INTERPRETATION OF GROUNDWATER DATA IN THE VICINITY OF A LONG ESTABLISHED SANDSTONE QUARRY

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ABSTRACT

The Pilkington Quarry is located on the west-facing lower slopes of Winter Hill north of Horwich near Bolton and works the Pennine Lower Coal Measures (PLCM) Ousel Nest Grit. The quarry's history dates from the second half of the 19th century hardly changing in size from the 1890s to recent years. The present owners have successfully applied to extend the working area southwards and also wish to infill the quarry with non-hazardous wastes. As part of the environmental assessments for these applications a series of piezometers were installed to allow the water table to be monitored. This paper is based on the geological and groundwater level data obtained from these boreholes.

Groundwater levels have been recorded monthly for some three years from which the water table elevations have been determined that define both the groundwater flow system and seasonal fluctuations. The impact of the quarry on the local groundwater conditions is evident from the modifications to the groundwater elevations and the seasonal amplitudes above and below the quarry void.

The paper discusses how these impacts have been caused and their significance; and also discusses the assessment of environmental impacts in the context of current Environment Agency requirements.

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INTRODUCTION

Any activity in England and Wales that may pose a threat to groundwater resources will require a hydrogeological assessment to satisfy the Environment Agency. These activities include new quarries and proposals for restoring quarries using tipped materials. The Agency and its predecessor regulators have published a policy for groundwater protection the latest being GP3 published on the Environment Agency website in November 2012 (Environment Agency, 2012). Guidance is also available from the Agency about how to undertake a hydrogeological risk assessment as part of the H1 Environmental Risk Assessment framework (Environment Agency, 2011) that provides information relevant to all sectors that are regulated under the Environmental Permitting Regulations (e.g. HM Government, 2010). The guidance for groundwater assessments is Annex J of the H1 Environmental Risk Assessment framework, comprising an overview guide and a set of eleven supporting technical annexes for specific risks.

Such hydrogeological risk assessments usually will require the construction of suitable boreholes for monitoring of the water table in the vicinity of the site. Investigations around quarries that have existed for many years before the boreholes are drilled are highly likely to encounter groundwater conditions that have been changed significantly by the presence of the quarry void even where dewatering has not being undertaken. The resulting groundwater level records need to be scrutinized to determine the extent of such effects so that the groundwater conditions may be predicted that will pertain once the quarry has been infilled.

This paper uses a case history example of the groundwater conditions in a sandstone aquifer that contains a long-established large sandstone quarry that has no historic groundwater data, to examine these effects and to describe an approach to the validation of such data that allows them to be used with confidence in hydrogeological assessments.

PILKINGTON QUARRY – LOCATION AND GEOLOGY

The Pilkington Quarry lies about 2.5km to the northeast of the town of Horwich on the west side of Bolton in Greater Manchester and east of the larger Montcliffe Quarry (see Figure 1). Quarrying started in the mid-19th century and grew very little over the following 150 years or so. It had been worked to the full extent allowed by the planning permission during the 1990's and later sold to its present owners who successfully applied to extend the working area southwards and has also applied to restore the quarry using non-hazardous material. As part of the environmental assessments for these applications a series of piezometers were installed in boreholes to monitor the water table which has provided the data set that is the basis of this paper.

The solid geology of the area to the north of Horwich comprises rocks from the upper part of the Namurian Series to the basal part of the Pennines Lower Coal Measures Formation that comprise a sequence of interbedded sandstones and shale with occasional coals. The solid rocks are overlain by patchy deposits of glacial and more recent materials that are generally limited to the valley bottoms except for areas of peat on parts of the upland areas. Figure 2 is an extract from the local British Geological Survey (BGS) 1:50 000 scale map and shows the solid geology of the surrounding area. Table 1 summarizes the stratigraphical sequence with approximate thicknesses given in the general area of the quarry.

