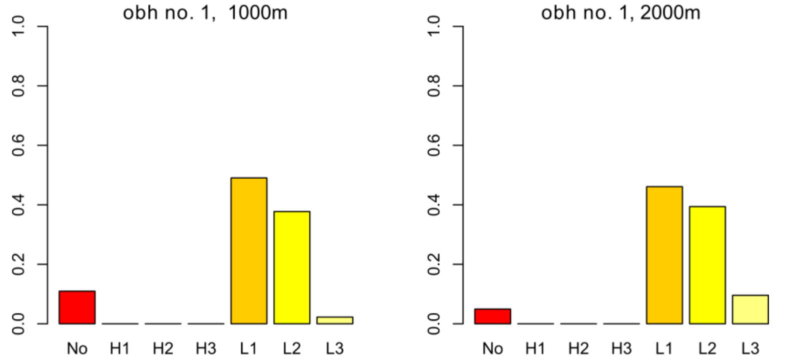


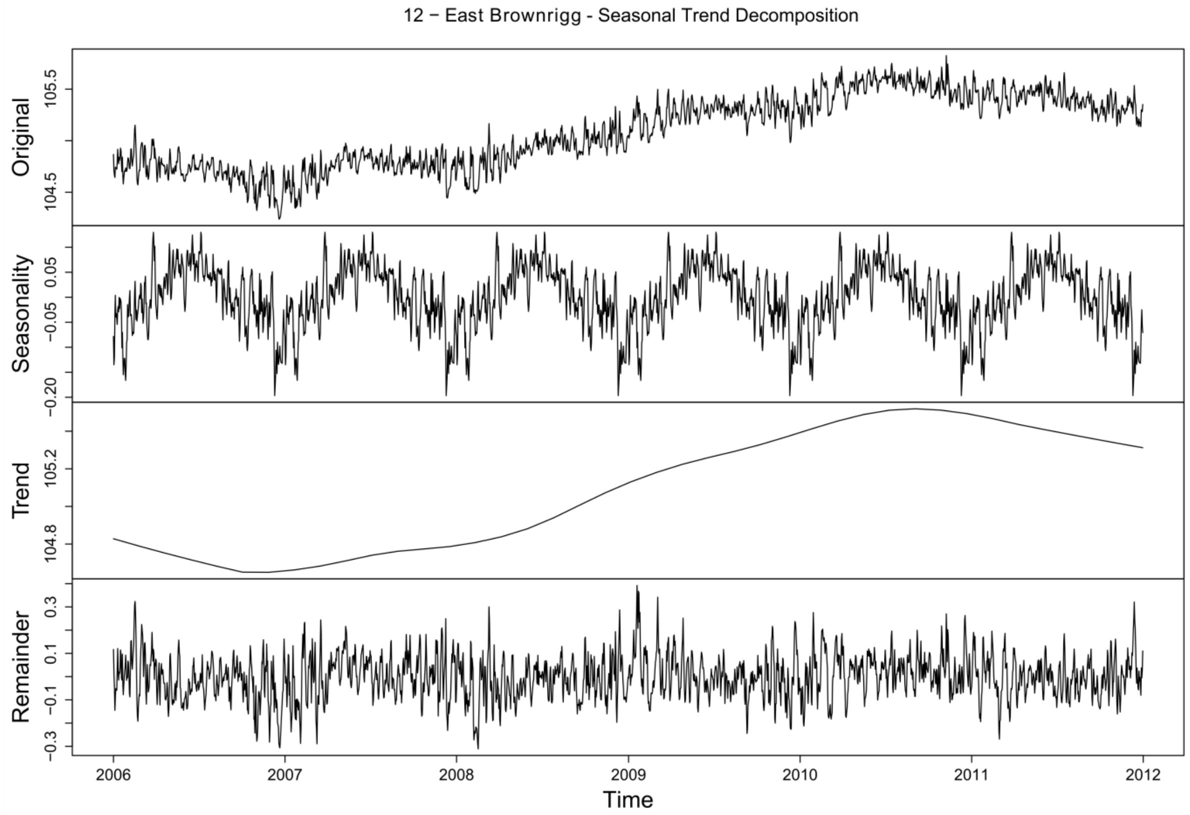
E BROWNRIGG N CUMBRI, Domains (Permeability)



12 – East Brownrigg – continuous recording





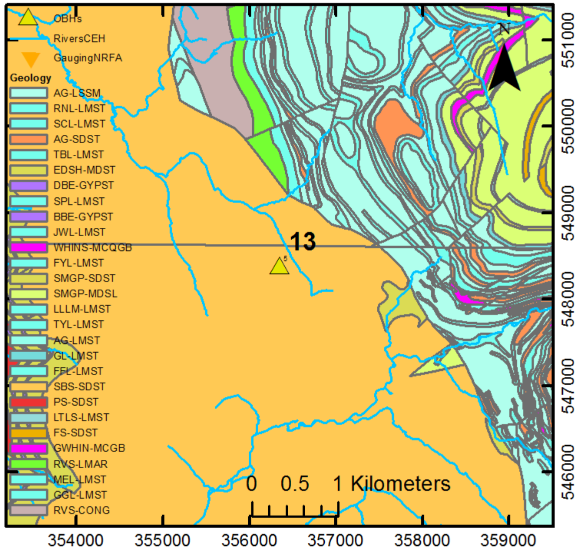


The water level ranges from 104.2 to 105.8 m AOD.
This borehole time series exhibits very rapid oscillations.
Clearly, the trend controls (variance ratio 82.8%) the behavior more than the seasonality (variance ratio 3.5%), though the latter can be observed.
Very often the short term variations probably related to rainfall events can be wider than the seasonal variability.
These rapid responses could be related to the presence of numerous fractures within the sandstone and the very weak seasonality component related to the presence of silicified sandstone that might isolate the borehole from the regional aquifer.
There is no substantive surface stream in the vicinity of this borehole also situated close to the boundary between two major sub catchments: River Eden to the east, River Petteril to the west.
The heterogeneity of the cementation causing large variations in hydraulic conductivity in the Penrith Sandstone should be represented on the conceptual model for the region, as well as the fracture zones.

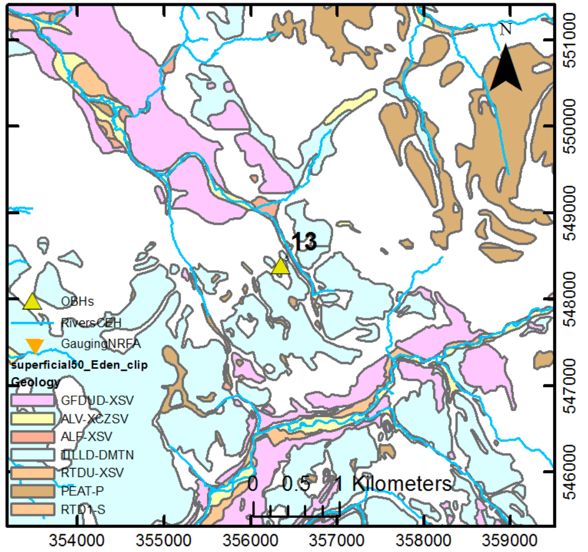
	Season.	Trend	Rem.	Original
Variance	0.0040	0.0944	0.0090	0.1141
Ratio (%)	3.5	82.8	7.9	100

12 – East Brownrigg – continuous recording

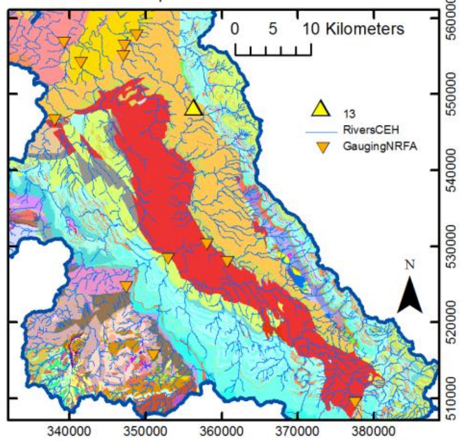
Croglin, Bedrock 50k



Croglin, Superficials 50k



General location map



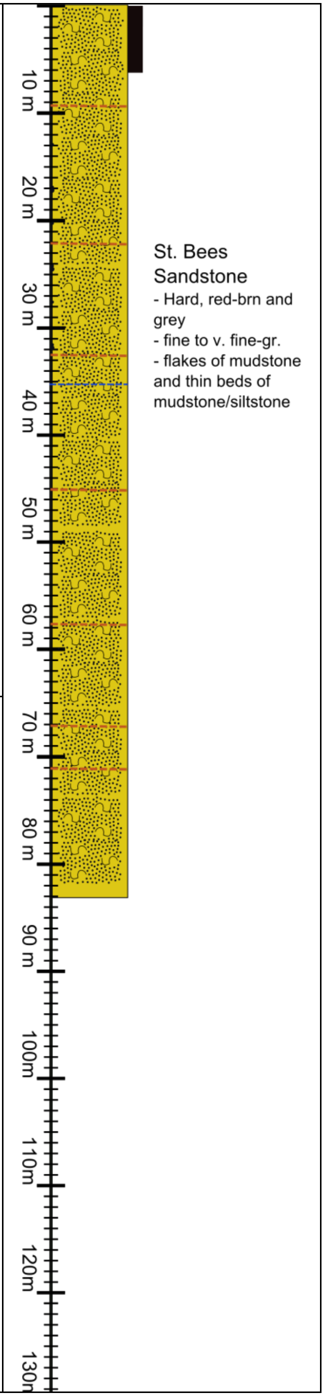
<u>*Bore name:*</u> CROGLIN OBH

<u>*Site no:*</u> NY54/54

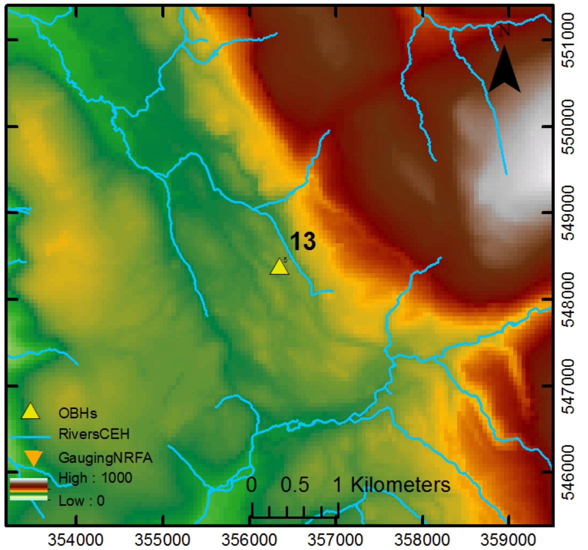
<u>*Ground Level:*</u> 201.6 m AOD

<u>*Datum Level:*</u>

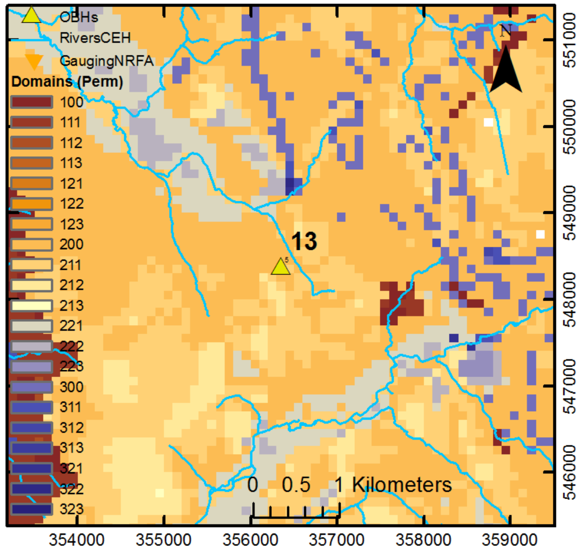
<u>*Drilled depth:*</u> 83.57 m



Croglin, Topography (DTM)



Croglin, Domains (Permeability)



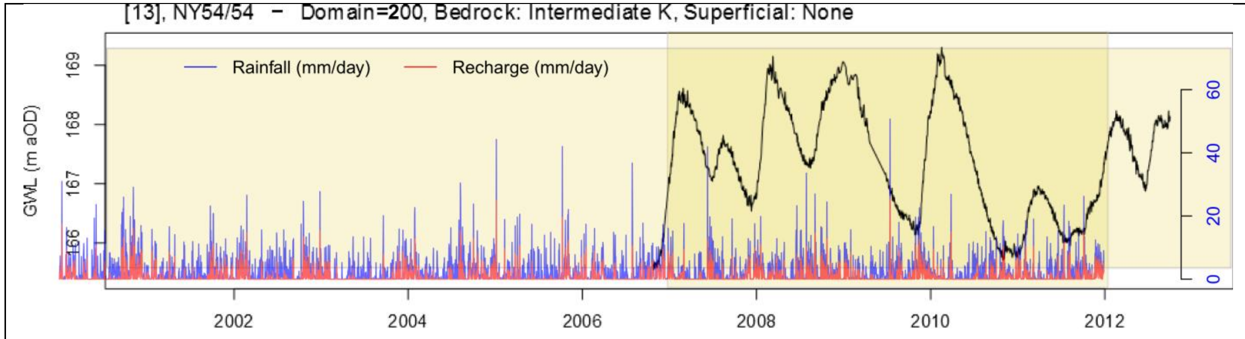
This borehole is situated north of Croglin village, close to the eastern limit of the St Bees Sandstone as it abuts fells of Carboniferous Limestone uplifted by the Pennine fault system. It is 4 km north to the Armathwaite Dyke.

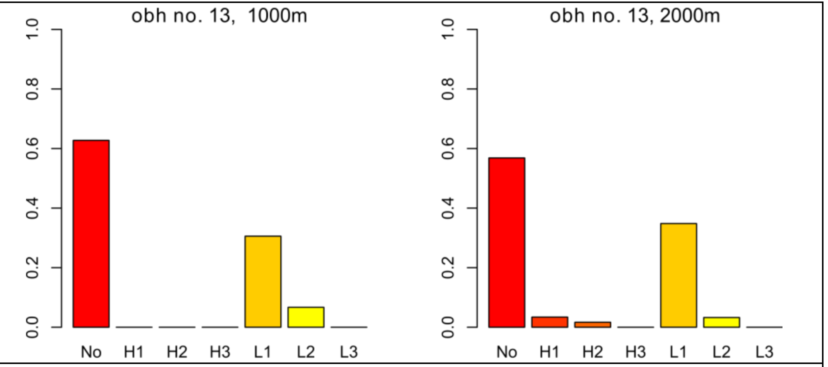
The borehole is entirely in St Bees Sandstone, the bedrock outcropping at the surface and appears to be quite homogeneous.

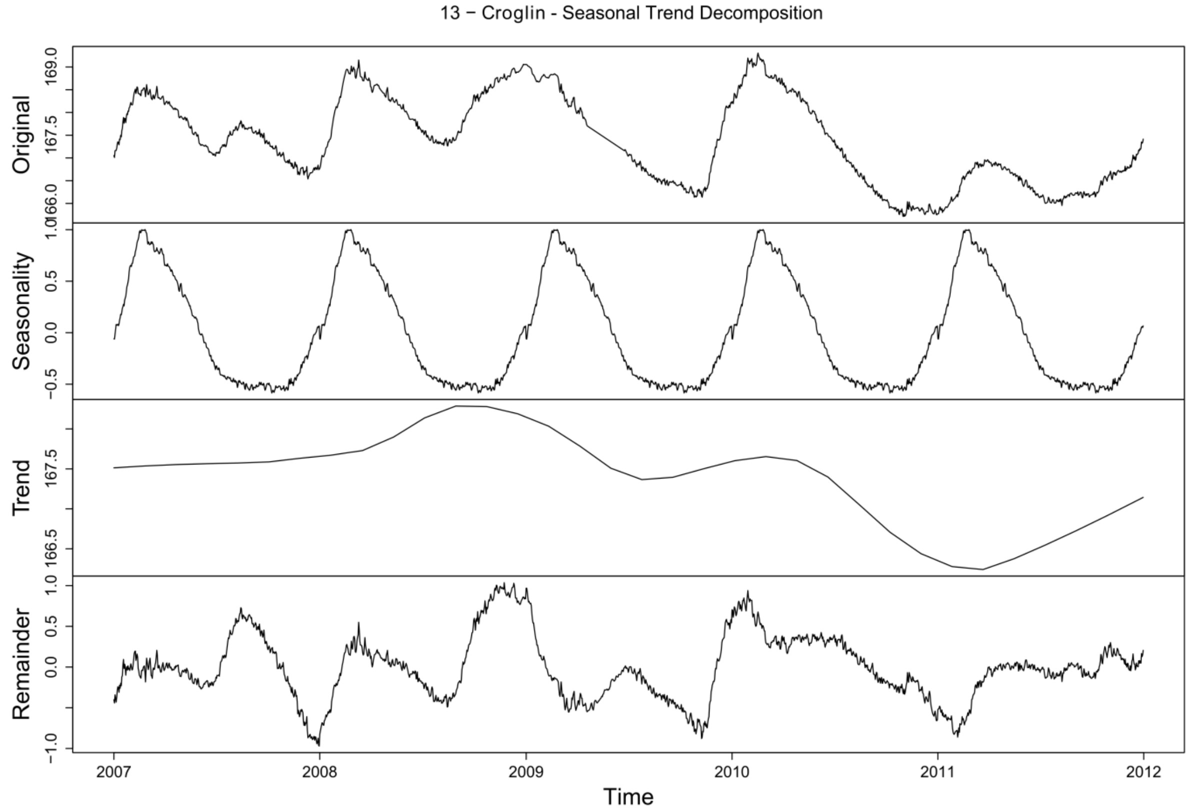
The rest water level is 35m below datum.

Large parts of the area situated around this borehole are free of superficial deposits, but some superficial deposits are present immediately south and east.

13 – Croglin – continuous recording





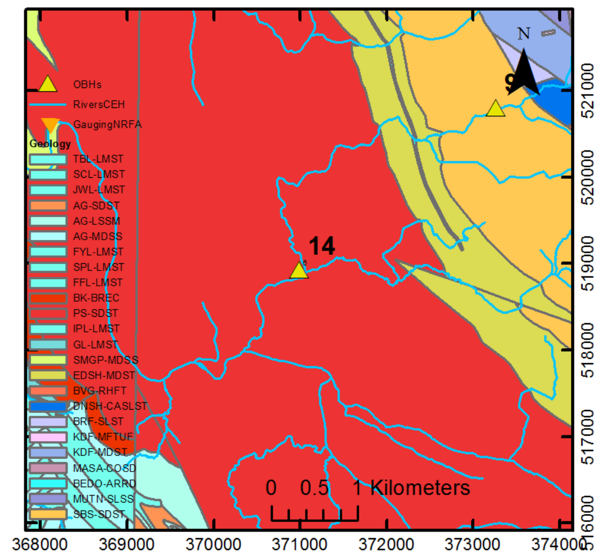


The water level ranges from 165.6 to 169.2 m AOD.
The variances associated to the general trend (33.5%) and the seasonality (33.0%) mainly explain the variance of the original signal. The short time scale events have little influence on the overall signal though they can be observed.
The groundwater hydrographs are dominated by the seasonality and the trend with a high amplitude (nearly 4m) reflecting the homogeneous nature of the St Bees Sandstone aquifer in comparison with the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability). Nevertheless frequent mud laminations and beds may limit vertical hydraulic conductivity.
This high seasonal amplitude could be related to proximity to areas receiving a high rainfall and recharge as well as perhaps a lowish storage capacity of the St. Bee's Sst.
A comparison with the borehole no 7 (Renwick) situated in the St Bees Sandstone at a comparable altitude but south of the Armathwaite Dyke shows that the Croglin borehole is characterized by a stronger seasonality, more intense response and a lower water table. This could indicate that the Armathwaite Dyke acts as a barrier to groundwater flow. A response to the wet summer of 2007 can be identified but this is not the case for the Renwick borehole.