Both the existing Pilkington Quarry and the proposed extension are excavated into the Ousel Nest Grit which is coarse-grained sandstone in the lower part of the Pennines Lower Coal Measures (LCM) Formation that occurs in the Rochdale-Chorley district (Jones *et al*, 1938; Aitkenhead *et al,* 2002). At the Pilkington Quarry it varies in thickness up to some 40 m and dips to the southwest by about 5°. There are two fault sets in the area; one trending to the northwest and the second trending to the east as can be seen on Figures 2 and 3. An easterly trending fault was exposed in the northern tip of the quarry and a north-westerly trending fault lies about 750 m to the southwest of the southern boundary of the present quarry void. Figure 3 provides more detail of the local geology and is an extract from the British Geological Survey 1:10,560 scale map published in 1932 and prepared by Jones *et al* (1938) during the 1923 – 1931 geological survey.

The geology of the immediate area surrounding the Pilkington Quarry has been defined in more detail using information from the various boreholes that were drilled to prove the mineral reserves in the extension area and later to provide more groundwater locations. The positions of the boreholes are shown in Figure 4. Boreholes A – E were drilled in June/July 2008 and

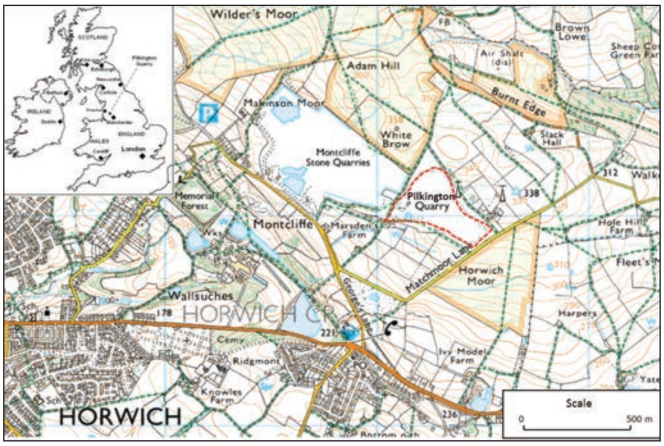


Figure 1. *Location map. The present (2012) extent of the quarry is shown on the map; the area for the permitted future extension lies to the south. (Reproduced with permission of the © Ordnance Survey. All rights reserved.)*

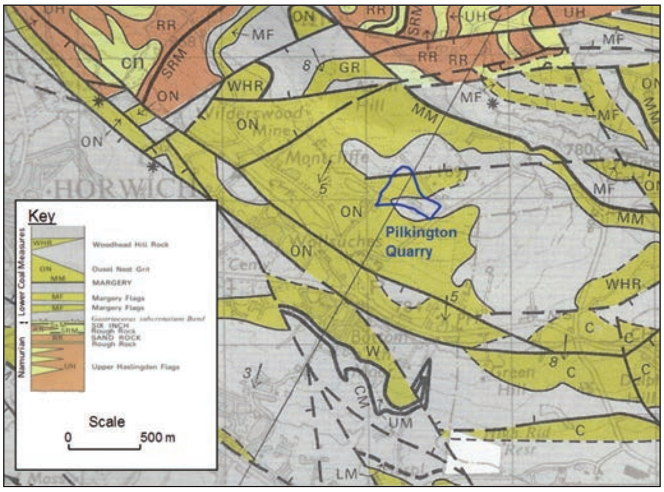


Figure 2. *Geology of the area north of Horwich (Extracted from the Wigan Sheet 84 (Solid) 1:50,000 Series map (1977) with the permission of the British Geological Survey © NERC. All rights reserved. Background map reproduced with permission of the © Ordnance Survey. All rights reserved.)*

Stratigraphy		Lithology	Thickness (m)
Quaternary/Recent		diamictite and some hill peat	0 - 3
Pennines Lower Coal Measures Formation	Woodhead Hill Rock	fine- & medium-grained sandstone with siltstone	8
	Intermediate beds	mainly shales	5
	Ousel Nest Grit	coarse-grained sandstone	50
	Margery Mine	coal seam	0.5
	Intermediate beds	mainly shales	14.5
	Margery Flags	fine- & medium-grained flaggy sandstone	10 - 12
	Intermediate beds	mainly shales	4 - 6
	Margery Flags	fine- & medium-grained flaggy sandstone	8 - 10
	Intermediate beds	mainly shales	18
Namurian	Six Inch Mine	coal seam	0.2
	Intermediate beds	mainly shales with some thin sandstones	15
	Sand Rock Mine	coal seam	2
	Rough Rock	coarse-grained sandstone	10
	Intermediate beds	mainly shales	2
	Upper Haslingden Flags	fine- & medium-grained flaggy sandstone	15
	Intermediate beds	mainly shales	20
	Lower Haslingden Flags	fine- & medium-grained flaggy sandstone	30

Table 1. *Summary of stratigraphy in the Pilkington Quarry area.*

Boreholes F – N during October/November 2010. Borehole 'Old' was pre-existing the recent investigations, having been drilled during the 1990's by the previous quarry owner.

Correlations between the boreholes are given in Figures 5 and 6 with the logs simplified as sandstone or shale beds and plotted with elevation in metres above Ordnance Datum (mOD). Figure 5 shows the boreholes across the northern part of the area surrounding the quarry and Figure 6 shows those across the southern part. The geology proved in the boreholes has been summarized in Table 2 that provides thicknesses of the Ousel Nest Grit, the overlying shale and the Woodhead Hill Rock with an indication of where the stratigraphical unit was only partly penetrated.

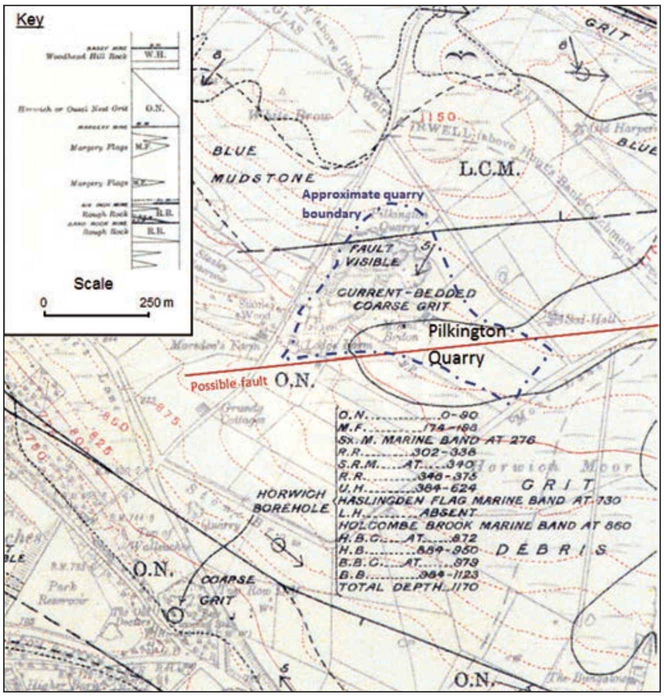


Figure 3. *Geology of the Pilkington Quarry. The larger scale map includes more detail including the surveyors' notes. The extent of the quarry is approximate. (Extracted from the 1:10,560 scale geological map SD61SE (1938) with the permission of the British Geological Survey © NERC. All rights reserved. Background map reproduced with permission of the © Ordnance Survey. All rights reserved.)*