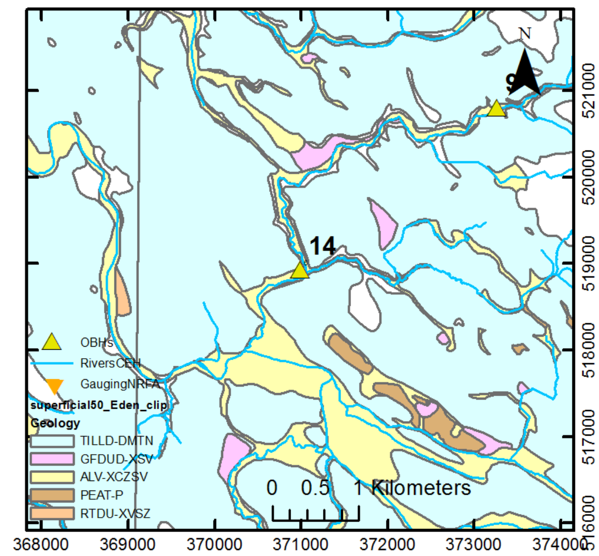
	Season.	Trend	Rem.	Original
Variance	0.3078	0.3124	0.1638	0.9330
Ratio (%)	33.0	33.5	17.6	100

13 – Croglin – continuous recording

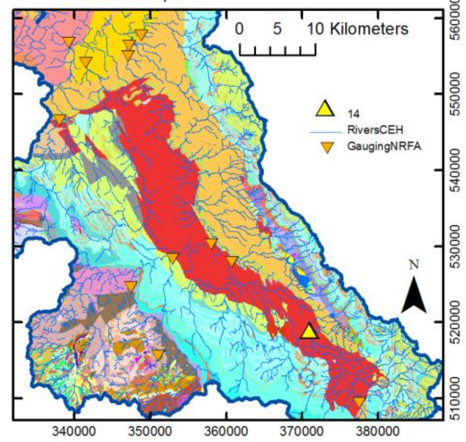
Coupland, Bedrock 50k



Coupland, Superficials 50k



General location map



__Bore name:__ COUPLAND OBH

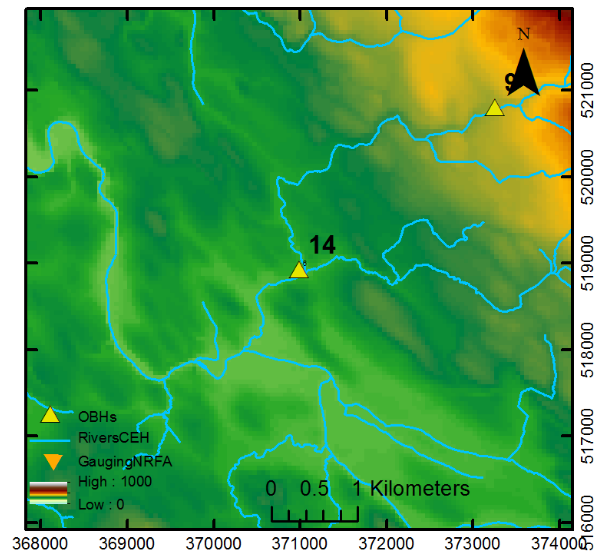
__Site no:__ NY71/23

__Ground Level:__ 142.8 m AOD

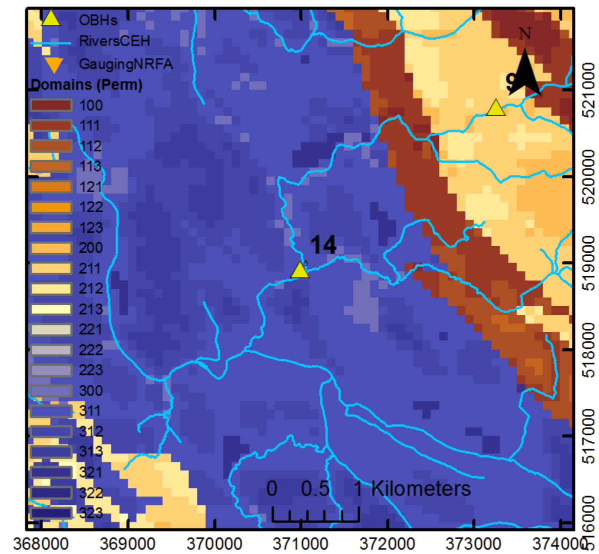
__Datum Level:__

__Drilled depth:__ 84.39 m

Coupland, Topography (DTM)



Coupland, Domains (Permeability)

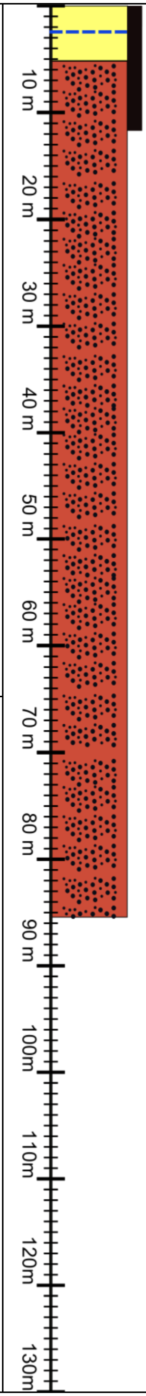


This borehole is situated south east of Appleby, in Coupland village, at the confluence of the Hilton Beck with the George Gill, forming the Coupland Beck, itself flowing into the River Eden 1km to the south.

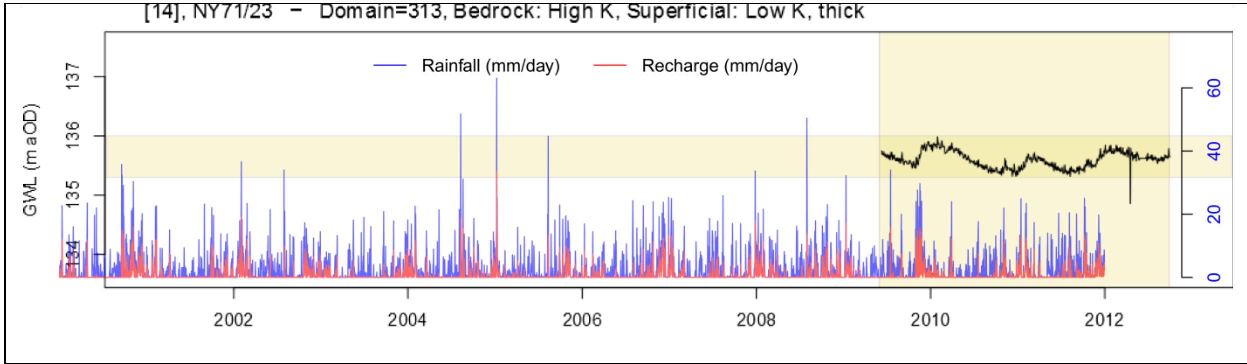
The main aquifer is within the Penrith Sandstone, covered by 5m of sandy clay alluvium (Coupland Beck flood plain).

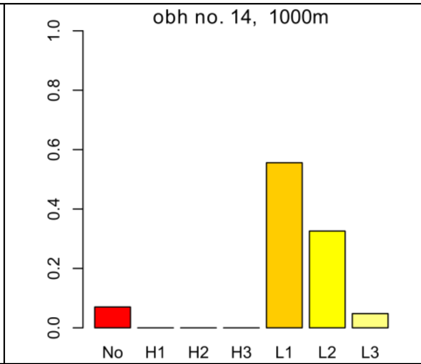
The rest water level is 2.3m below the datum.

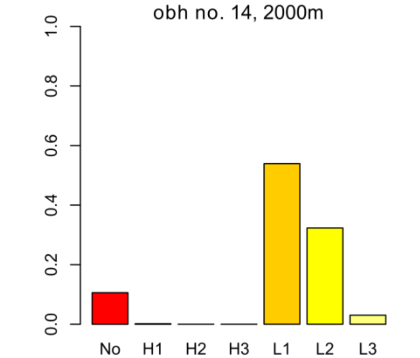
The superficial deposits around the borehole are sandy clay alluvium in the flood plain, but there some windows at the edges of the plains and glacial deposits everywhere else. The domain class 313 denotes thick superficial deposits whereas the log indicates only 5m. This inconsistency can be explained by the uncertainties associated to the domain mapping.

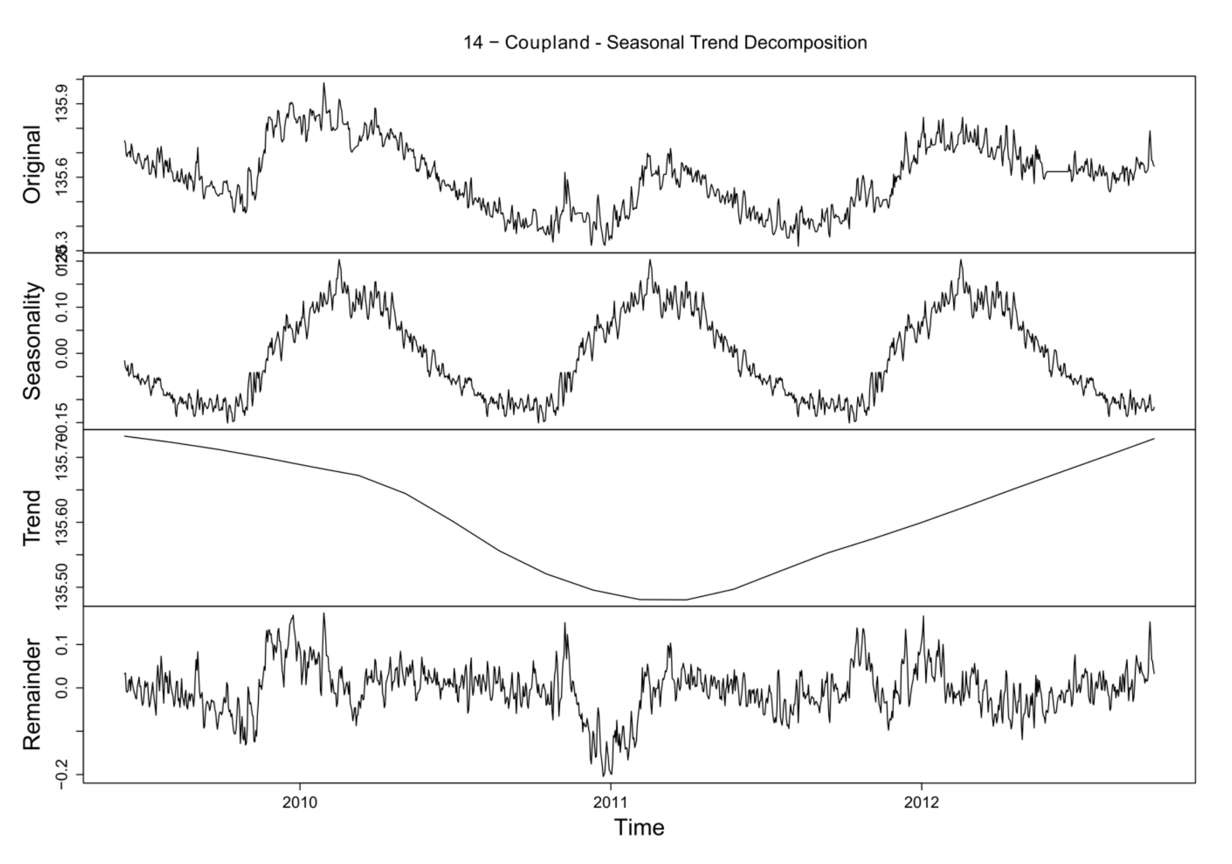


14 – Coupland – continuous recording







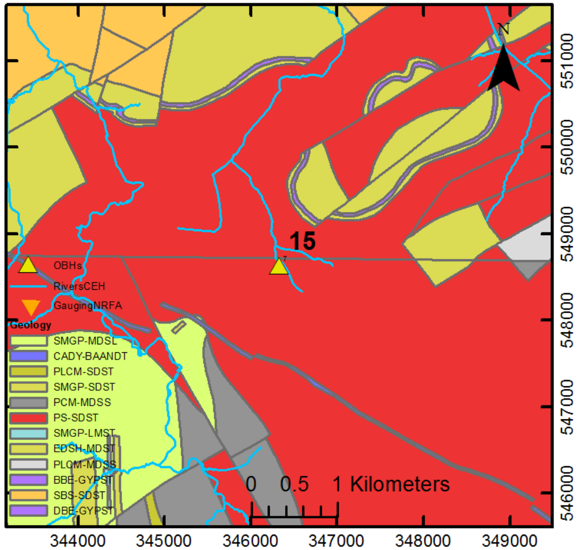


The water level ranges from 135.2 to 136 m AOD.
The variances related to the seasonality (44.5%) and to the trend (37.6%) explain most of the variance related to the original signal, though the remainder signal is noticeable.
These high frequency perturbations could be explained by connections with the surrounding surface streams.
Comparison with the Borehole no 9 (Hilton) situated on the same surface stream but in the St Bees Sandstone shows that he amplitudes of the variations are completely different, but the Coupland borehole is much closer to the River Eden (cross correlation to test, the influence of each components of the decomposition are relatively close).

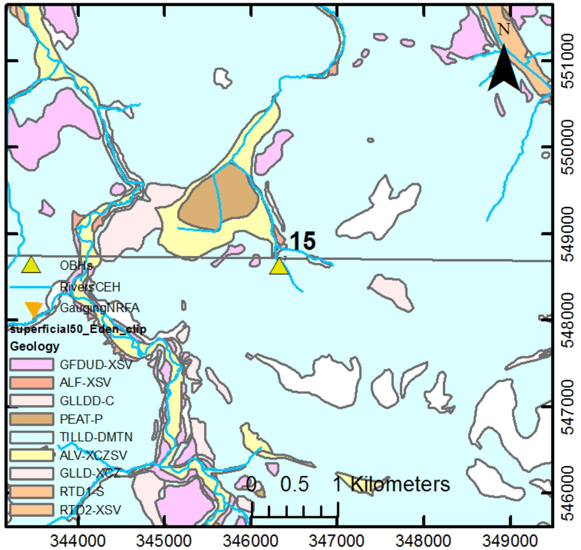
	Season.	Trend	Rem.	Original
Variance	0.0089	0.0075	0.0032	0.0201
Ratio (%)	44.5	37.6	16.1	100

14 – Coupland – continuous recording

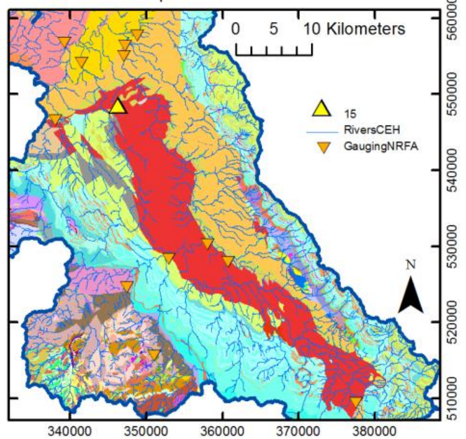
COTEHILL N CUMBRIA O, Bedrock 50k



COTEHILL N CUMBRIA O, Superficials 50k



General location map



<u>Bore name:</u> NORTH CUMB. OBH16, COTEHILL, CARLISLE

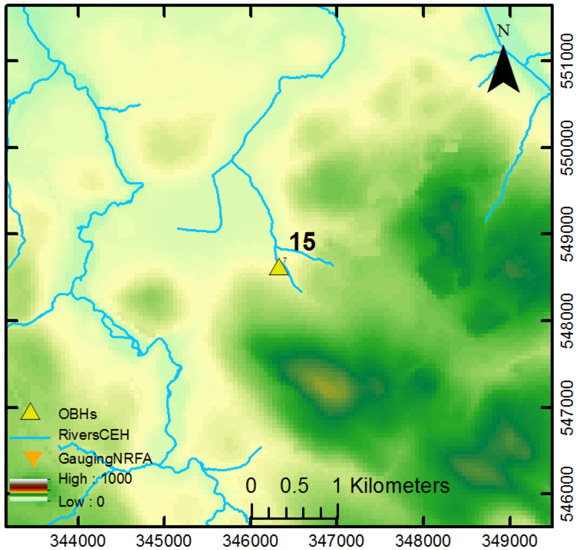
<u>Site no:</u> NY44/9

<u>Ground Level:</u> 84.6 m AOD

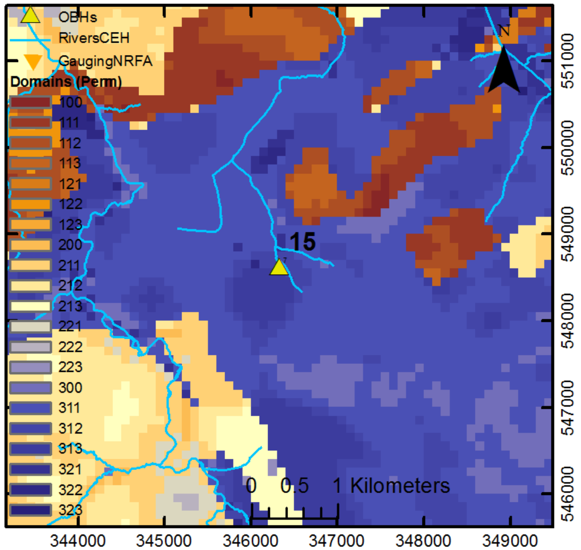
<u>Datum Level:</u>

<u>Drilled depth:</u> 91.50 m

COTEHILL N CUMBRIA O, Topography (DTM)



COTEHILL N CUMBRIA O, Domains (Permeability)



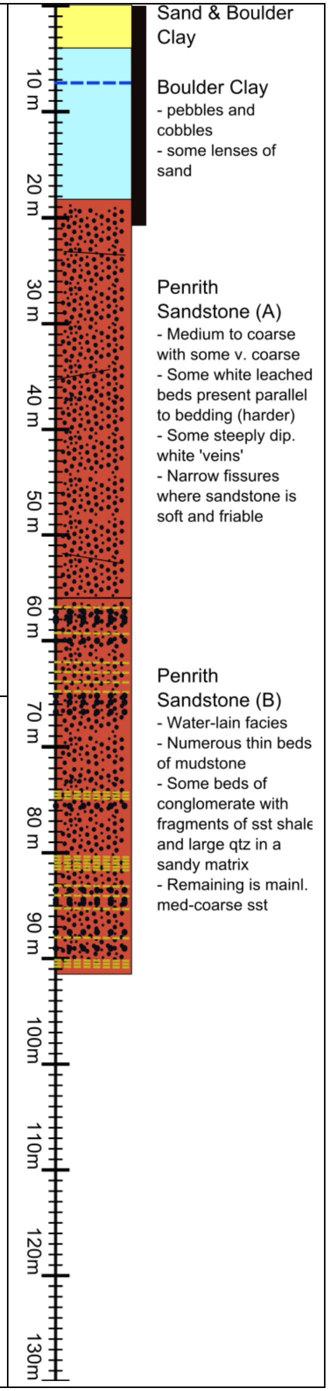
This borehole is situated south of Cotehill and south east of Carlisle.

The main aquifer is the Penrith Sandstone, which is covered by 14 m of boulder clay and 4m of alluvium.

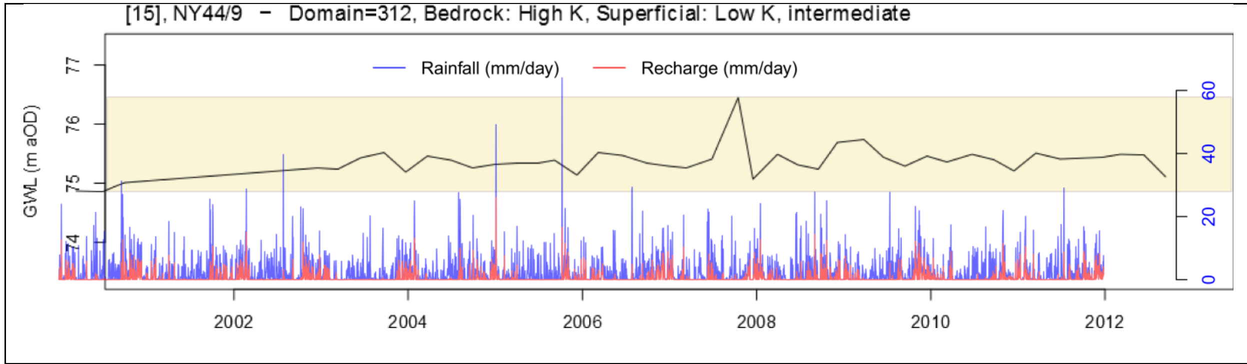
The borehole is partially surrounded to the east by a fault system.

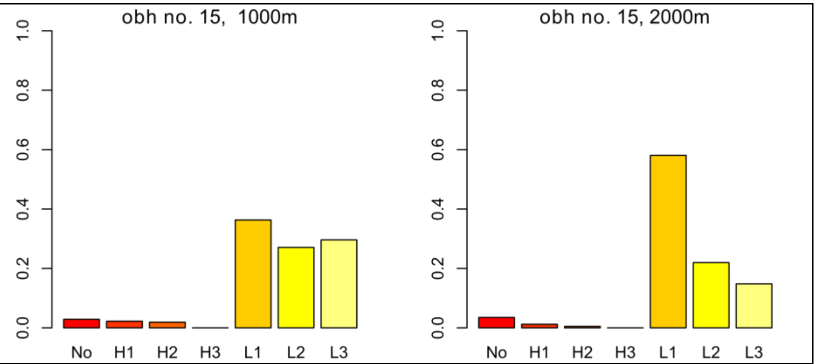
The rest water level is at 7m below the datum.

The superficial deposits around the borehole are mainly glacial deposits and low permeability alluvium.



15 – Cotehill, Carlisle – manually read





The water level ranges from 74.9 to 76.4 (only one measurement above 75.5, in Summer 2007) m AOD .

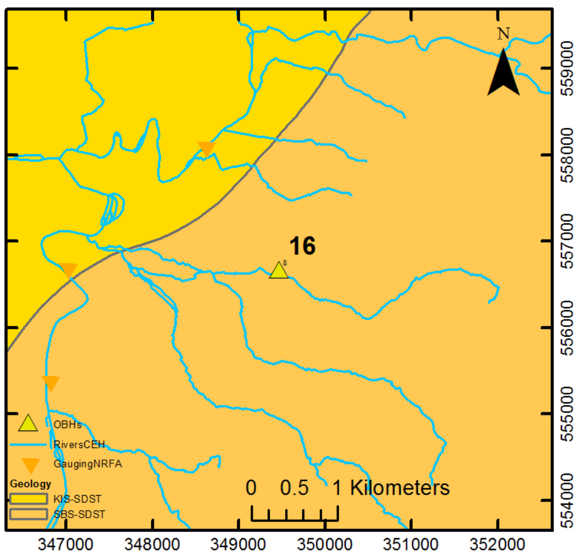
It is quite difficult to identify a seasonal variation by eye.

The superficial cover and the heterogeneity of the Penrith Sandstone may mean that this borehole is isolated from the main aquifer.

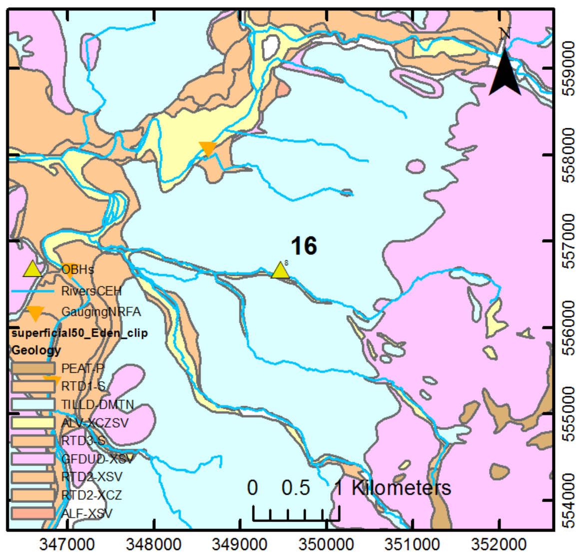
There is no major surface stream in the proximity.