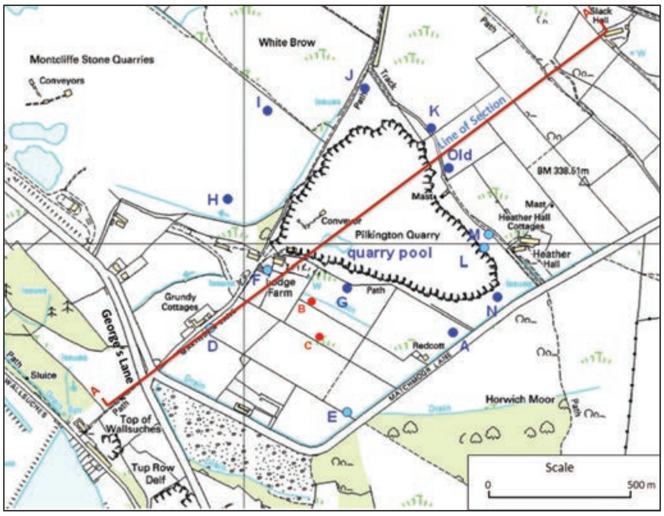


Figure 4. *Borehole locations. Boreholes B and C (shown in red) were constructed to provide geological information and were not used for groundwater monitoring. The line of the cross section (Figure 8) is also shown. (Reproduced with permission of the © Ordnance Survey. All rights reserved.)*

The borehole evidence shows that the thickness of the Ousel Nest Grit varies across the site; Boreholes J and K (Figure 5) both penetrate the full sequence of the Ousel Nest Grit proving some 45m and Boreholes A, C and E (Figure 6) each prove more than 45m although none penetrate the full thickness of the sandstone. Contrary to this however, Boreholes B and N both also penetrate the full thickness the sandstone although only proving about 25m. These differences in the thickness of the Ousel Nest Grit may be the result of a previously unidentified fault penetrated only in Boreholes B and N (see Figure 4). Such a fault is postulated with a downthrow to the south and running parallel to the fault mapped by BGS and shown on Figure 3.

A comparison between the borehole logs and the published BGS mapping shows good agreement except for sandstone encountered from ground level to 13m depth in Borehole N and in the first 1.4m below the

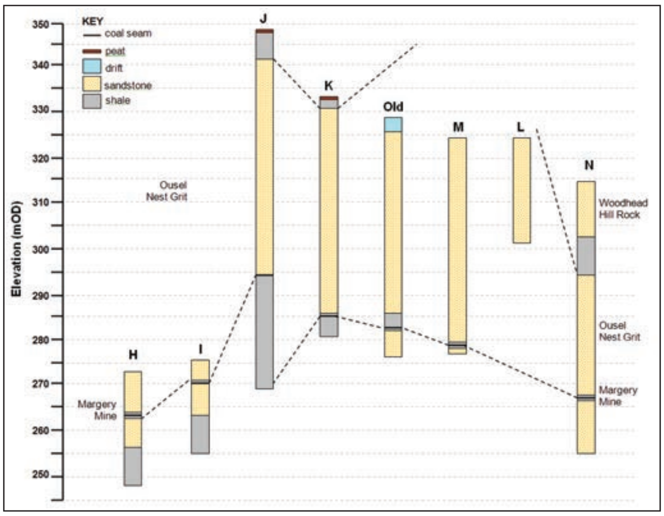


Figure 5. *Correlation of the geology between boreholes drilled above the quarry including Borehole N (also included in Figure 6). The Margery Mine coal seam was identified in 12 of the 15 boreholes and has been used to correlate between the boreholes. The contact between the Ousel Nest Grit and the overlying shale has been identified in six of the borehole and has also been used in the correlation.*