15 – Cotehill, Carlisle – manually read

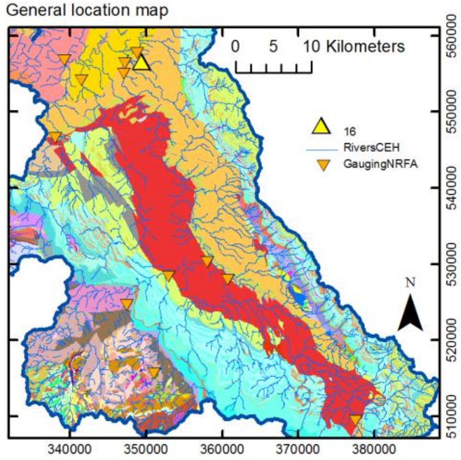
CORBY HILL N CUMBRIA, Bedrock 50k



CORBY HILL N CUMBRIA, Superficials 50k



General location map



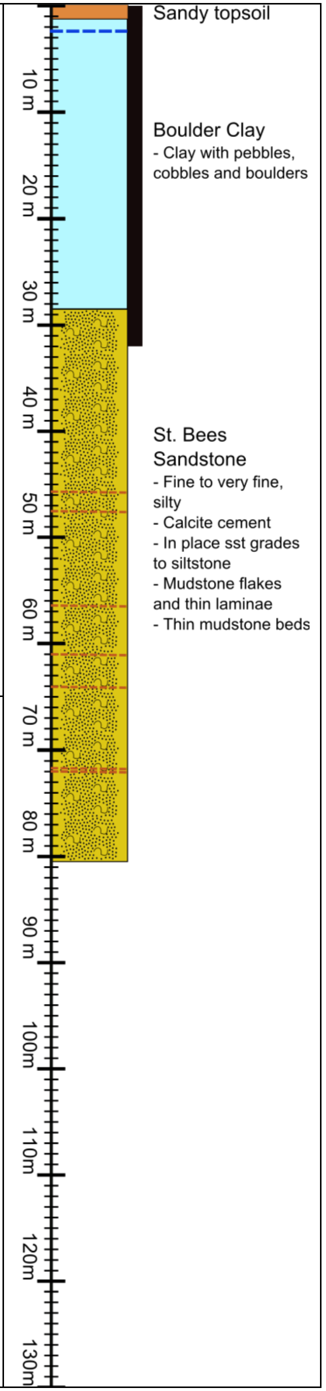
<u>*Bore name:*</u> NORTH CUMB. OBS. WELL 8, CORBY HILL

<u>*Site no:*</u> NY45/16

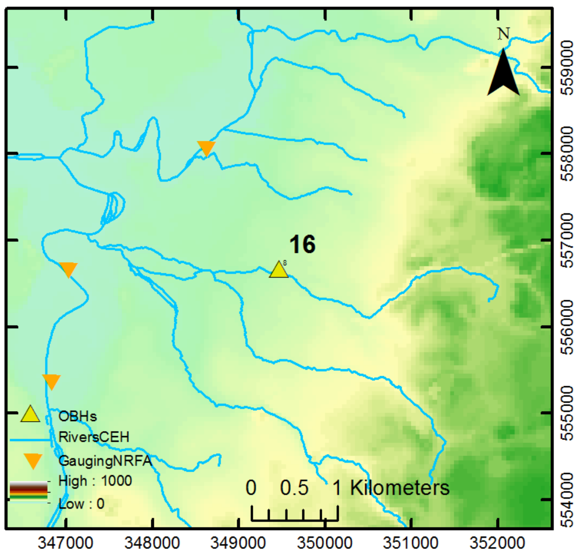
<u>*Ground Level:*</u> 51.46 m AOD

<u>*Datum Level:*</u>

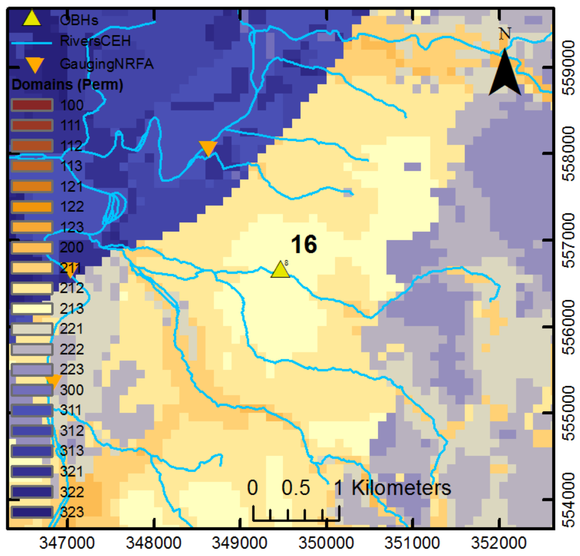
<u>*Drilled depth:*</u> 80.41 m



CORBY HILL N CUMBRIA, Topography (DTM)

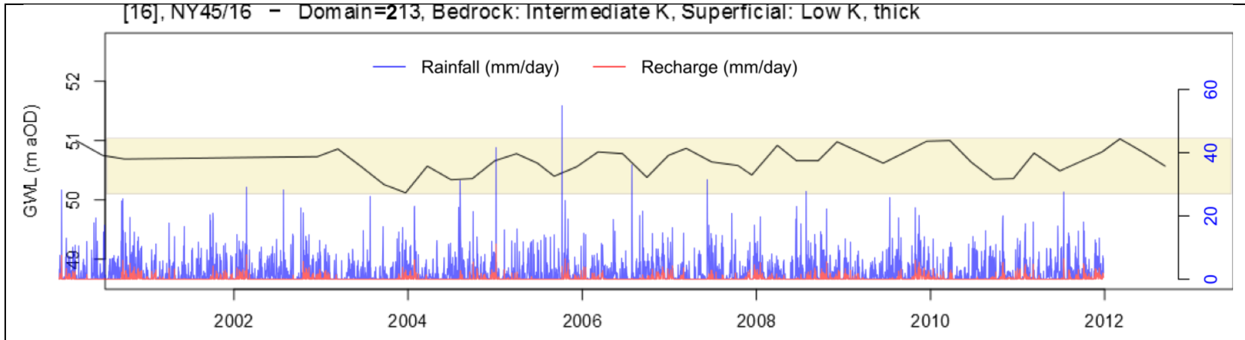


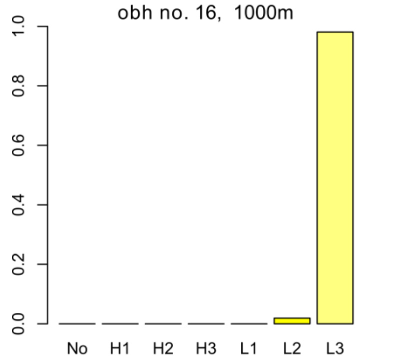
CORBY HILL N CUMBRIA, Domains (Permeability)

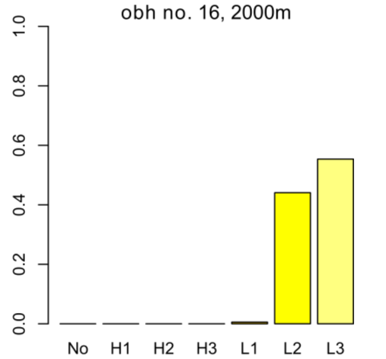


This borehole is situated in Corby Hill, 2km east of Warwick Bridge where the River Eden is gauged (NRFA gauging station). The main aquifer is the St Bees Sandstone, covered by 28m of Boulder Clay. The rest water level is 2.3m below the datum. Most of the area around the borehole is covered by thick boulder clay.

16 – Corby Hill – manually read



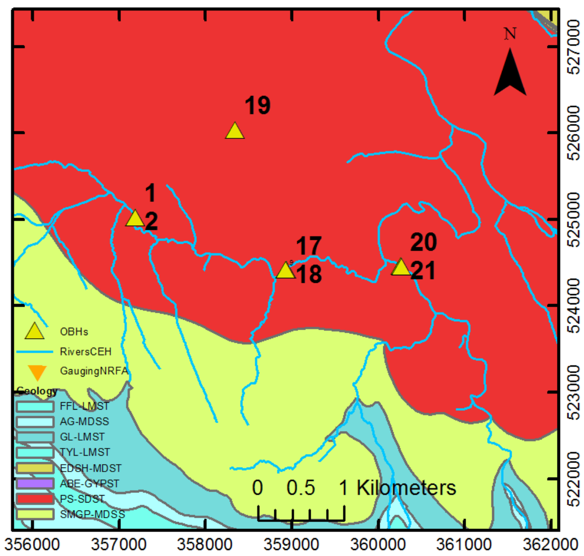




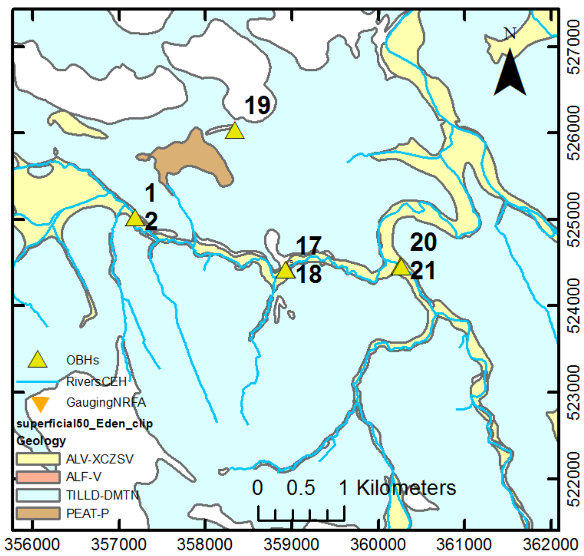
The water level ranges from 50.1 to 51.1 m AOD .
Relatively low seasonal variations (60cm) can be well identified.

16 – Corby Hill – manually read

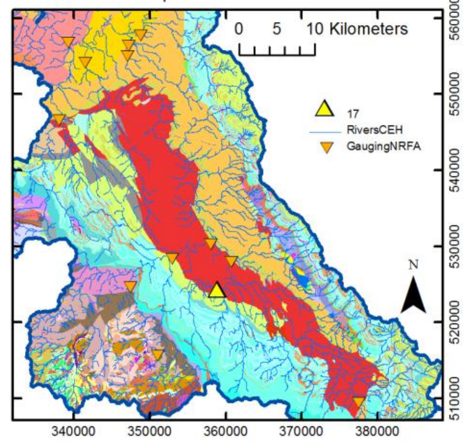
Cliburn Town Bridge OBH 2, Bedrock 50k



Cliburn Town Bridge OBH 2, Superficials 50k



General location map



Bore name: CLIBURN TOWN BRIDGE OBH 2 (EA Leith Project, Site 3)

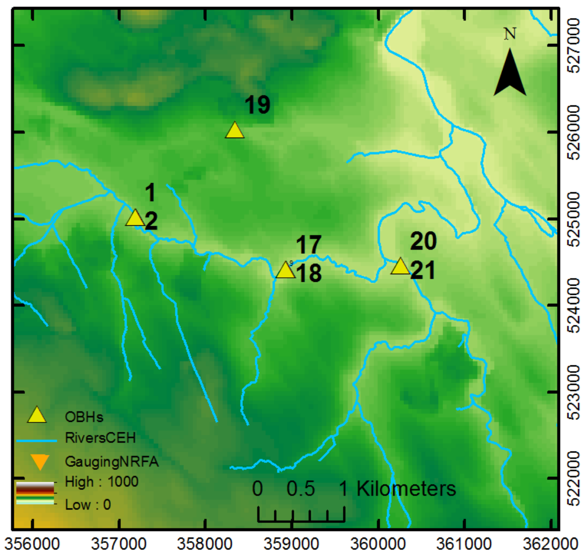
Site no: NY52/26

Ground Level: 110.95 m AOD

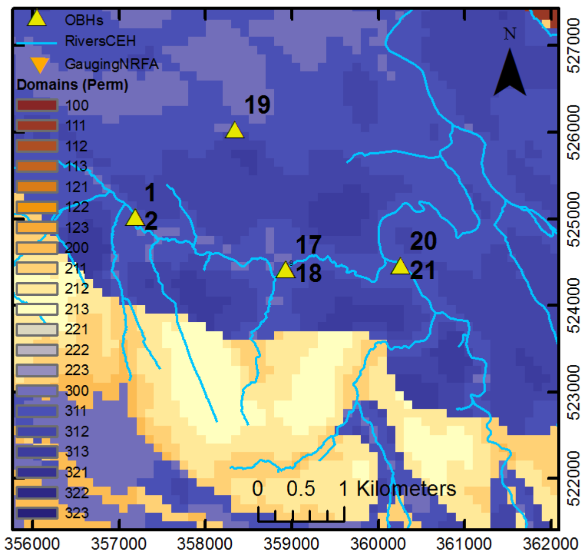
Datum Level: 112.23 m AOD

Drilled depth: 47.68 m

Cliburn Town Bridge OBH 2, Topography (DTM)



Cliburn Town Bridge OBH 2, Domains (Permeability)



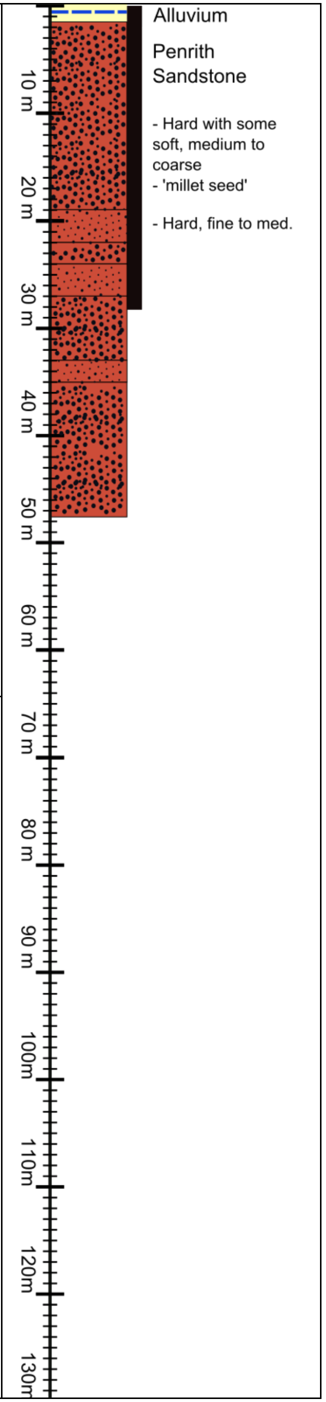
This borehole is situated on the bank of the River Leith, just south of Cliburn.

It is paired with the Obh no 18, and is part of an observation network installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith).

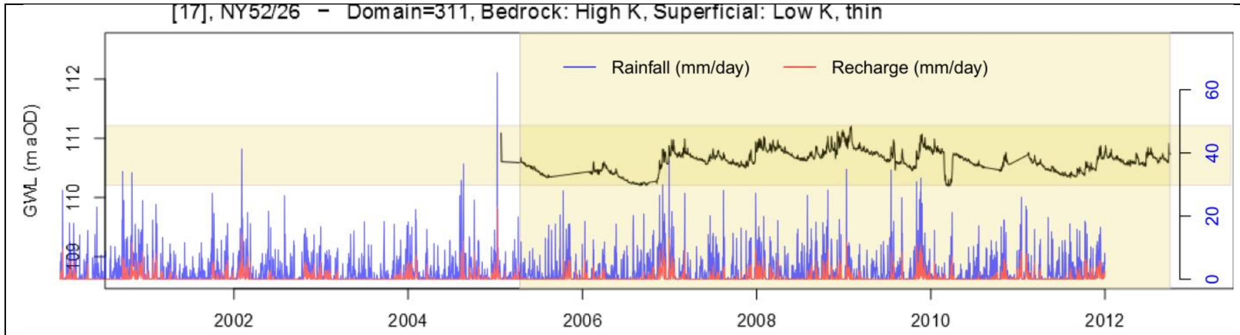
The main aquifer is the Penrith Sandstone. There are thin (1.5m) permeable quaternary alluvial deposits (the Obh is situated within the flood plain, the surrounding formations are mainly covered by superficial deposits).

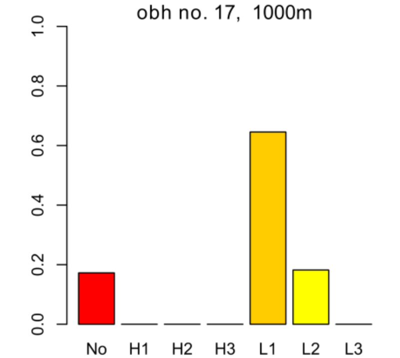
Carboniferous formations outcrop close to the borehole (<1km), made up of Millstone Grit, then the underlying Carboniferous Limestone. Upstream, the River Leith and its tributaries are fed from Carboniferous formations. Drilled to 47.68 m, screened below 28m.

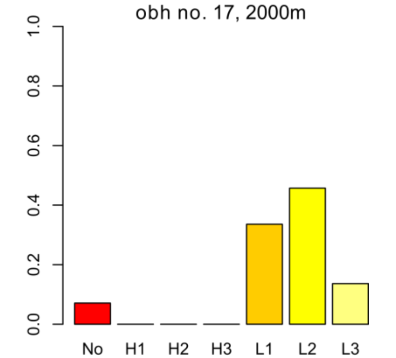
Rest water level is at 0.8m below datum.

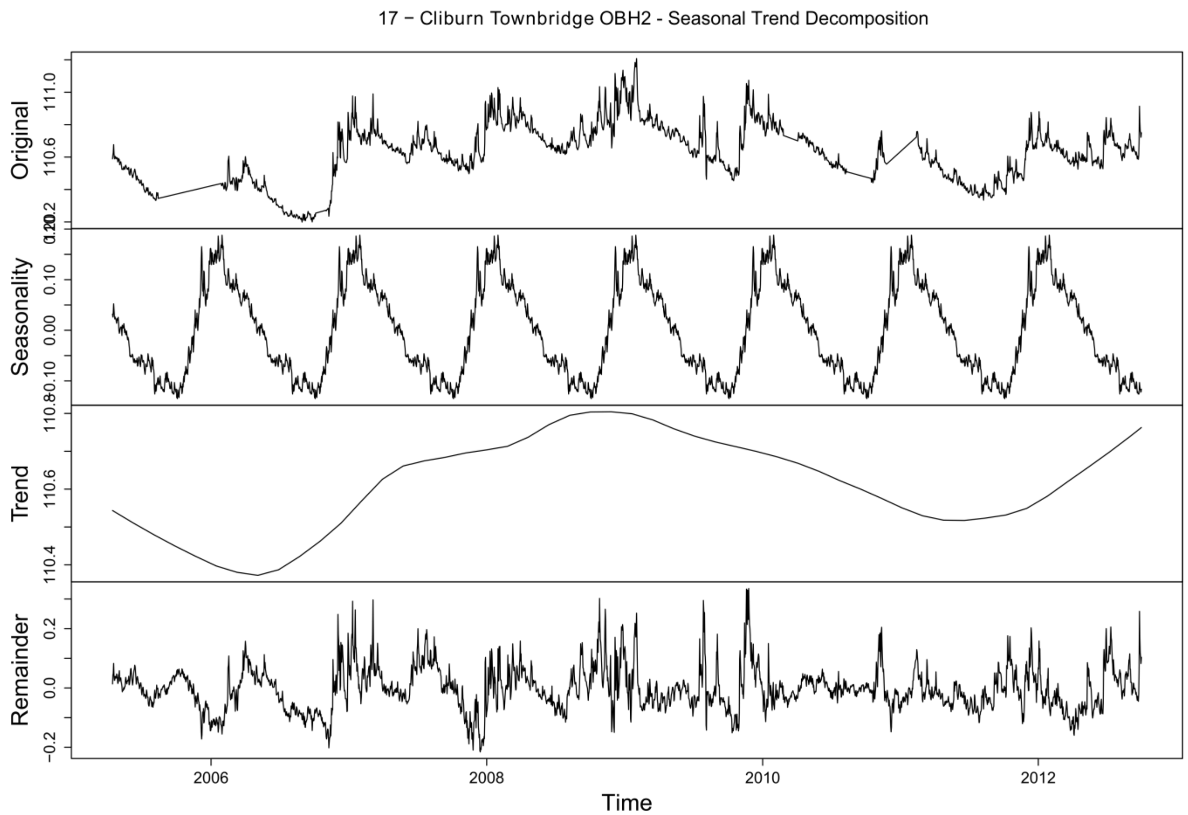


17 – Cliburn, Town Bridge (deep) – continuous recording









The water level ranges from 110.2 to 111.2 m AOD.

Paired (deep and shallow) monitoring boreholes were designed to investigate whether the aquifer is layered (vertical heterogeneity and head gradients) and the hydraulic relationship with the stream.

This deep (50m) borehole is investigating heads in the Penrith Sandstone. The groundwater head is higher in this borehole than in the shallow one (obh 18) indicating potential upward groundwater movement It seems likely that this is due to some degree of vertical heterogeneity within the Penrith Sandstone aquifer. The head in this deeper piezometer is above the bed level of the Leith, so there is potential groundwater to enter the river.

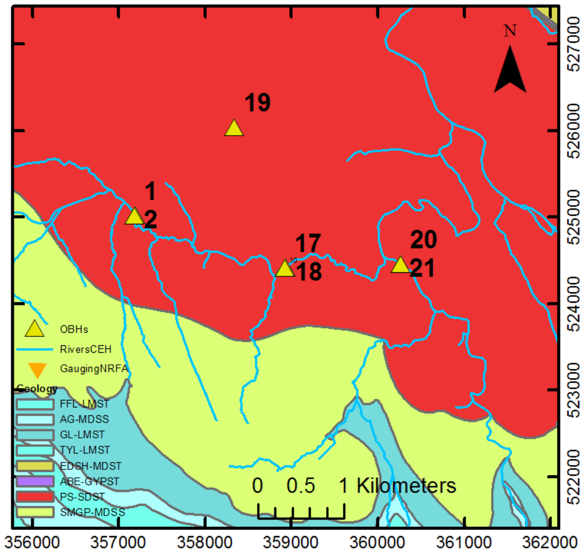
The variance associated with the general trend (47.9%) has the most important influence on the hydrograph in this case. The influence of the short time scale events is less important than in the case of the shallow piezometer. According to the EA report, this piezometer responds to barometric pressure changes rather than rainfall or river events, which means that the deeper parts of the aquifer must be confined by lower permeability layers.

This vertical heterogeneity can be explained by the presence of low permeability siliceous layers and variations in grain size of the sandstone (observed in the related geological log). This is characteristic of the Penrith Sandstone elsewhere in the Eden Valley (EA report 2008, Younger and Milne 1997, etc.).