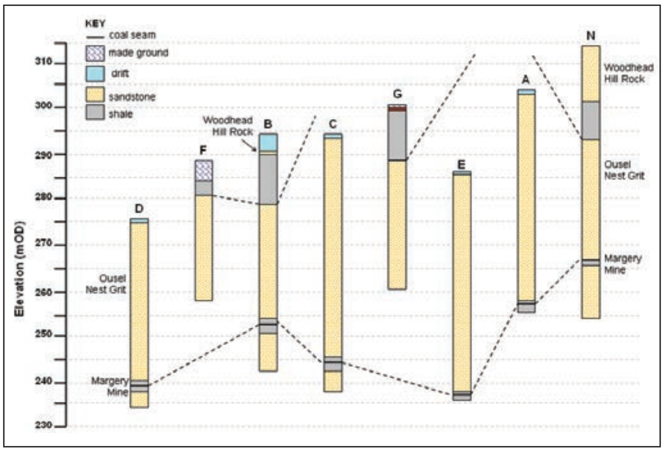
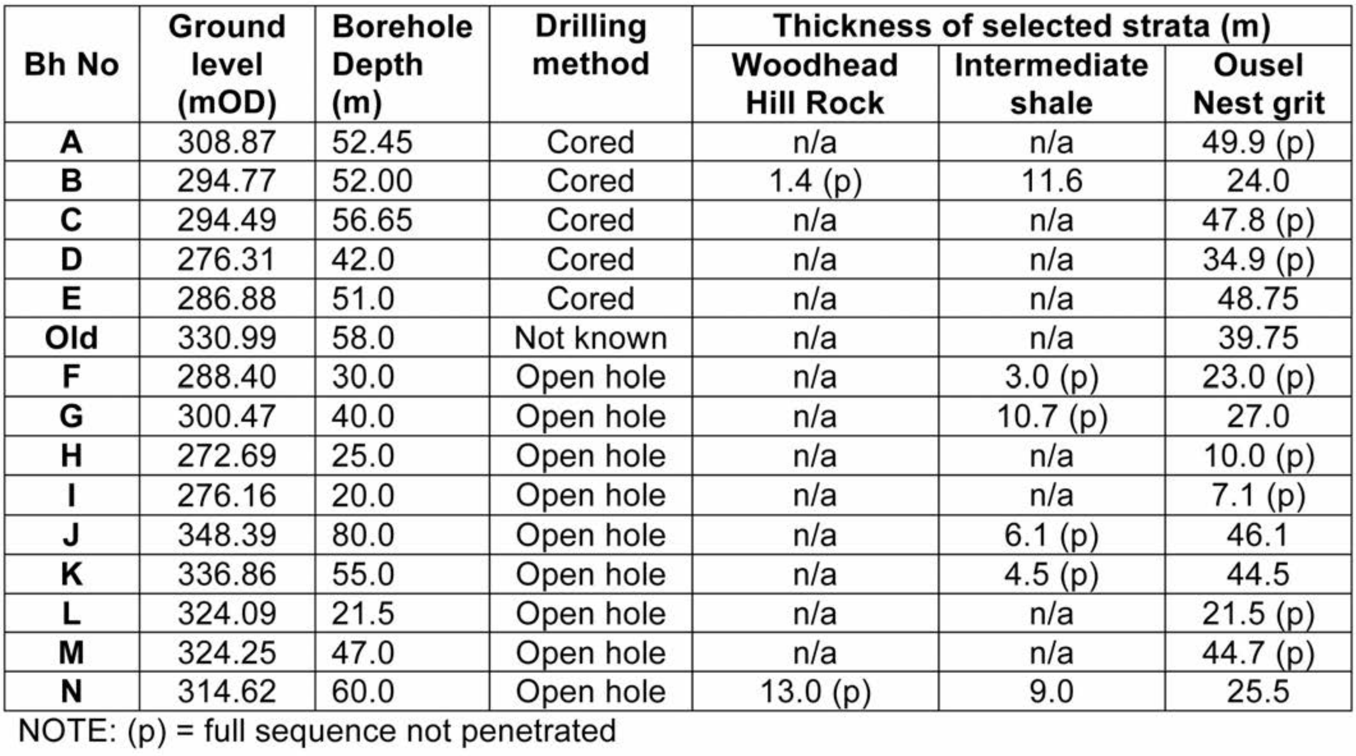


Figure 6. *Correlation of the geology between boreholes drilled below the quarry including Borehole N that is also shown in Figure 5.*



Bh No	Ground level (mOD)	Borehole Depth (m)	Drilling method	Thickness of selected strata (m)		
				Woodhead Hill Rock	Intermediate shale	Ousel Nest grit
A	308.87	52.45	Cored	n/a	n/a	49.9 (p)
B	294.77	52.00	Cored	1.4 (p)	11.6	24.0
C	294.49	56.65	Cored	n/a	n/a	47.8 (p)
D	276.31	42.0	Cored	n/a	n/a	34.9 (p)
E	286.88	51.0	Cored	n/a	n/a	48.75
Old	330.99	58.0	Not known	n/a	n/a	39.75
F	288.40	30.0	Open hole	n/a	3.0 (p)	23.0 (p)
G	300.47	40.0	Open hole	n/a	10.7 (p)	27.0
H	272.69	25.0	Open hole	n/a	n/a	10.0 (p)
I	276.16	20.0	Open hole	n/a	n/a	7.1 (p)
J	348.39	80.0	Open hole	n/a	6.1 (p)	46.1
K	336.86	55.0	Open hole	n/a	4.5 (p)	44.5
L	324.09	21.5	Open hole	n/a	n/a	21.5 (p)
M	324.25	47.0	Open hole	n/a	n/a	44.7 (p)
N	314.62	60.0	Open hole	13.0 (p)	9.0	25.5

NOTE: (p) = full sequence not penetrated

Table 2. *Summary of geology proved in exploratory boreholes.*

rockhead in Borehole B. This sandstone is interpreted here as an outlier of the Woodhead Hill Rock although its presence was not recorded on the 1938 BGS map. At the time of the geological survey the limit of the quarry was some 100m from the present eastern face; in addition, the borehole evidence cited here did not exist and there are no local natural outcrops with the area covered by typical moorland vegetation. The exposure of the supposed Woodhead Hill Rock in the northeast corner of the quarry face is shown in Figure 7.

A possible alternative interpretation is that the Ousel Nest Grit includes a shale lense that was proved to be about 16m thick in Borehole B and 9m thick in Borehole N. The mapping by Jones *et al* (1938) indicates that the shale between the Ousel Nest Grit and the Woodhead Hill Rock to be between 5m and 50m and describes the Ousel Nest Grit as a coarse feldspathic sandstone and grit, pebbly in places and give thicknesses in the range 28 – 37m which contrasts with the thickness up to 45m found in the boreholes.

A more recent version of the BGS map was published in 2013 and shows a different interpretation of the geology in the vicinity of the Pilkington Quarry that does not accord with the geological data from the investigation boreholes discussed here and it is understood that the borehole data were not available when the new interpretation was made. For the purpose of this paper, the interpretation of the borehole data is in the context of the previously published map, which has been taken to be a more accurate description of the local geology.

The borehole evidence has been used to construct a cross section drawn to scale and following the direction of dip (to the southwest) to end just short of the fault system near George's Lane that lies to the southwest of the site (see Figure 4). The section shown in Figure 8 runs through Borehole D and close to Boreholes F, K and Old. Data from the remaining boreholes have been projected onto the line. The thickness of the Woodhead Hill Rock and the underlying shale is based on Boreholes B and N and an assumption that theses beds also dip to the southwest.

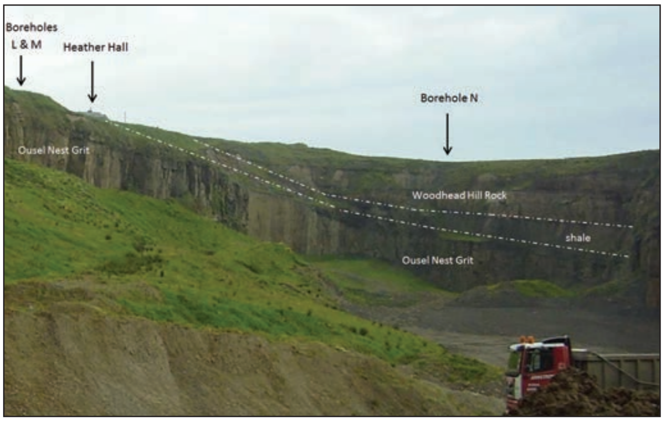


Figure 7. *Photograph of the eastern end of the quarry face from a location north of the quarry pool shown on Figure 4. The location of Boreholes L, M and N are shown together with the base of the sandstone proved in Borehole N and interpreted as the Woodhead Hill Rock. (Photograph by courtesy of The Mineral Planning Group.)*

Groundwater levels have been indicated for the boreholes shown on the section and their significance is discussed later in this paper. The cross section serves to illustrate the significance of the quarried void in terms of the aquifer thickness with almost all the sandstone being removed leaving only some 10m at the base.