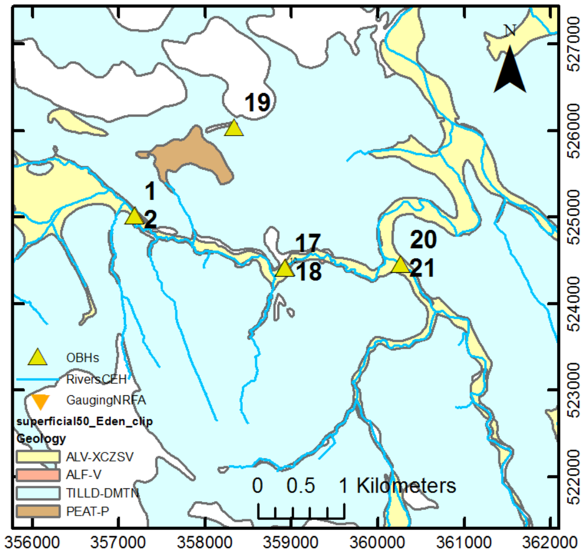
	Season.	Trend	Rem.	Original
Variance	0.0103	0.0159	0.0057	0.0332
Ratio (%)	31.1	47.9	17.2	100

17 – Cliburn, Town Bridge (deep) – continuous recording

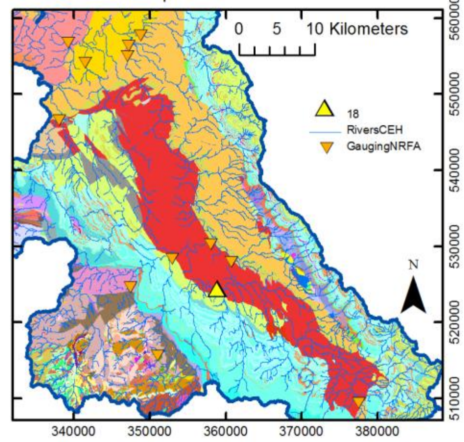
Cliburn Town Bridge OBH 1, Bedrock 50k



Cliburn Town Bridge OBH 1, Superficials 50k

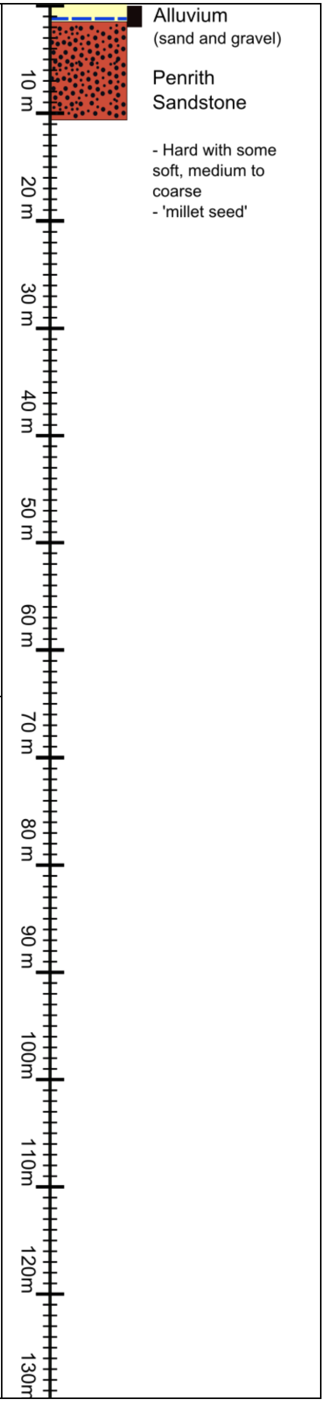


General location map

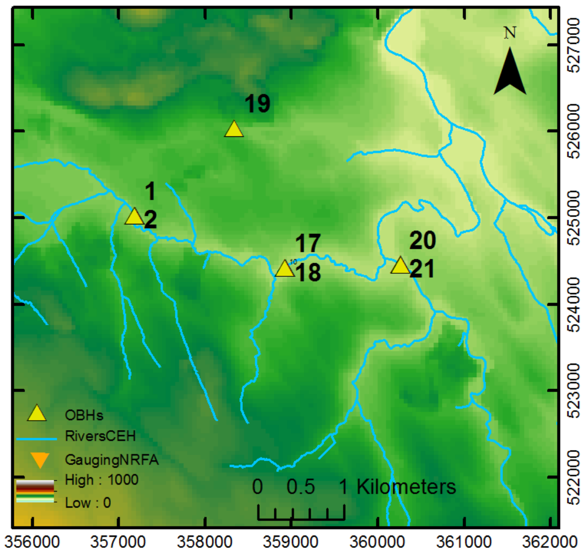


__Bore name:__ CLIBURN TOWN BRIDGE OBH 1 (EA Leith Project, Site 3A)
__Site no:__ NY52/25
__Ground Level:__ 110.93 m AOD
__Datum Level:__ 112.23 m AOD
__Drilled depth:__ 10.87 m

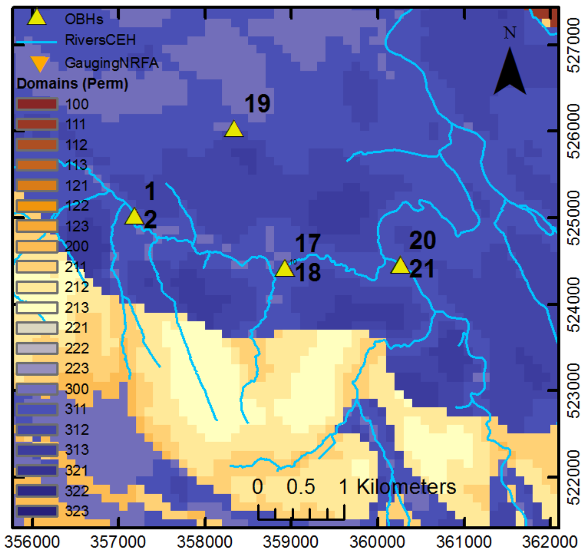
This borehole is situated on the bank of the River Leith, just south of Cliburn.
It is paired with the Obh no 17, and is part of an observation network installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith).
The main aquifer is the Penrith Sandstone. There are thin (1.5m) permeable quaternary alluvial deposits (the Obh is situated within the flood plain, the surrounding formations are mainly covered by superficial deposits).
Carboniferous formations outcrop close to the borehole (<1km), made up of Millstone Grit, then the underlying Carboniferous Limestone. Upstream, the River Leith and its tributaries are fed from Carboniferous formations.
Drilled to 10.87m, screened below 2m.
The rest water level is at 1.1m (Alluvium).



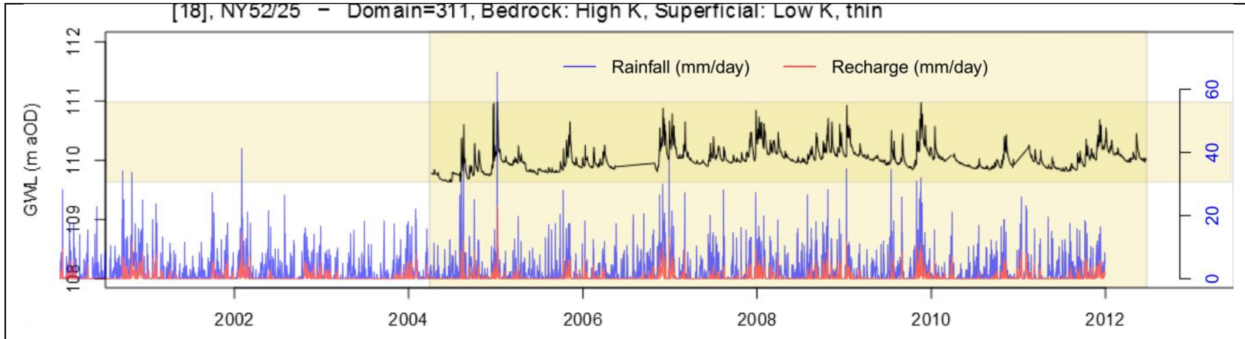
Cliburn Town Bridge OBH 1, Topography (DTM)

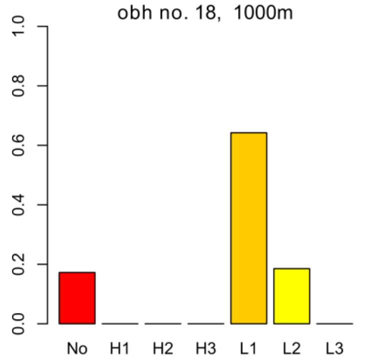


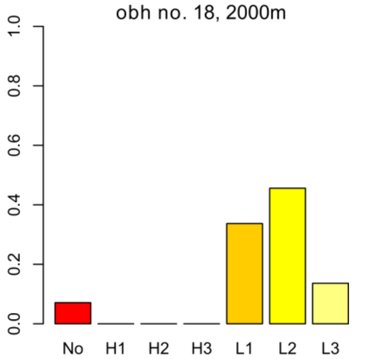
Cliburn Town Bridge OBH 1, Domains (Permeability)

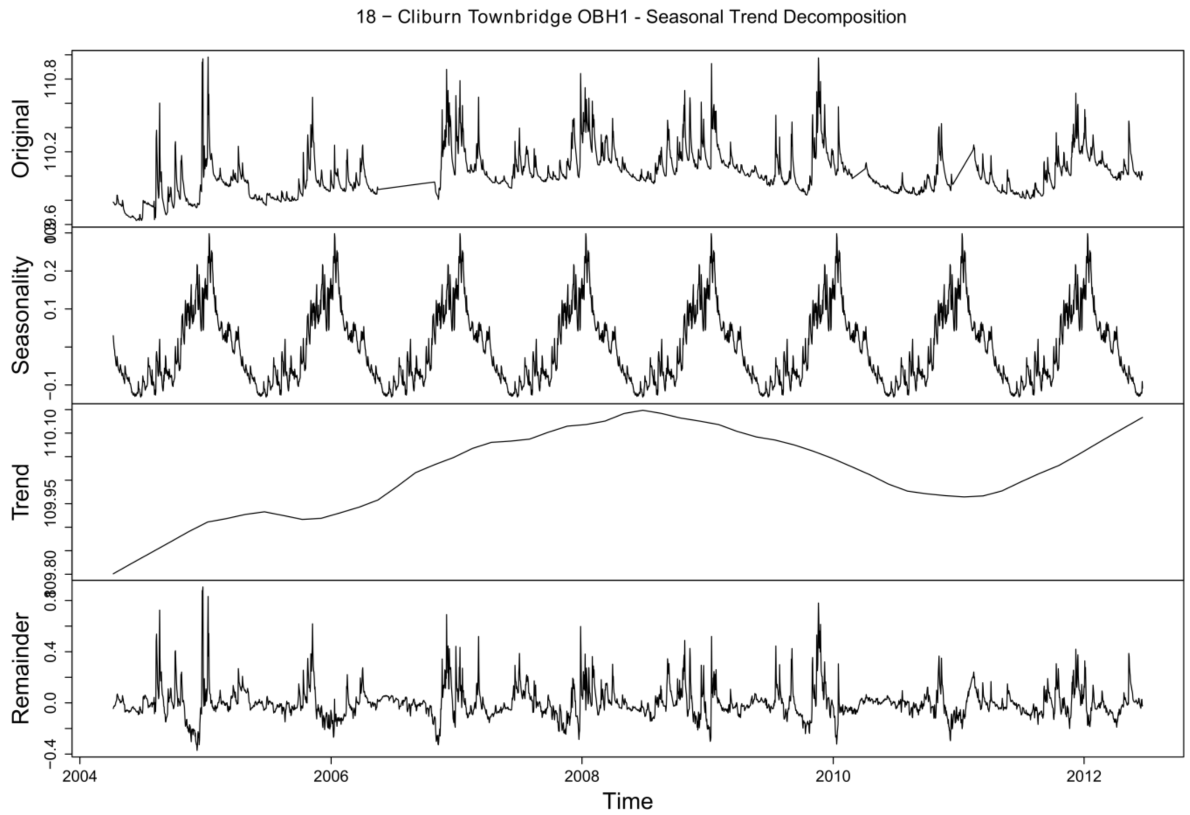


18 – Cliburn, Town Bridge (shallow) – continuous recording









The water level ranges from 109.6 m AOD to 111.0 m AOD.

Paired (deep and shallow) monitoring boreholes were designed to investigate whether the aquifer is layered (vertical heterogeneity and head gradients) and the hydraulic relationship with the stream.

This shallow observation borehole targets the same response zone as the river and associated superficial deposits.

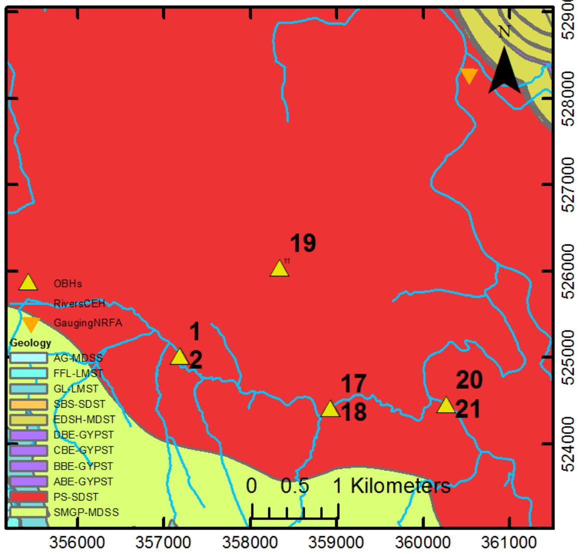
The seasonal trend decomposition shows that the variance associated to the general trend has only a slight (21.9%) influence on the variance of the original time series. The remainder appears to be the most influential component (44.7%). This seems to indicate major influence of the short time scale events, which is consistent with the shallow construction of this borehole and the proximity to the river.

The hydrograph looks very similar to that of a river stream (According to the EA report, the responses are very similar to the Leith levels and flows) indicating good connectivity between the river and the shallower parts of the sandstone and alluvial deposits.

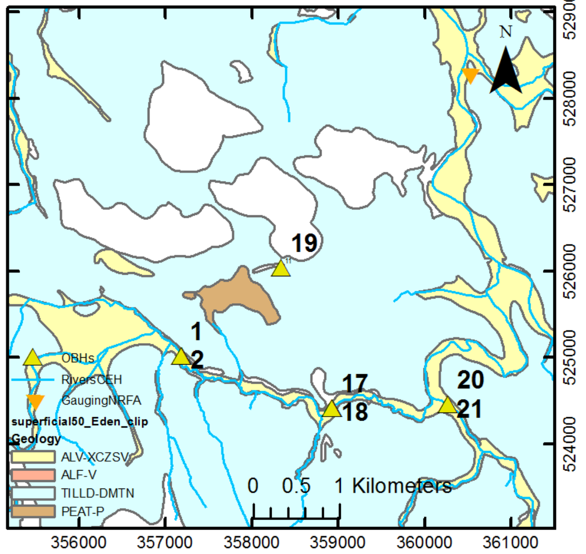
	Season.	Trend	Rem.	Original
Variance	0.0100	0.0075	0.0153	0.0342
Ratio (%)	29.3	21.9	44.7	100

18 – Cliburn, Town Bridge (shallow) – continuous recording

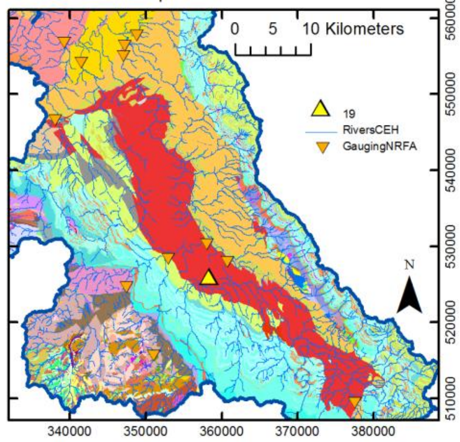
CLIBURN 3A REP NO.3, Bedrock 50k



CLIBURN 3A REP NO.3, Superficials 50k



General location map



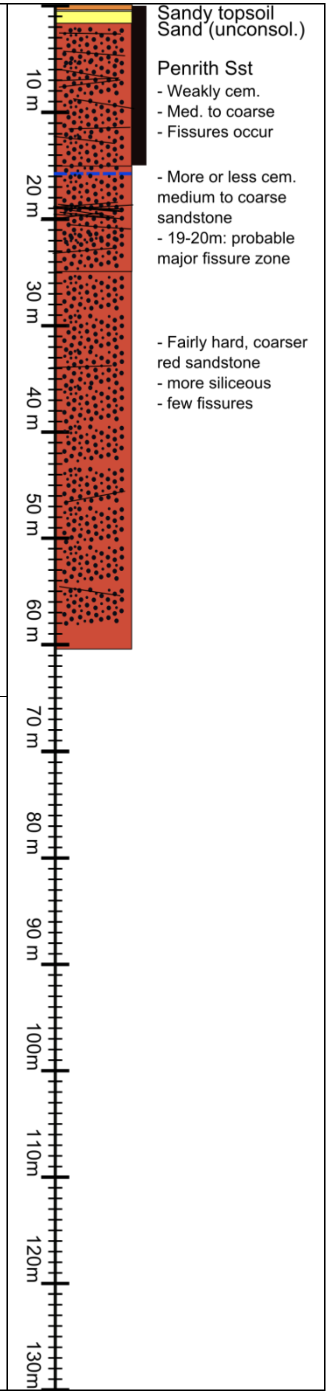
<u>*Bore name:*</u> CLIBURN OBH 3A

<u>*Site no:*</u> NY52/2H

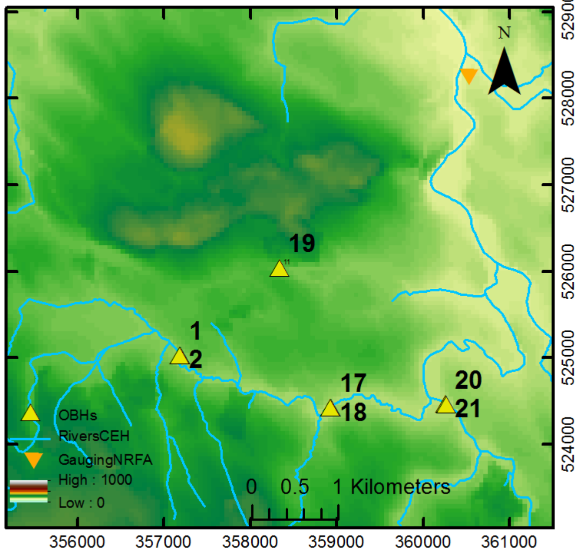
<u>*Ground Level:*</u> 130.2 m AOD

<u>*Start height:*</u> 128.61 m

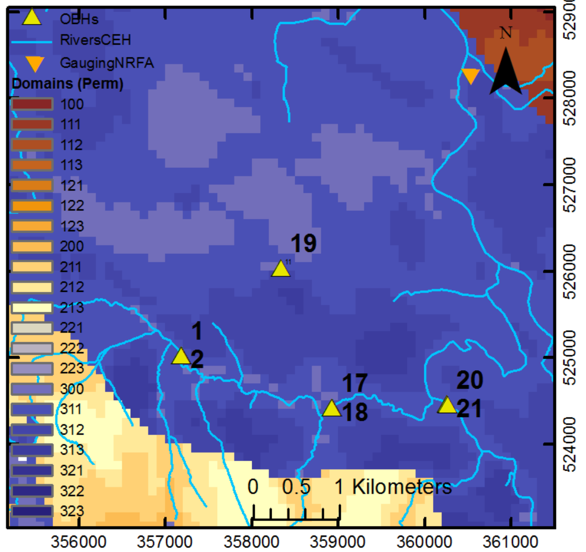
<u>*Drilled depth:*</u> 60 m



CLIBURN 3A REP NO.3, Topography (DTM)

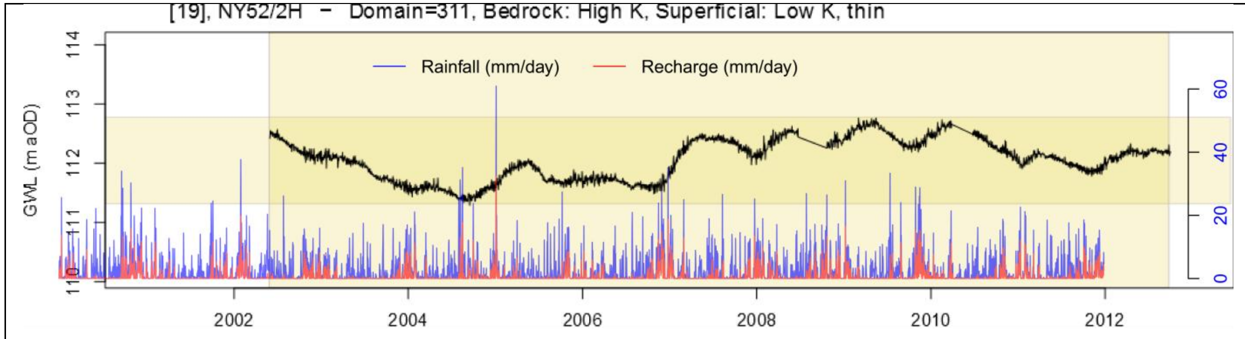


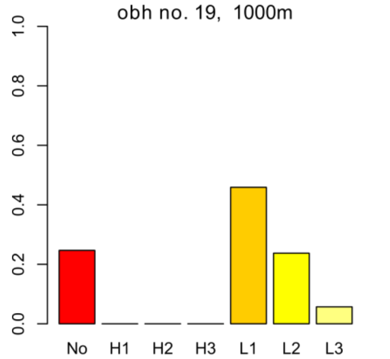
CLIBURN 3A REP NO.3, Domains (Permeability)

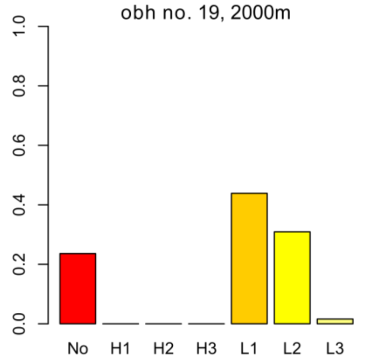


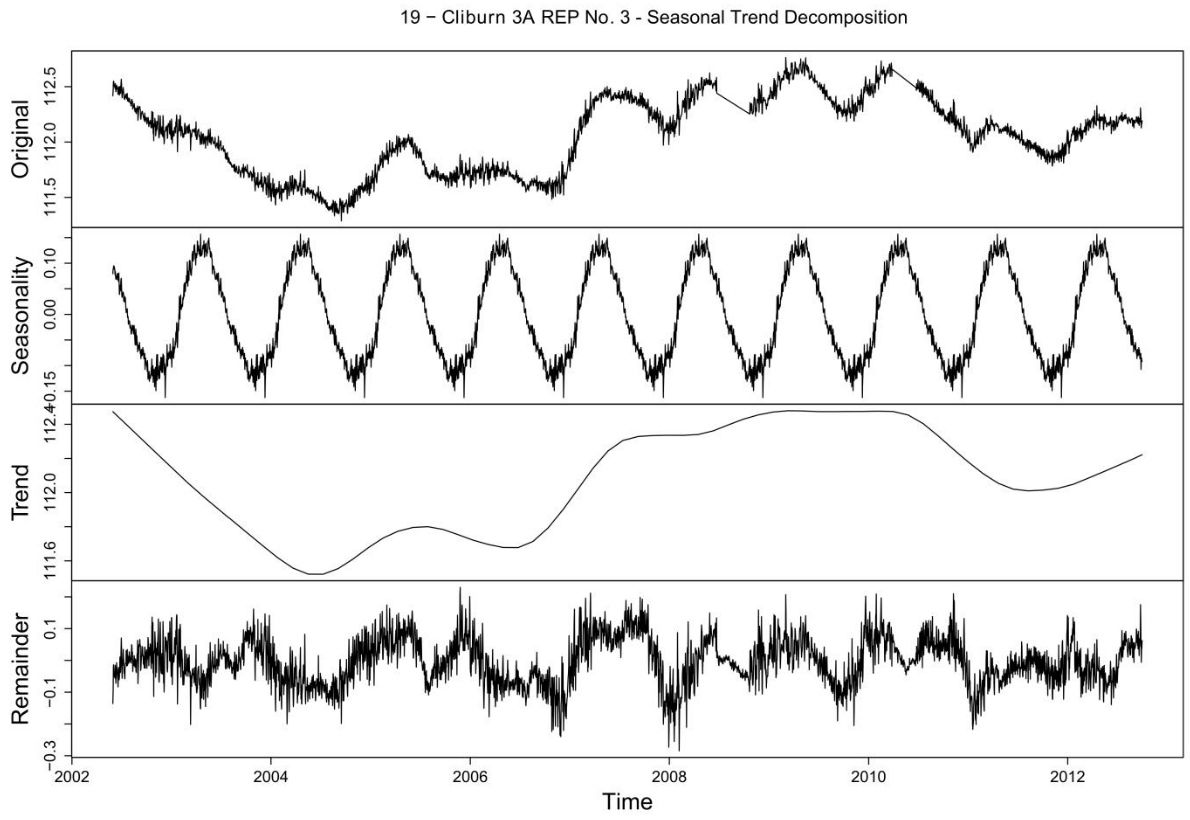
This borehole is situated North of Cliburn, just south of the Whinfell Forest (silicified Penrith Sandstone outcrop, Holiday Village) and East of the Cliburn Moss National Nature Reserve which is peat covered.
The main aquifer is the Penrith Sandstone Formation, with unconsolidated sand at the top.
The rest water level is at 16m below the datum.
South of the borehole, the sandstone is mainly covered by superficial depoaits, while harder sandstone outcrops to the north.