PILKINGTON QUARRY - HYDROGEOLOGY

The sandstones within the Namurian and Coal Measures sequences act as a series of separate aquifers. In such a multi-layered aquifer system the groundwater in individual aquifers behave separately and are not

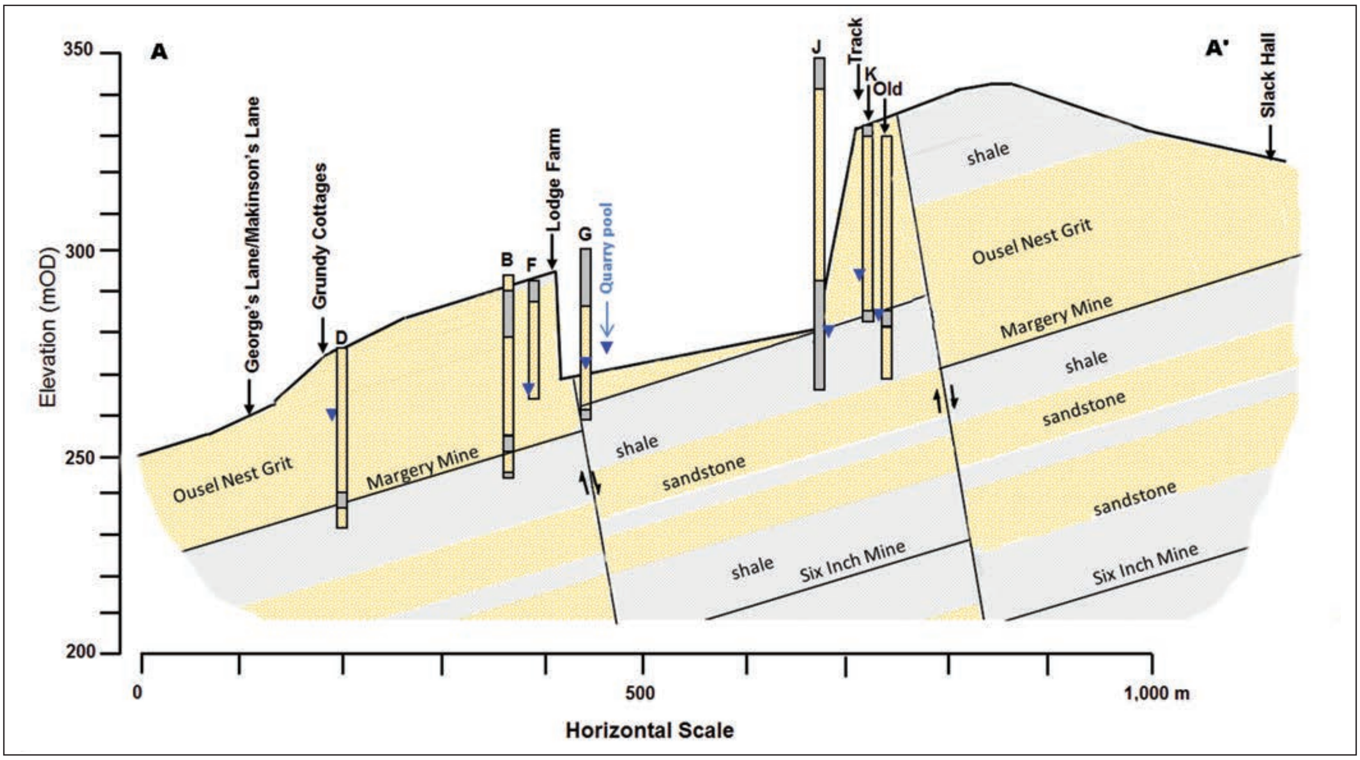


Figure 8. *Cross section A-A' shown on Figure 4. Only Borehole D lies on the line of section and data from the other boreholes have been projected onto the line. Groundwater elevations are shown as inverted blue triangles.*

connected through the strata except where they are displaced by faulting. Such individual aquifers may be connected artificially by boreholes and the different head conditions will drive groundwater flow along the borehole with the resulting rest water level being a balance between the hydraulic pressures in the different aquifers (Brassington, 1992).