19 – Cliburn OBH 3A – continuous recording









The water level ranges from 111.3 to 112.8 m AOD.

The variance related to the trend (81.2%) explains most of the variance in the original signal.

Low permeability siliceous layers and variations in grain size of the sandstone are seen in the borehole geological log). This is characteristic feature of the Penrith Sandstone elsewhere in the Eden Valley (EA report 2008, Younger and Milne 1997, etc.).

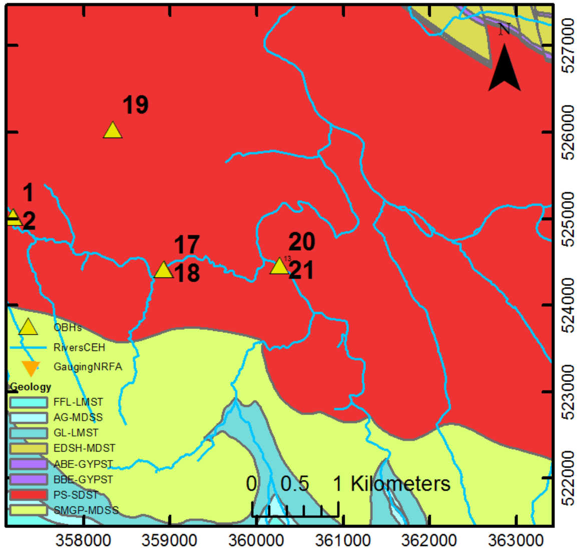
Seasonality and trend can be easily observed, but the amplitude of the seasonality is lower than the amplitude of the general trend. There are oscillations related to short term events, but these are not as important as for the borehole situated very close to the River Leith .

There is no surface stream near this observation borehole.

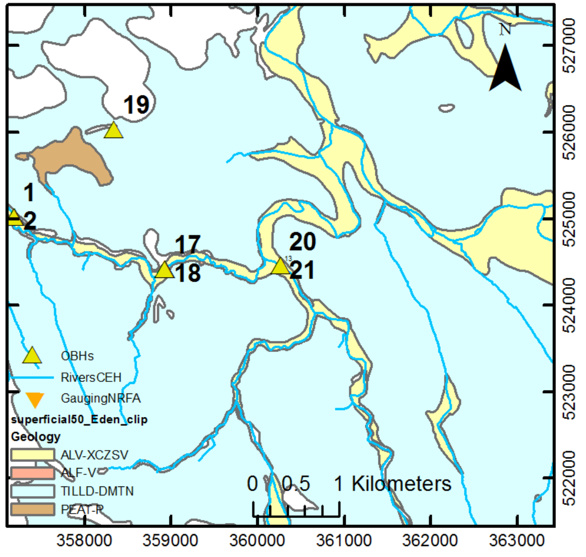
	Season.	Trend	Rem.	Original
Variance	0.0080	0.1006	0.0055	0.1239
Ratio (%)	6.4	81.2	4.4	100

19 – Cliburn OBH 3A – continuous recording

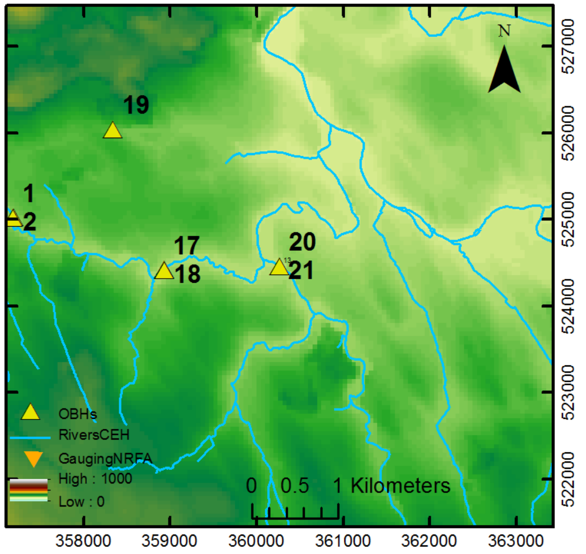
Cliburn Mill River Lyvennet OB, Bedrock 50k



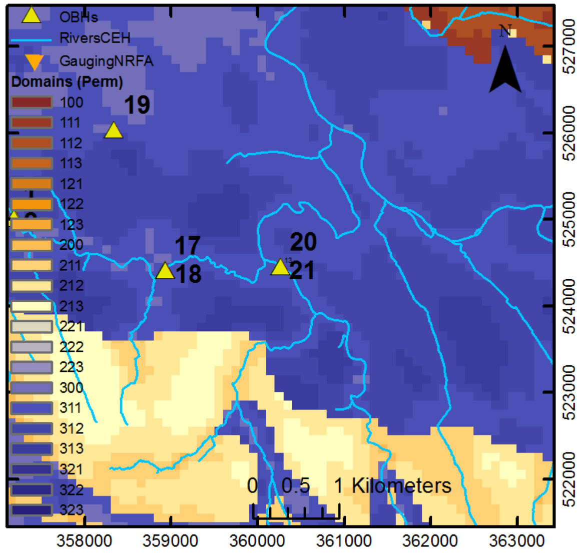
Cliburn Mill River Lyvennet OB, Superficials 50k



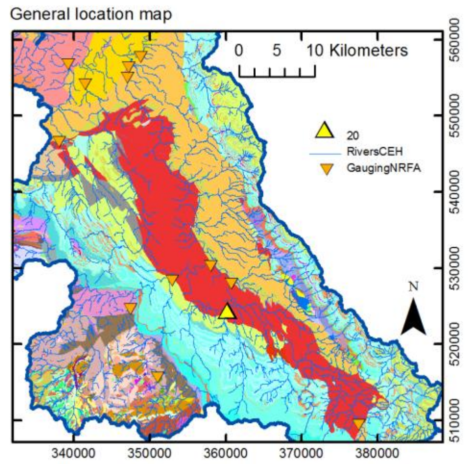
Cliburn Mill River Lyvennet OB, Topography (DTM)



Cliburn Mill River Lyvennet OB, Domains (Permeability)

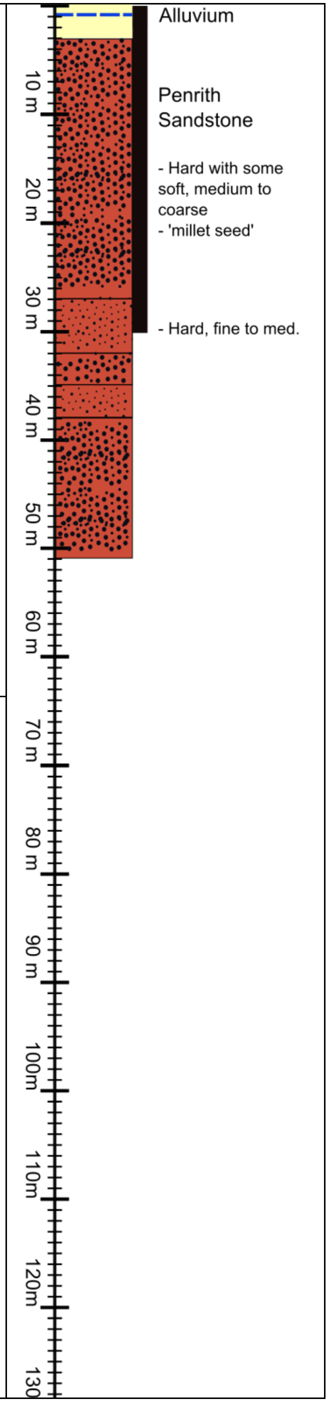


General location map

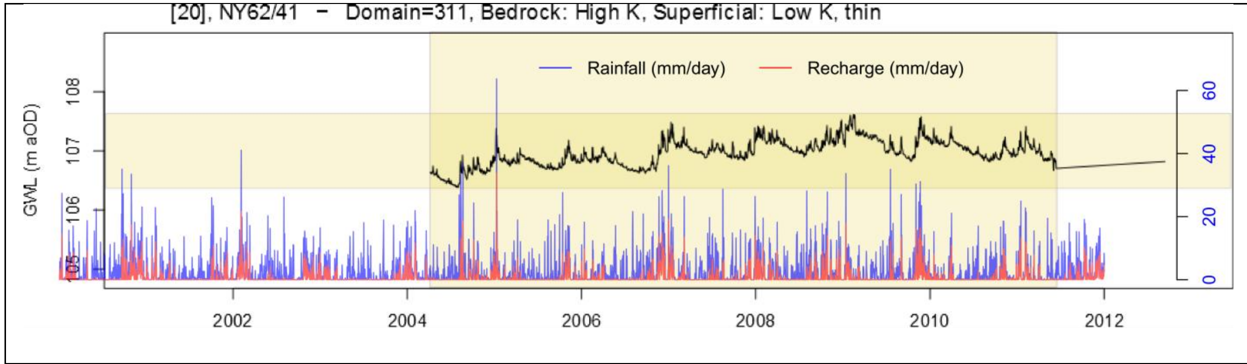


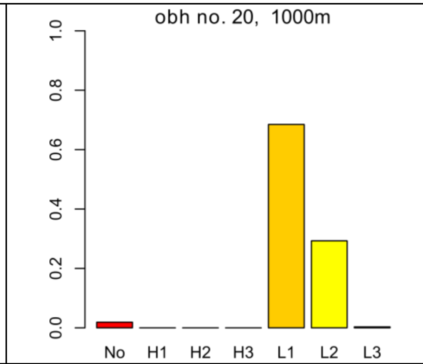
Bore name: CLIBURN MILL, RIVER LYVENNET 2 (EA Leith Project, Site 4)
Site no: NY62/41
Ground Level: 107.68 m AOD
Datum Level: 108.95 m AOD
Drilled depth: 51.07 m

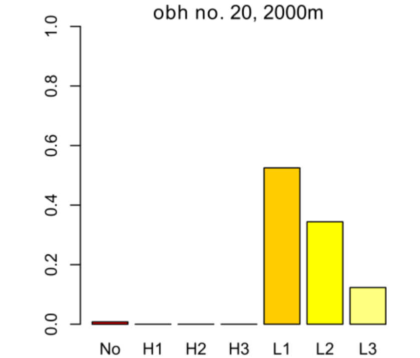
This borehole is situated at the confluence of the River Leith with the River Lyvennet. It is paired with the Obh no 21, and is part of an observation network installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith). Main aquifer is the Penrith Sandstone. Relatively thin (3.0m) permeable quaternary alluvial deposits, overlie the Penrith Sst. The borehole is situated within the flood plain and the surrounding formations are mainly covered by glacial superficial deposits. Carboniferous formations outcrop close to the borehole (<1km) comprising Millstone Grit, then the underlying Carboniferous Limestone. The upstream River Leith and the Lyvennet and its tributaries flow over Carboniferous formations.
Drilled to 51.07 m, screened below 30m.
The rest water level is at 0.9m below dip.

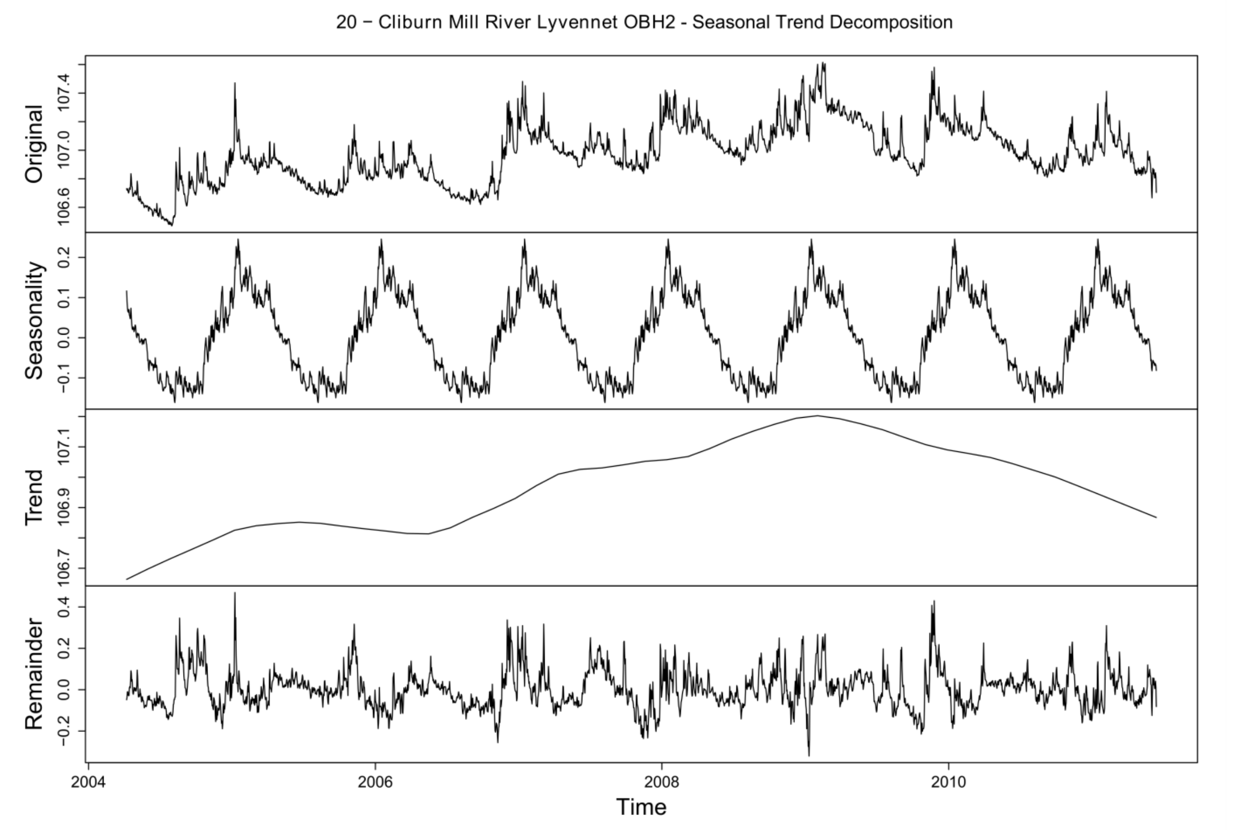


20 – Cliburn, Lyvennet (deep) – continuous recording







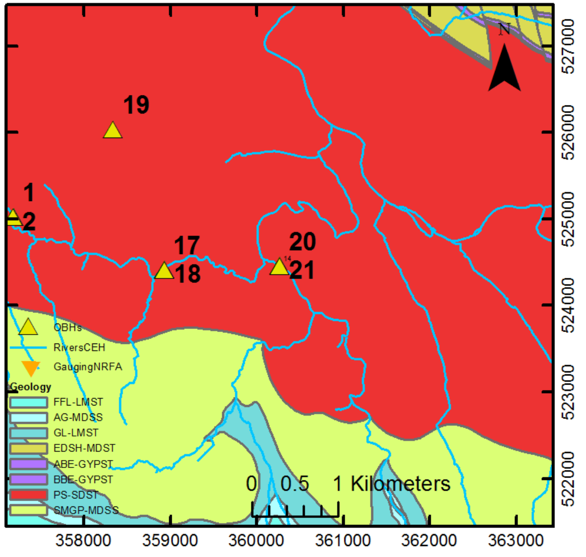


The water level ranges from 106.4 to 107.6 m AOD.
Paired (deep and shallow) monitoring boreholes were designed to investigate whether the aquifer is layered (vertical heterogeneity and head gradients) and the hydraulic relationship with the stream.
This deep (50m) borehole is investigating heads in the Penrith Sandstone. The groundwater head is higher in this borehole than in the shallow one (obh 21) indicating potential upward groundwater movement. It seems likely that this is due to some degree of vertical heterogeneity within the Penrith Sandstone aquifer. The head in this deeper piezometer is above the bed level of the river, so there is potential groundwater to enter the river.
The variance associated to the general trend (66.3%) has the most important influence in this case. The influence of the short time scale events is less important than in the case of the shallow piezometer.
According to the EA report, this piezometer responds to barometric pressure changes rather than rainfall or river events, which means that the deeper parts of the aquifer must be confined by lower permeability layers. This vertical heterogeneity can be explained by the presence of low permeability siliceous layers and variations in grain size of the sandstone which were observed in the geological log. This is characteristic of the Penrith Sandstone elsewhere in the Eden Valley (EA report 2008, Younger and Milne 1997, etc.).

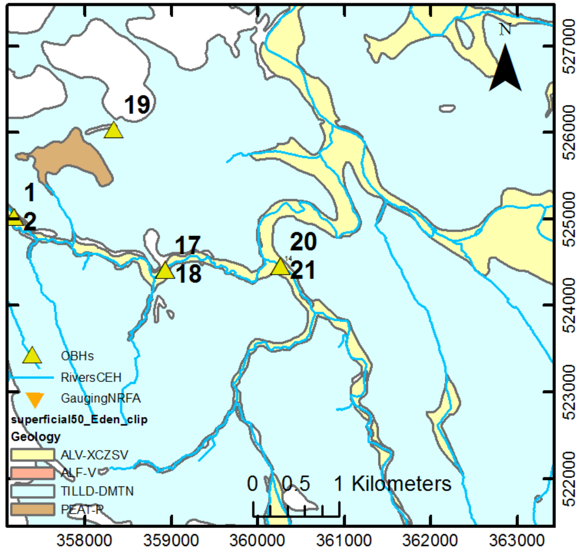
	Season.	Trend	Rem.	Original
Variance	0.0093	0.0416	0.0091	0.0627
Ratio (%)	14.8	66.3	14.5	100

20 – Cliburn, Lyvennet (deep) – continuous recording

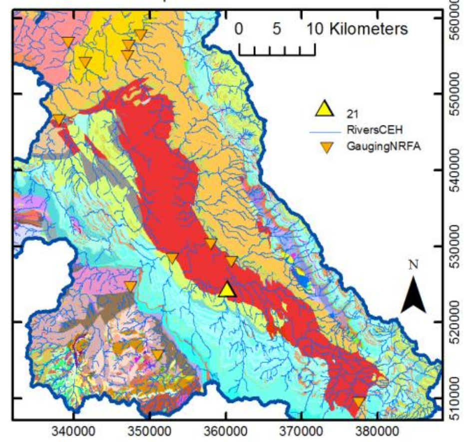
Cliburn Mill River Lyvennet OB, Bedrock 50k



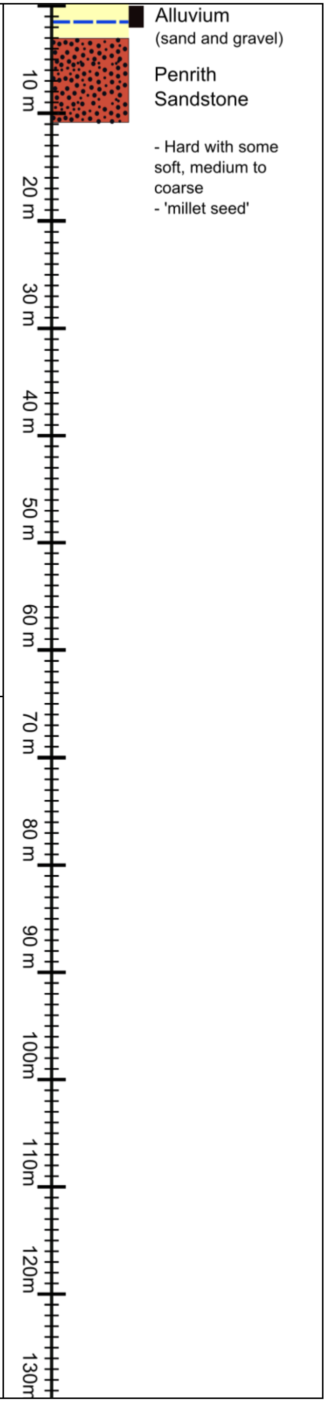
Cliburn Mill River Lyvennet OB, Superficials 50k



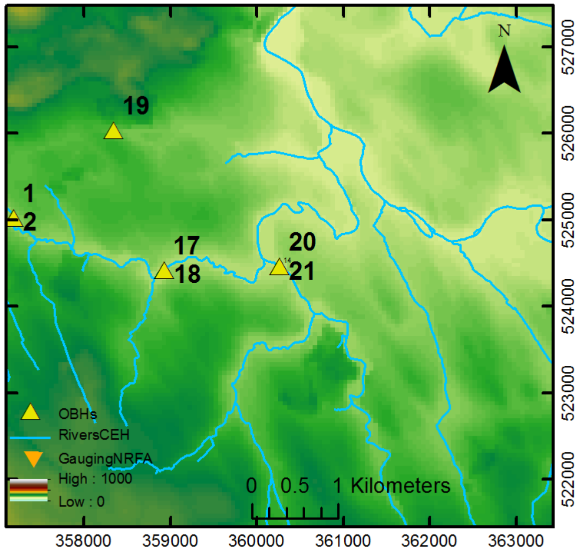
General location map



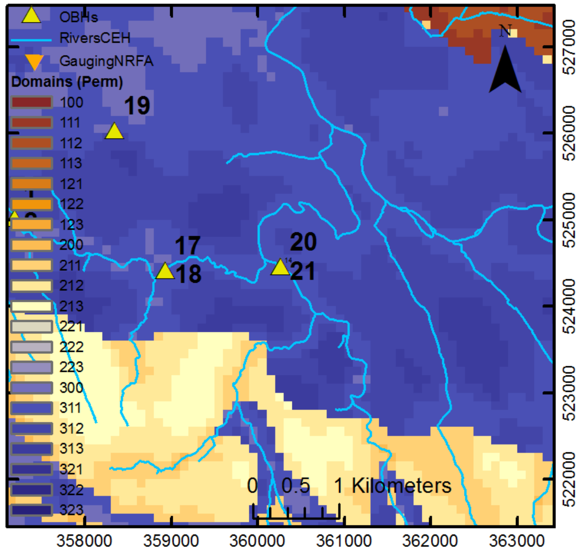
Bore name: CLIBURN MILL, RIVER LYVENNET 1 (EA Leith Project, Site 4A)
Site no: NY62/40
Ground Level: 107.65 m AOD
Datum Level: 108.85 m AOD
Drilled depth: 10.94 m



Cliburn Mill River Lyvennet OB, Topography (DTM)

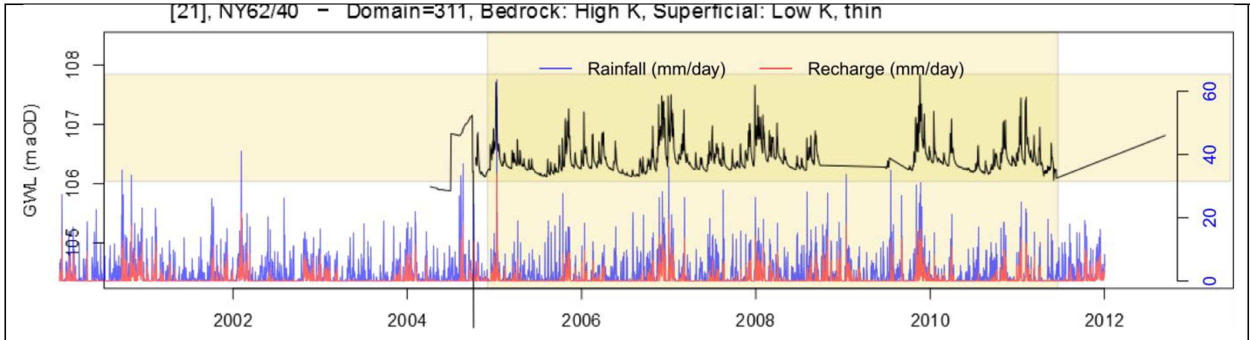


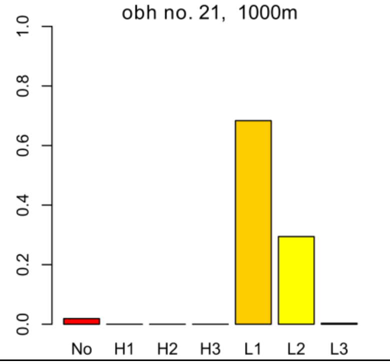
Cliburn Mill River Lyvennet OB, Domains (Permeability)

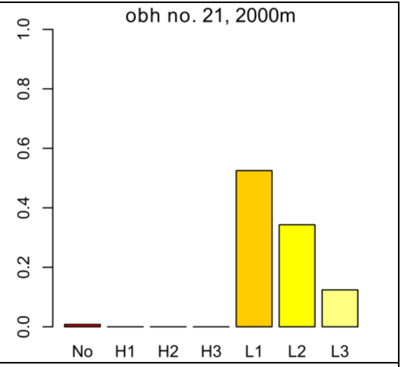


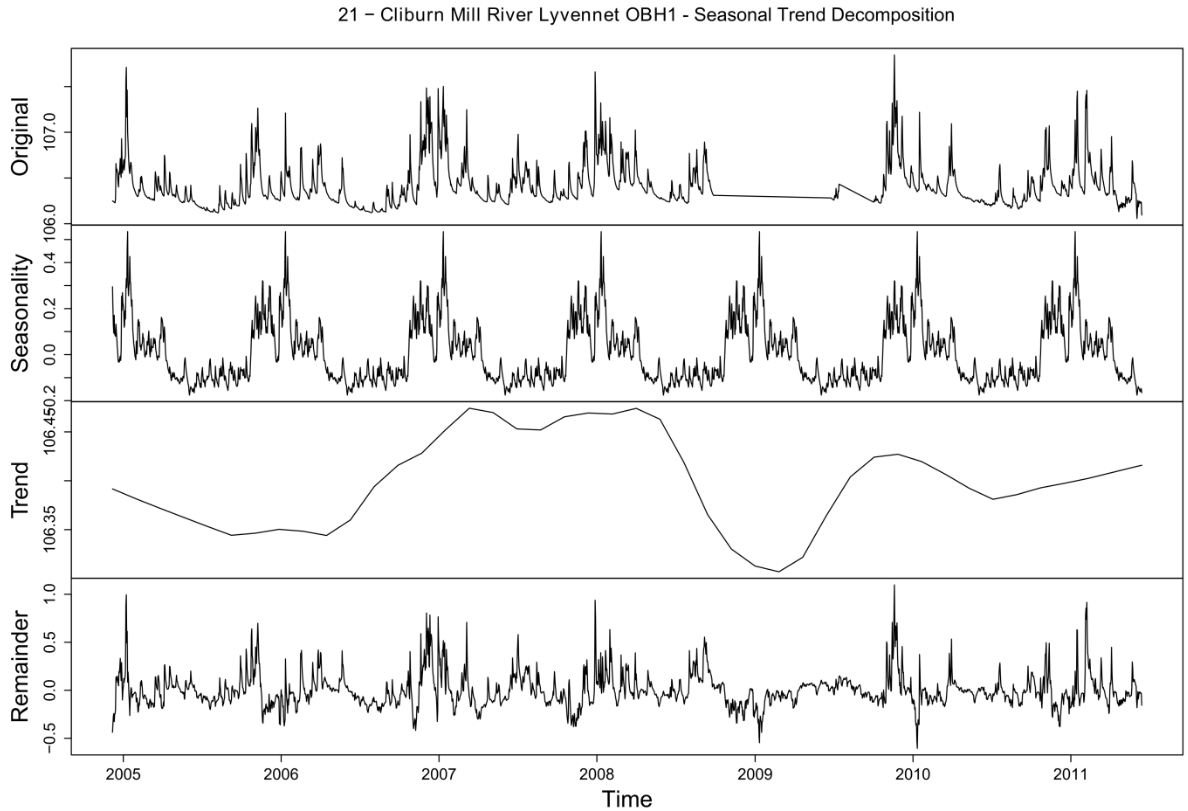
This borehole is situated at the confluence of the River Leith with the Lyvennet.
It is paired with the Obh no 20, and is part of an observation network installed by the EA in 2004 (groundwater-surface water interactions and the impact of abstractions on the River Leith). Main aquifer is the Penrith Sandstone. Relatively thin (3.0m) permeable quaternary alluvial deposits overlie the Penrith Sst. The borehole is situated within the flood plain and the surrounding formations are mainly drift covered. Carboniferous formations outcrop close to the borehole (<1km) comprising Millstone Grit, then the underlying Carboniferous Limestone.
The upstream River Leith the Lyvennet and its tributaries is fed by Carboniferous formations.
Drilled to 10.94m, screened below 2m.
The rest water level is at 1.5m below dip.

21 – Cliburn, Lyvennet (shallow) – continuous recording







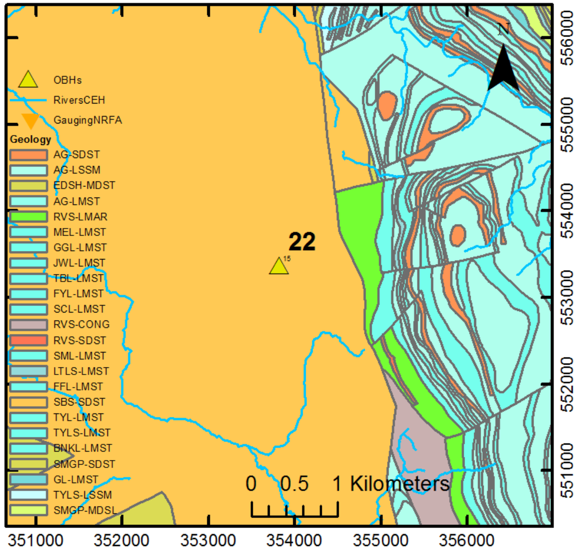


The water level ranges from 106.0 m AOD to 107.8 m AOD.
Paired (deep and shallow) monitoring boreholes were designed to investigate whether the aquifer is layered (vertical heterogeneity and head gradients) and the hydraulic relationship with the stream.
This shallow observation borehole targets the same response zone as the river and associated superficial deposits.
The seasonal trend decomposition shows that the variance associated to the general trend has only a slight influence on the variance of the original time series. The remainder and the seasonality appear to be the most influential components (49 and 48% respectively): major influence of the short time-scale events, which is consistent with the shallow construction of this borehole.
The recorded water levels hydrograph looks very similar to that of a river stream (According to the EA report, the responses are very similar to the Leith levels and flows): that indicates a reasonable connectivity between the river and the shallower parts of the sandstone and alluvial deposits.

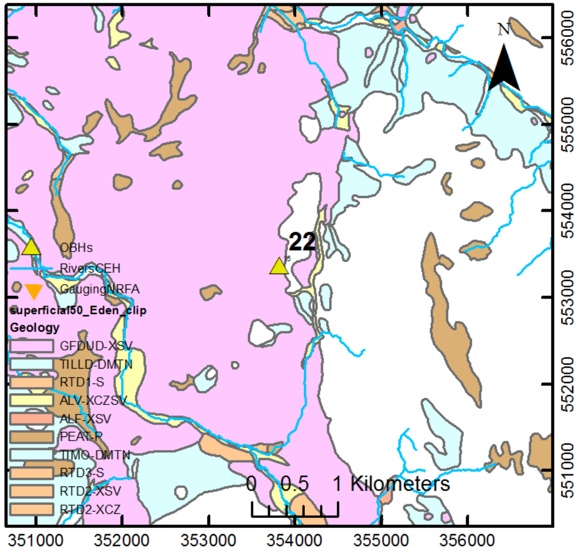
	Season.	Trend	Rem.	Original
Variance	0.0275	0.0039	0.0281	0.0574
Ratio (%)	48.0	6.8	48.9	100

21 – Cliburn, Lyvennet (shallow) – continuous recording

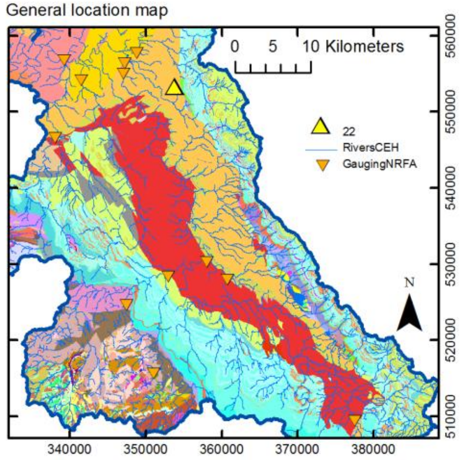
Castle Carrock BH, Bedrock 50k



Castle Carrock BH, Superficials 50k



General location map



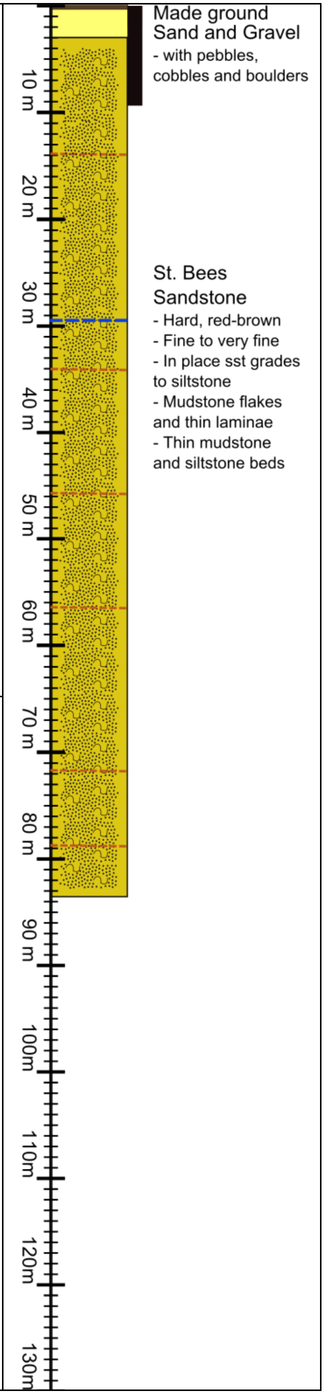
<u>Bore name:</u> CASTLE CARROCK OBH

<u>Site no:</u> NY55/71

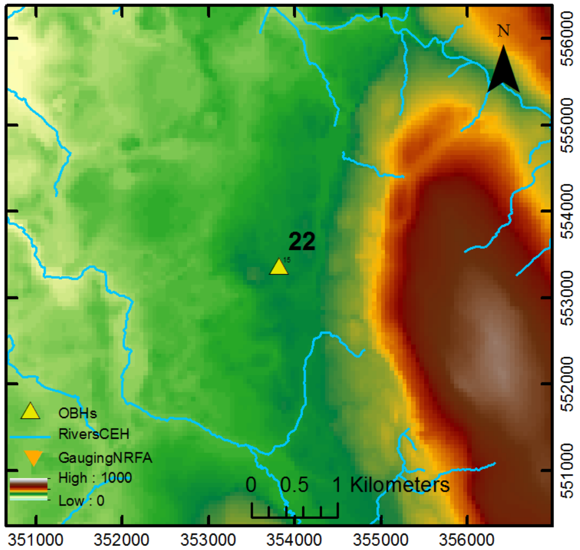
<u>Ground Level:</u> 162.7 m AOD

<u>Datum Level:</u>

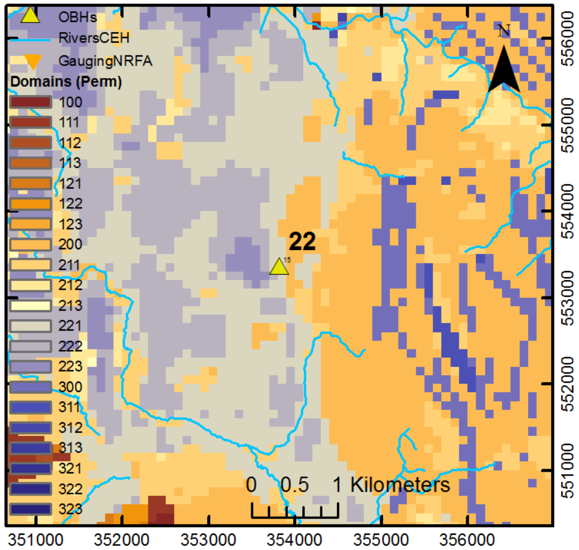
<u>Drilled depth:</u> 83.68 m



Castle Carrock BH, Topography (DTM)



Castle Carrock BH, Domains (Permeability)



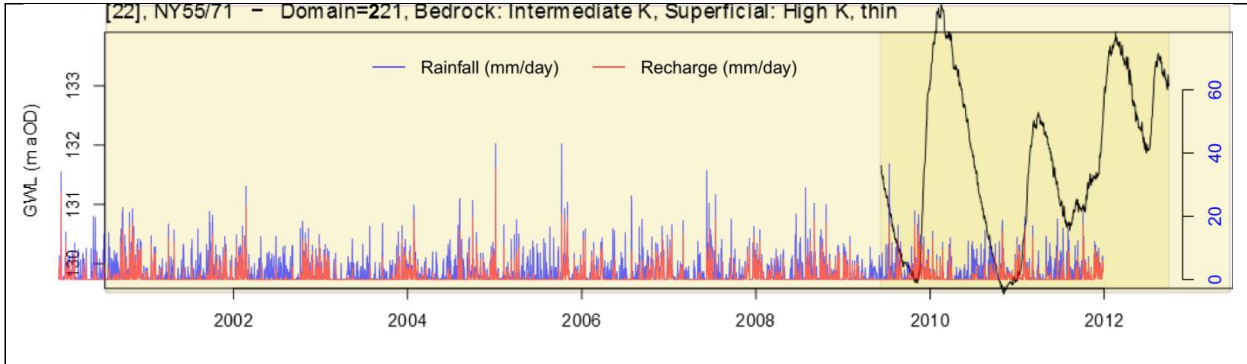
This borehole is situated north east of Brackenthwaite and south of Castle Carrock, near to the Pennine Fault that separates the St Bees Sandstone and the Carboniferous Limestone of the fells.

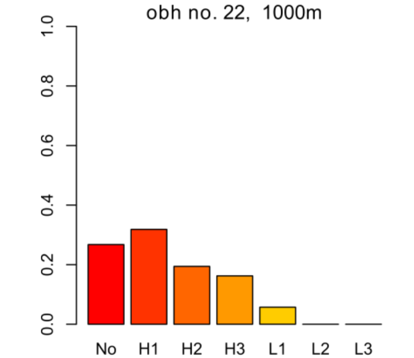
The main aquifer is the St Bees Sandstone, covered by 3m of sand and gravel of glacio-fluvial origin.

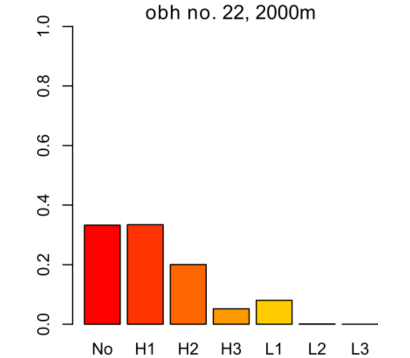
The rest water level is 29.5m below the datum.

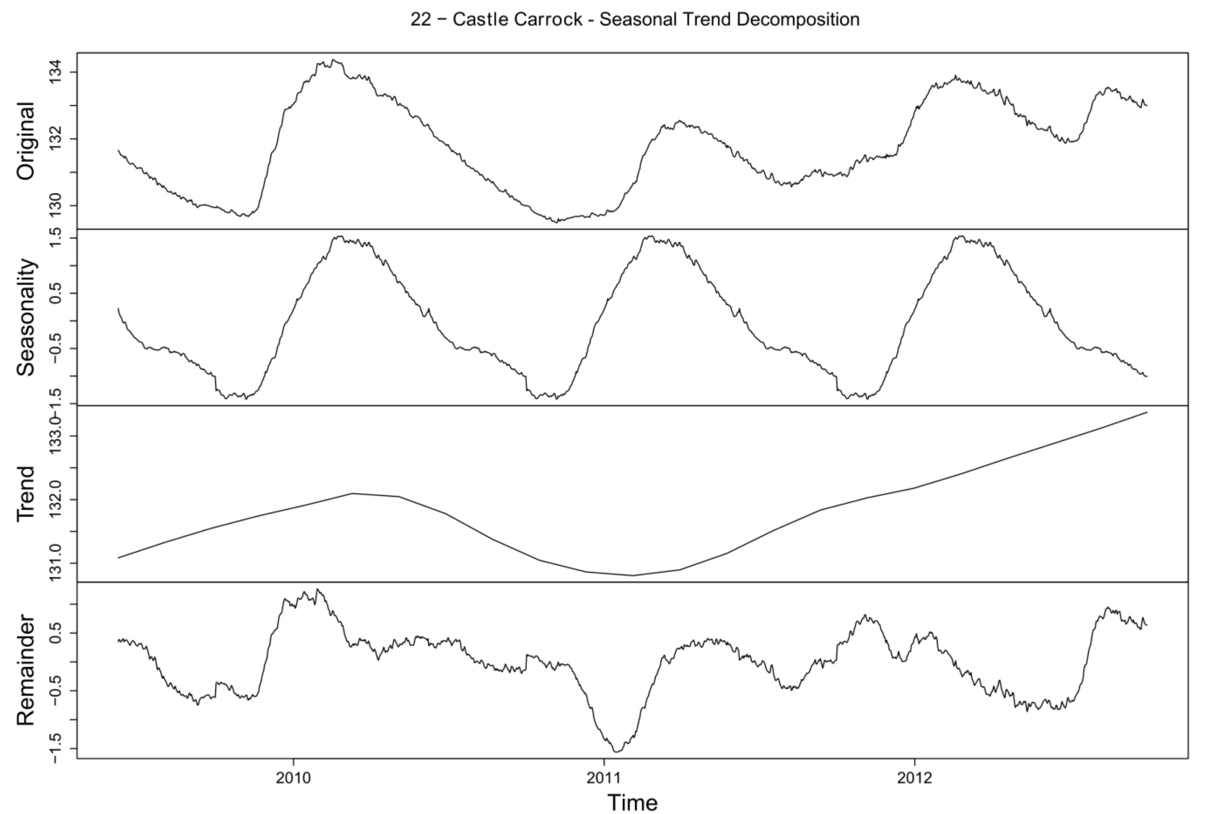
30% of area around the borehole has no superficial cover and the remainder is mostly covered by alluvium and glacio-fluvial deposits composed of relatively permeable, sand and gravels.

22 – Castle Carrock – continuous recording









The water level ranges from 129.7 to 134.2 m AOD.

The variance associated to the seasonality (64.8 %) has the largest influence on the variance associated to the original time series.

The seasonal amplitude is very large at more than 4m, but it is probably difficult to identify a trend, as the time series is less than 3 years long.

The time series is similar to the one displayed by the borehole no 13 (Croglin), situated similarly close to the Pennine Fault further south.

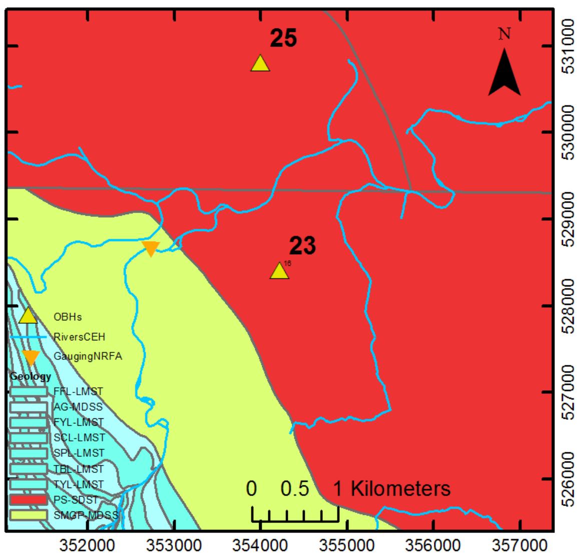
The variations of the groundwater level are dominated by the seasonality and the trend with a high amplitude (nearly 4m) only slightly perturbed by small time scale events. This could reflect the homogeneity of the St Bees Sandstone aquifer in comparison with the Penrith Sandstone (the intergranular porosity is generally less variable than that of the Penrith, with a cementation more laterally uniform, and a greater horizontal permeability but the frequent mud laminations may limit vertical hydraulic conductivity).

The amplitude is particularly high and highly controlled by the trend and the seasonality. This high seasonal amplitude could be related to the proximity of the areas receiving a high rainfall and hence recharge on the Pennines fells, and the presence of superficial windows.

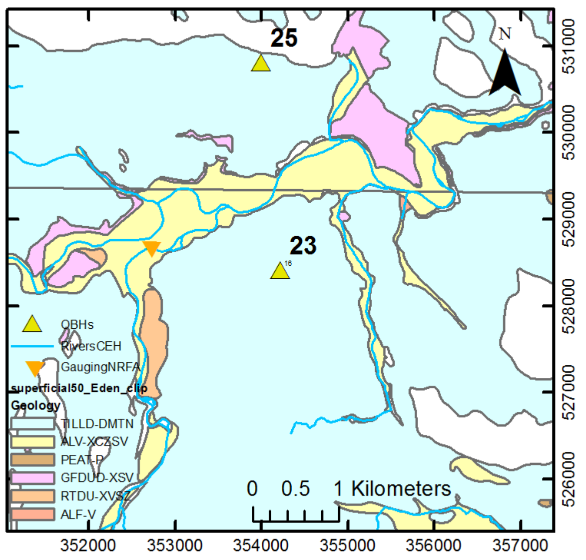
	Season.	Trend	Rem.	Original
Variance	1.0779	0.2297	0.2504	1.6645
Ratio (%)	64.8	13.8	15.0	100

22 – Castle Carrock – continuous recording

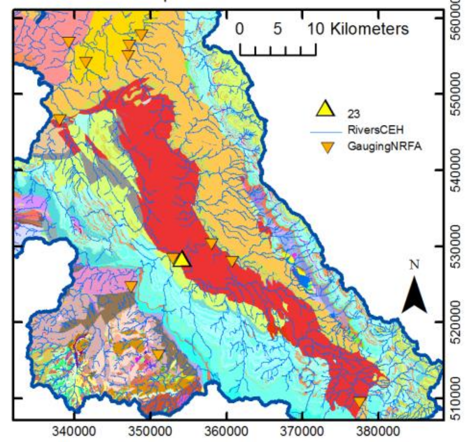
BROUGHAM NORTH CUMBR, Bedrock 50k



BROUGHAM NORTH CUMBR, Superficials 50k



General location map



__Bore name:__ NORTH CUMB. OBH.3, FREMINGTON FARM NEAR BROUGHAM

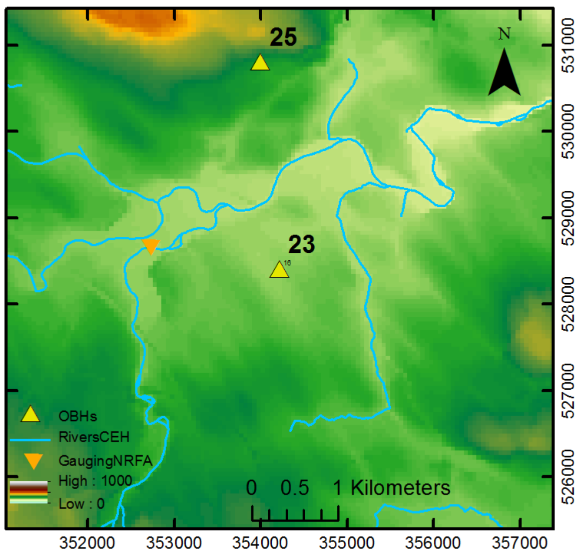
__Site no:__ NY52/3

__Ground Level:__ 118.69 m AOD

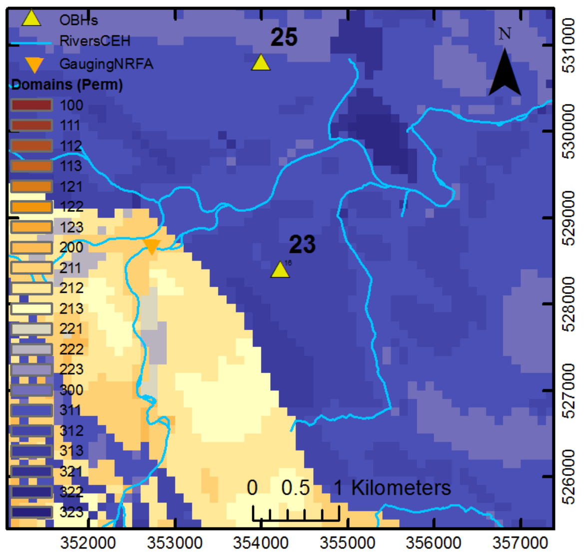
__Datum Level:__

__Drilled depth:__ 110.5 m

BROUGHAM NORTH CUMBR, Topography (DTM)



BROUGHAM NORTH CUMBR, Domains (Permeability)



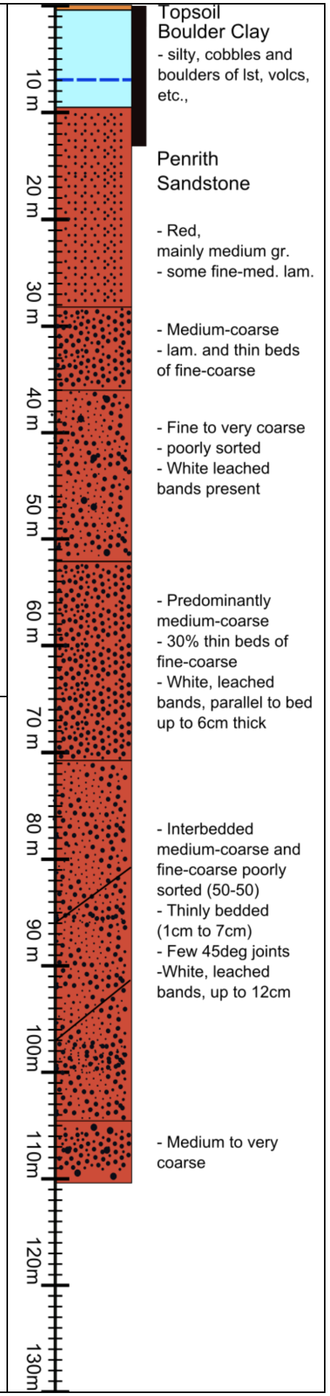
This borehole is situated in Brougham Castle, north east of Eamont Bridge and south east of Penrith.

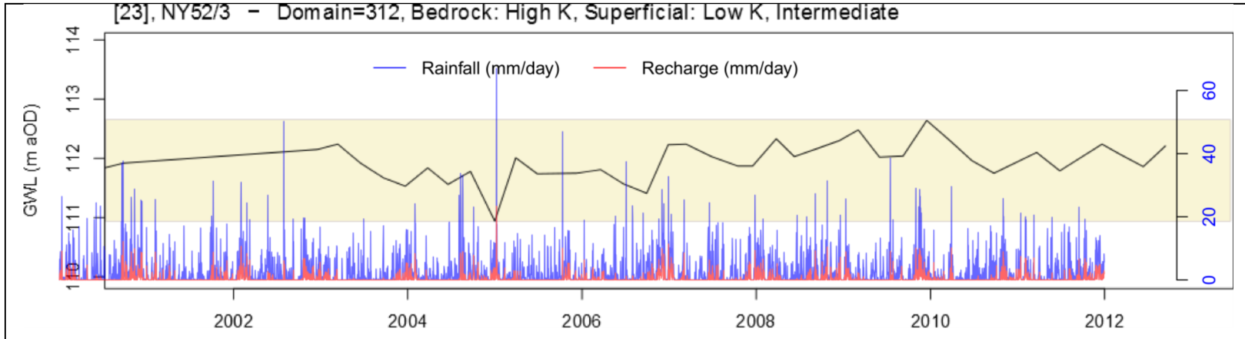
The main aquifer is the Penrith Sandstone, with a 10m boulder clay cover.

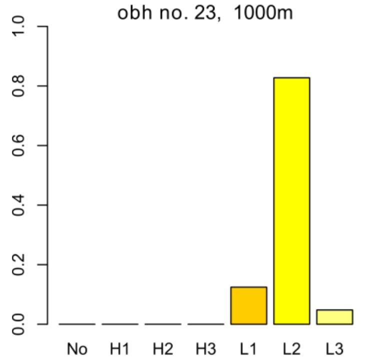
The rest water level is at 7 m below the datum.

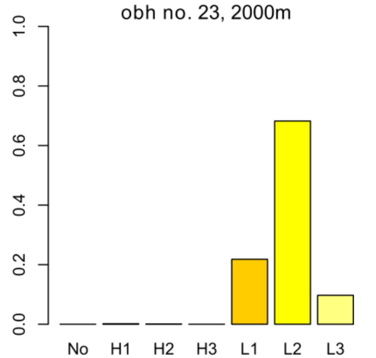
Superficial cover is present everywhere everywhere 1km around the borehole.

No surface streams are in close proximity.





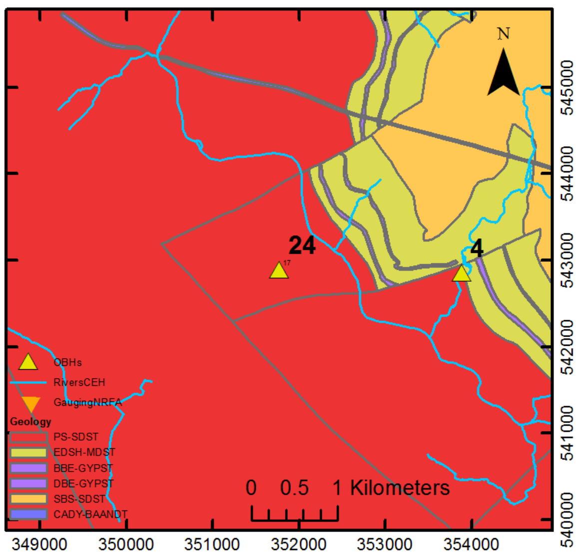




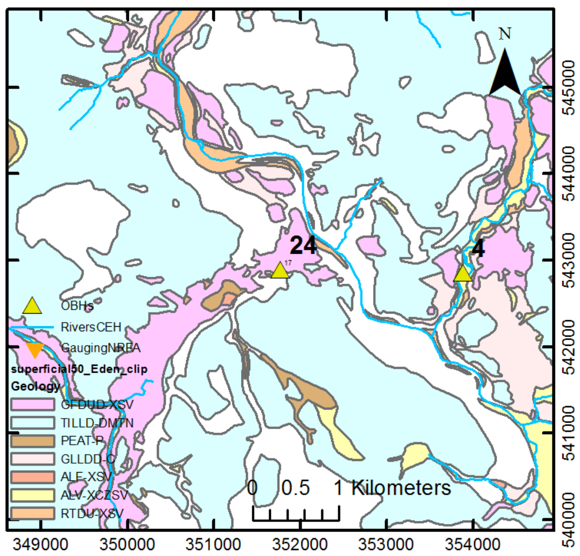
The water level ranges from 111 to 112.7 m AOD .
Seasonal variations (60cm) can be reasonably well identified.
The superficial cover and the heterogeneity of the Penrith Sandstone may be important in influencing the character of the water level response, and there is no major surface stream in the vacinity.

23 – Brougham – manually read

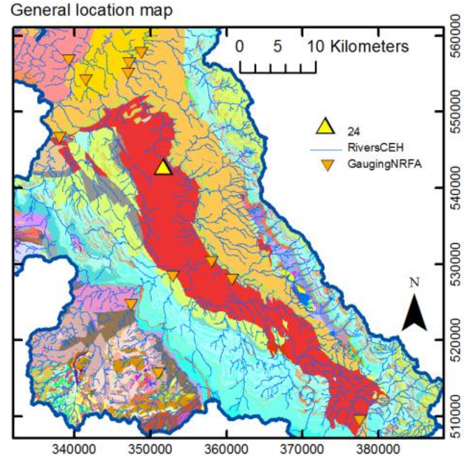
Baronwood, Bedrock 50k



Baronwood, Superficials 50k



General location map



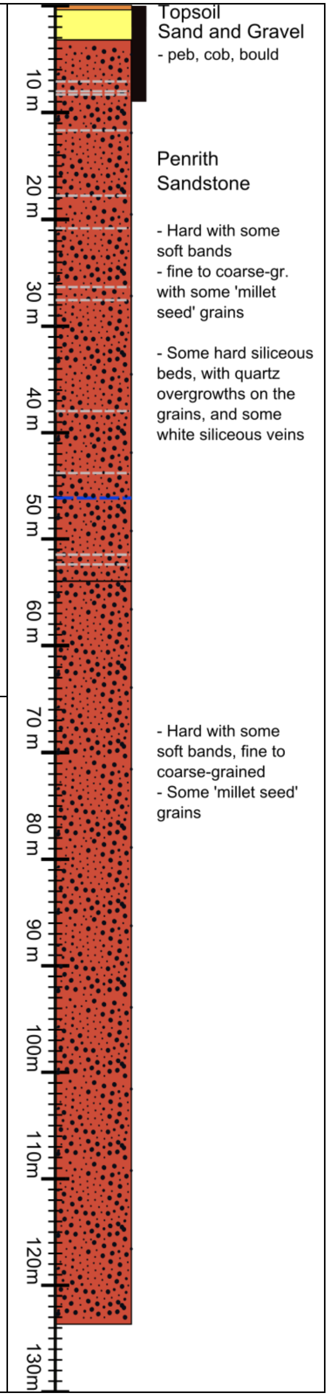
<u>Bore name:</u> BARONWOOD OBH

<u>Site no:</u> NY54/56

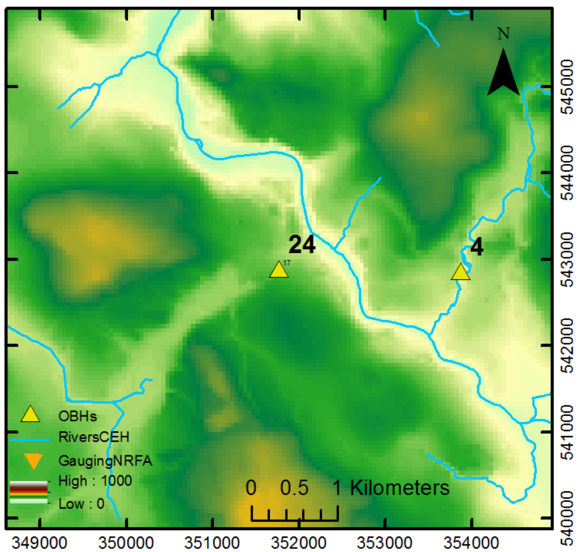
<u>Ground Level:</u> 130.2 m AOD

<u>Datum Level:</u>

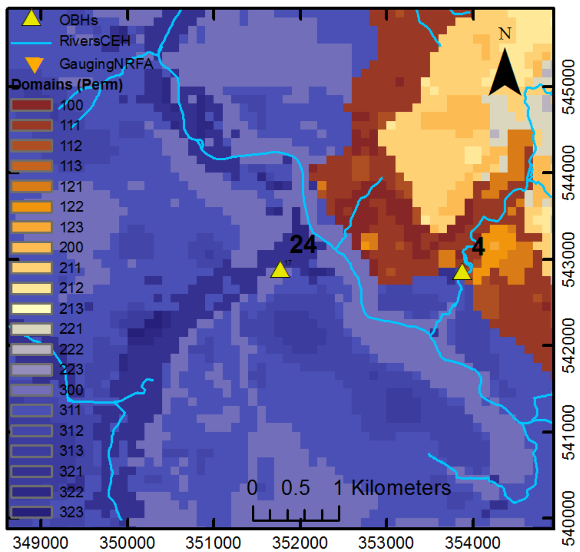
<u>Drilled depth:</u> 123.72 m



Baronwood, Topography (DTM)



Baronwood, Domains (Permeability)



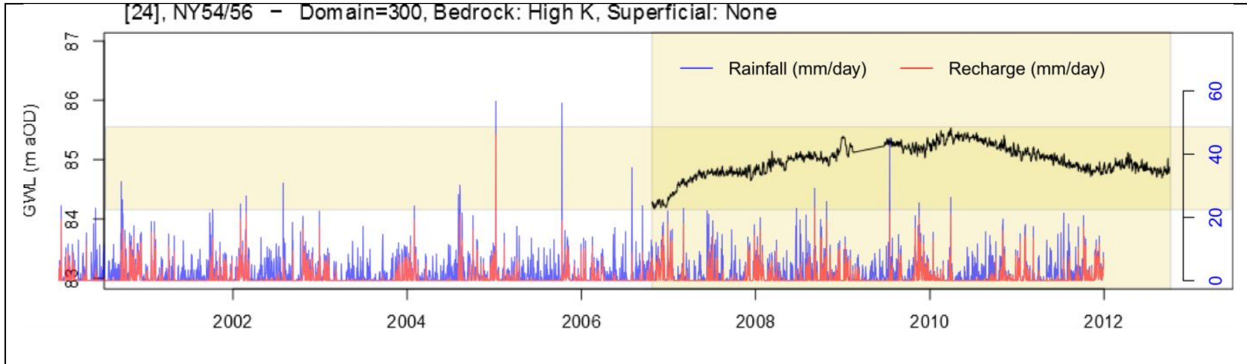
This borehole is situated 2 km south of Armathwaite village, close to the River Eden.

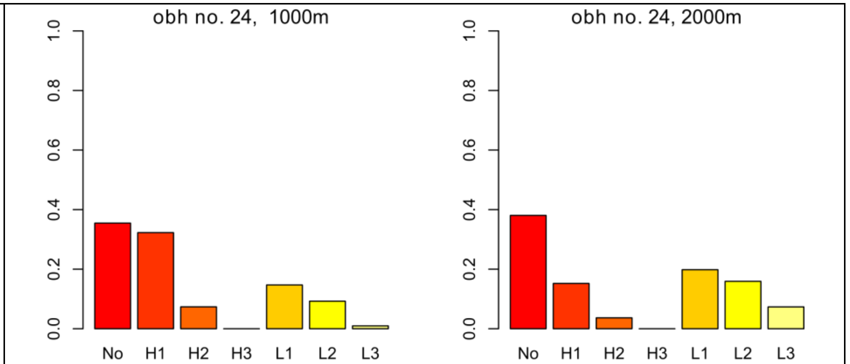
The main aquifer is the Penrith Sandstone, covered by 3m thick glaciofluvial deposits comprising sand and gravel.

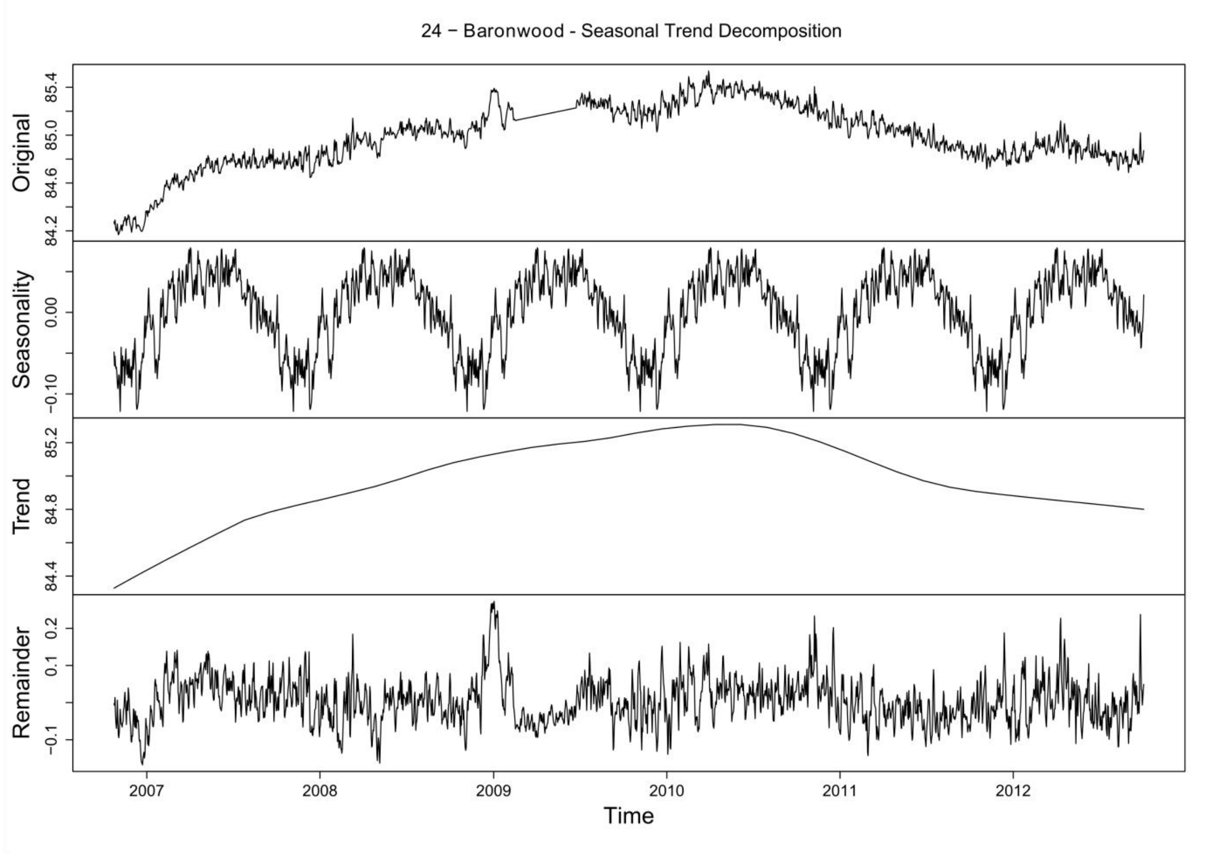
The rest water level is at 46m below the datum.

A part of the area situated around the borehole is free of superficial deposits, while the remainder is covered by variable permeability and thickness deposits (glaciofluvial, till, etc.).

24 – Baronwood – continuous recording





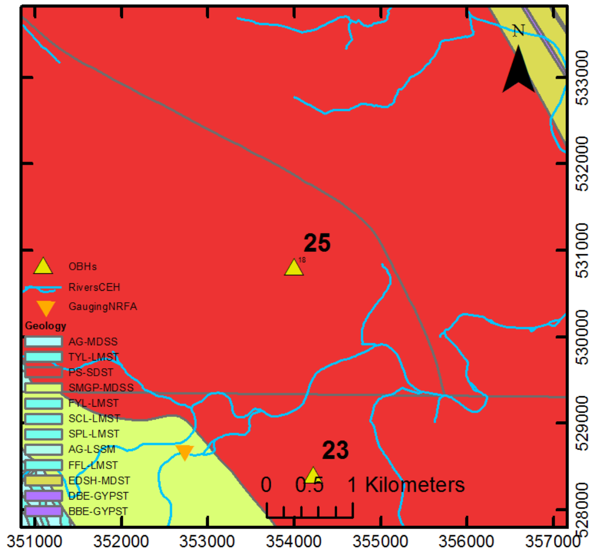


The water level ranges from 84.1 to 85.6 m AOD.
The variance associated to the trend (86.2%) explains most of the variance associated with the original time series.
The sandstone is silicified in parts, and hard siliceous beds can be observed in the upper part of the core. This is typical of Penrith Sandstone outcropping in the northern area. Such layers characterized by a low hydraulic conductivity could explain the predominance of the variance associated to the trend.
On the other hand, the seasonality appears very weak (variance ratio 3.2%).
And the amplitude of the variation in a hydrological year is quite low.
The borehole is located within a fault system, which may have an effect on the hydrograph. The relative proximity to the River Eden may also dampen the response.

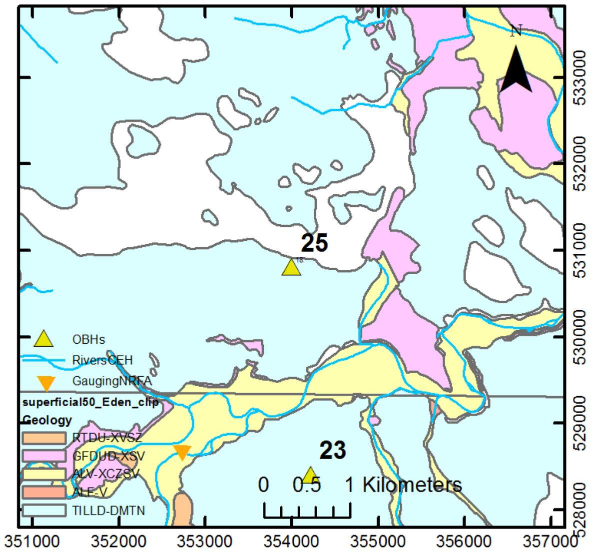
	Season.	Trend	Rem.	Original
Variance	0.0024	0.0636	0.0038	0.0737
Ratio (%)	3.2	86.2	5.1	100

24 – Baronwood – continuous recording

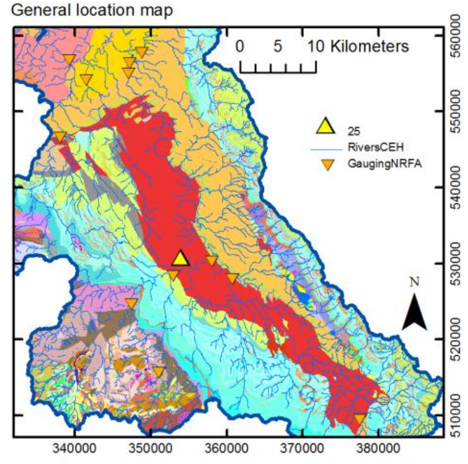
PENRITH NORTH CUMBRI, Bedrock 50k



PENRITH NORTH CUMBRI, Superficials 50k



General location map



<u>Bore name:</u> NORTH CUMBRIA OBH.17, CARLETON, PENRITH

<u>Site no:</u> NY53/11

<u>Ground Level:</u> 160.7 m AOD

<u>Datum Level:</u>

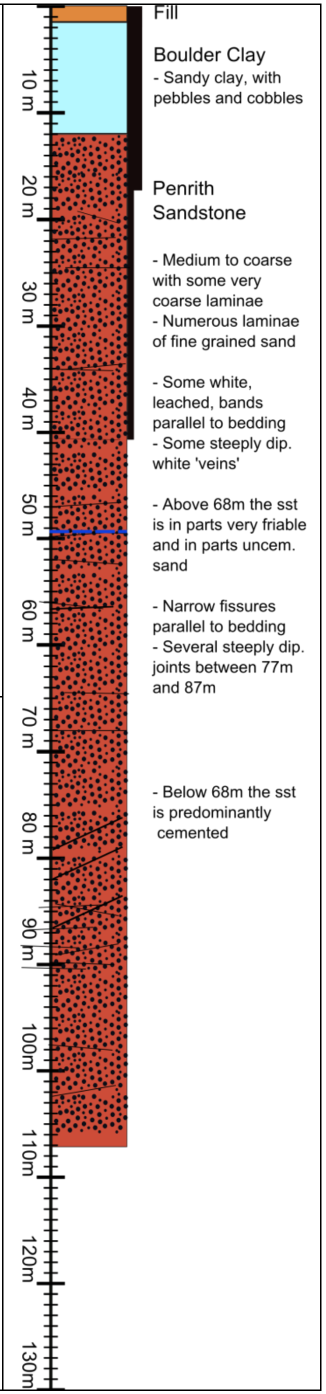
<u>Drilled depth:</u> 107.10 m

The borehole is situated north east of Penrith.

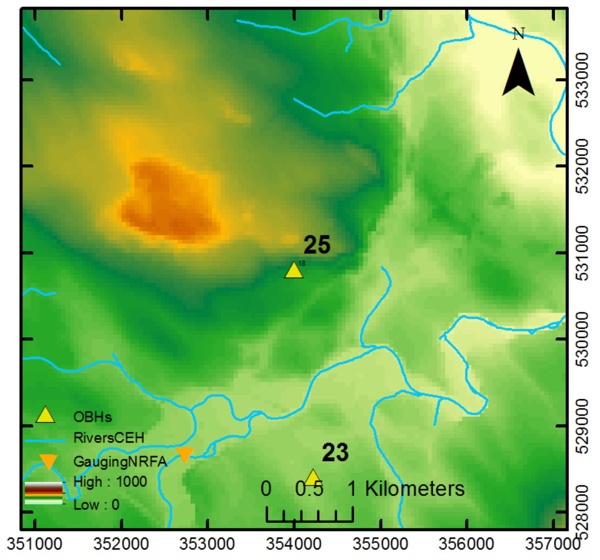
The main aquifer is the Penrith Sandstone, covered by 12m of boulder clay.

The rest water level is at 50 below datum.

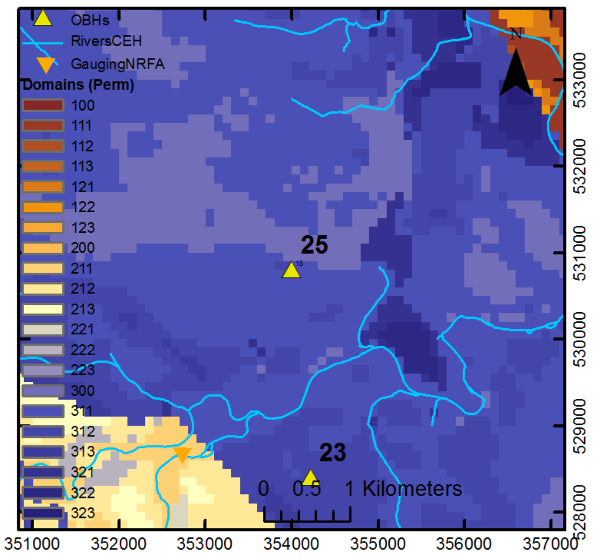
Situated south of a hill formed by an outcrop of probably harder silicified sandstone.



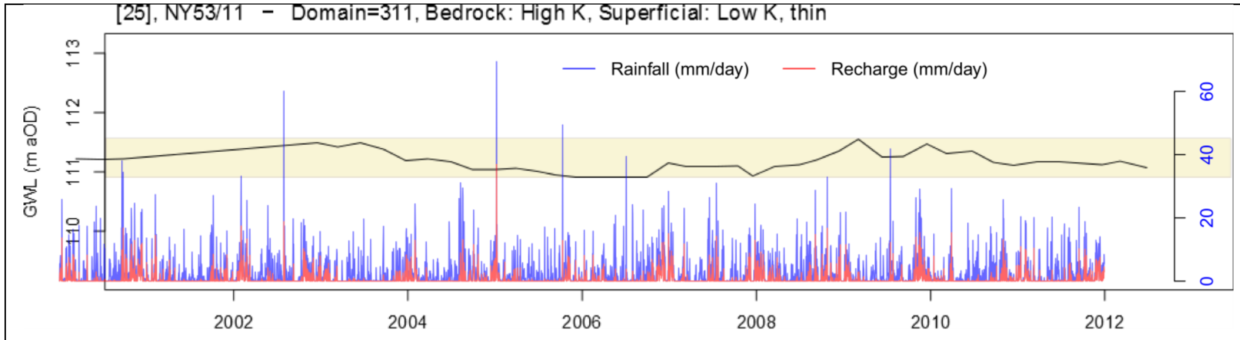
PENRITH NORTH CUMBRI, Topography (DTM)

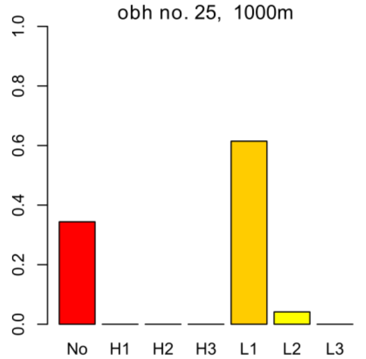


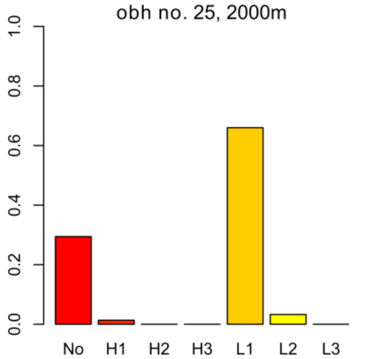
PENRITH NORTH CUMBRI, Domains (Permeability)



25 – Carleton, Penrith – manually read







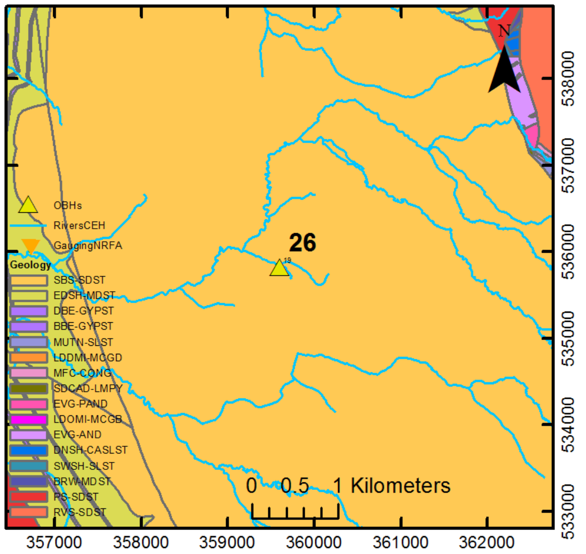
The water level ranges from 110.9 to 111.6 m AOD.

Silicified layers are observed on the geological log. The low amplitude of groundwater level variation is consistent with the findings associated to the boreholes situated in a similar area: Northern outcrops of Penrith sandstone.

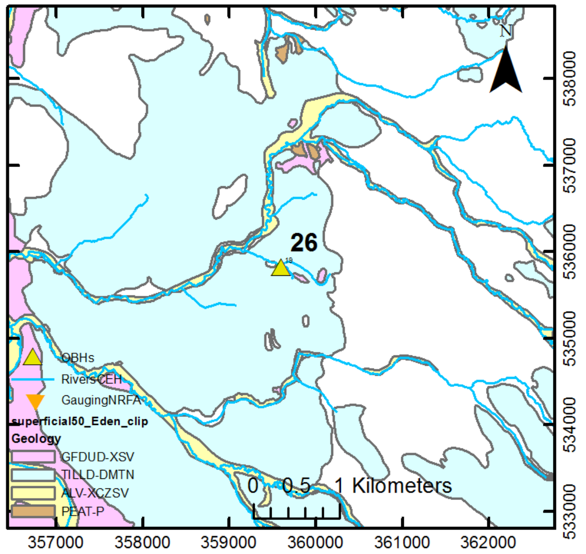
The seasonality is difficult to identify.

25 – Carleton, Penrith – manually read

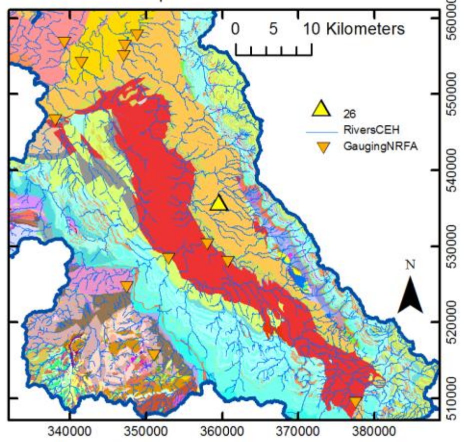
OUSBY MOOR NORTH CUM, Bedrock 50k



OUSBY MOOR NORTH CUM, Superficials 50k



General location map



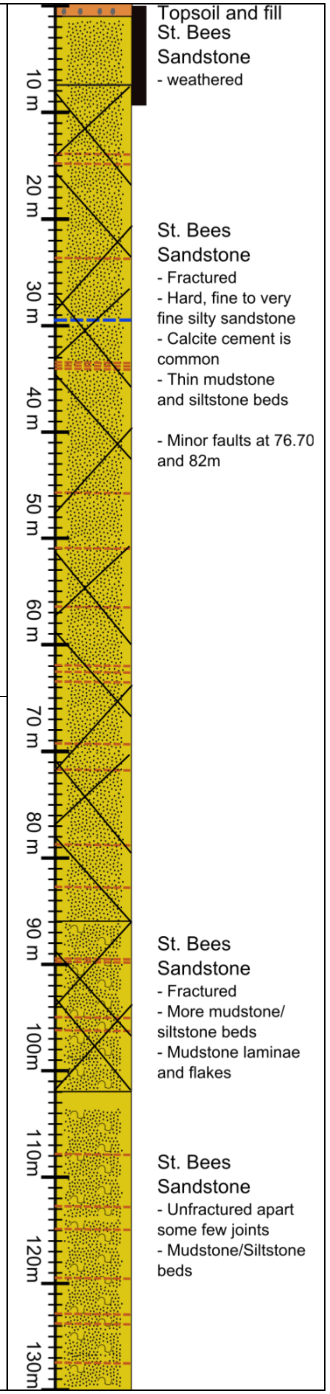
<u>Bore name:</u> NORTH CUMB. OBS. WELL 4, OUSBY MOOR

<u>Site no:</u> NY53/10

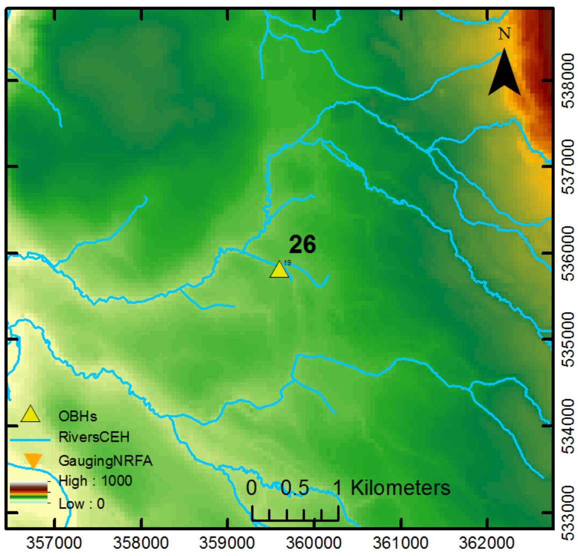
<u>Ground Level:</u> 124.72 m AOD

<u>Datum Level:</u>

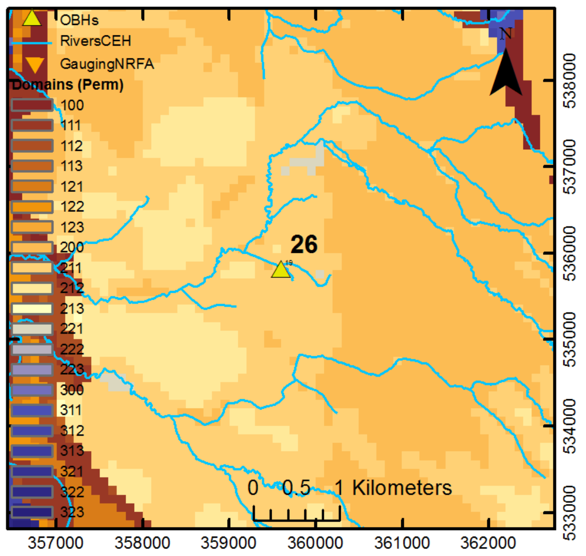
<u>Drilled depth:</u> 130.31 m



OUSBY MOOR NORTH CUM, Topography (DTM)



OUSBY MOOR NORTH CUM, Domains (Permeability)

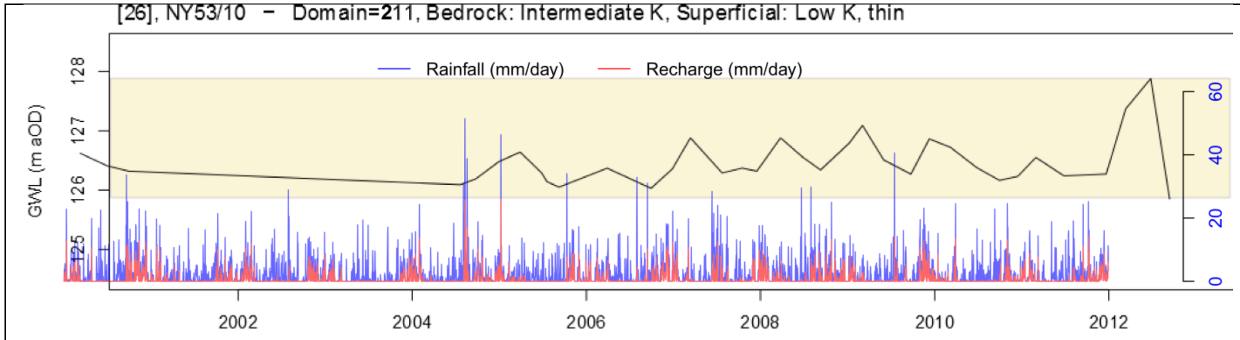


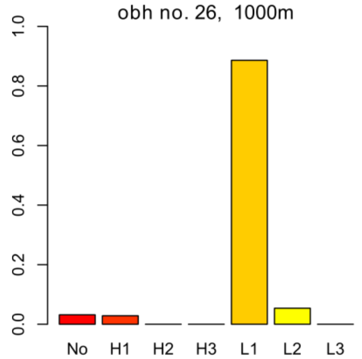
The borehole is situated in Ousby Moor, near to Robberby Water surface stream. The main aquifer is the St Bees Sandstone, which is highly fractured.

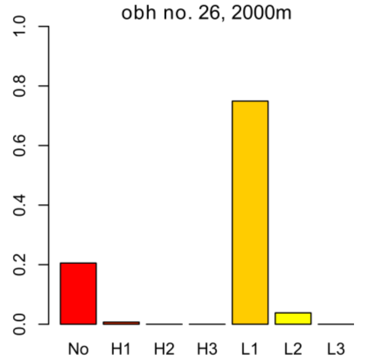
Most of the area surrounding the borehole is covered by superficial deposits.

The rest water level is 30m below the datum.

26 – Ousby Moor – manually read







The water level ranges from 125.9 to 127.9 m AOD.
The seasonality is well identified, with a high level in Winter 2012.

26 – Ousby Moor – manually read