The groundwater is stored in and moves through joints and fractures with a relatively small proportion contained within the rock matrix (Jones *et al*, 2000). The groundwater elevations in each aquifer may differ from the others reflecting the geological structure and factors such as the relative elevations of the recharge area and the discharge zones.

Groundwater levels have been monitored in the vicinity of the Pilkington Quarry by monthly dip readings in the borehole network listed in Table 3. Records began on 24th June 2008 for Boreholes A, D, E and Old and on 22nd November 2010 for the remainder with the data set used in this paper extending until 31st August 2011 although monitoring has continued since that date. The monthly readings are complete except for August and November in 2008 and February in 2009; two reading were also taken in January 2011 but none in February 2011. The number of measurements in Boreholes H and I in the adjacent Montcliffe Quarry were restricted by access problems on four separate occasions for each borehole.

Bh No	Response Zone (depth in metres)	Start of record	Aquifer(s)	Location	Fall in level Feb- April 2011 (m)	Comment on groundwater record
A	32 – 52	24 July 2008	Ousel Nest Grit	130 m below quarry void	3.03	Seasonal fluctuations
D	21 – 42	24 July 2008	Ousel Nest Grit	410 m below quarry void	1.5	Seasonal fluctuations
E	32 – 51	24 July 2008	Ousel Nest Grit	500 m below quarry void	7.73	Seasonal fluctuations
Old	0 – 58	24 July 2008	Ousel Nest Grit & Margery Flags	100 m above quarry void	0.07	Two aquifers & also affected by quarry
F	15 – 30	22 Nov 2010	Ousel Nest Grit	120 m below quarry void	2.6	Seasonal fluctuations
G	25 – 40	22 Nov 2010	Ousel Nest Grit	80 m below quarry void	4.24	Seasonal fluctuations
H	5 – 17	22 Nov 2010	Ousel Nest Grit & Margery Flags	210 m to the side of the quarry void	2.73	Limited record – pattern unclear
I	6.2 – 11.7	22 Nov 2010	Ousel Nest Grit & Margery Flags	250 m to the side of the quarry void	Not measured	Affected by quarry – pattern unclear
J	65 – 80	22 Nov 2010	shales	140 m above quarry void	0.03	Only in shale and sealed from sandstone aquifer
K	40 – 55	22 Nov 2010	Ousel Nest Grit	70 m above quarry void	0.69	Affected by quarry – pattern unclear
L	6.5 – 21.5	22 Nov 2010	Ousel Nest Grit	50 m above quarry void	0.72	Perched water table
M	25 – 45.8	22 Nov 2010	Ousel Nest Grit	50 m above quarry void	0.11	Affected by quarry
N	30 – 46.5	22 Nov 2010	Ousel Nest Grit	50 m to the side of quarry void	0.74	Affected by quarry

Table 3. *Details of the monitoring boreholes around the Pilkington Quarry.*

For the purpose of reviewing the groundwater records measured in these boreholes they have been divided into three groups: those that lie higher up the hillside from the quarry and are also up-dip in terms of the geology; those that lie further down the hillside from the quarry and are also down-dip; and those that are between these groups, lying to the side, along the strike. The first group consists of Boreholes J, K, L, M and Old and are referred to as being above the quarry; the second group consist of Boreholes A, D, E, F and G and are identified as being below the quarry; and the third group comprises Boreholes H, I and N.

The hydrographs for all the monitoring boreholes have been plotted as Figure 9 from which it can be seen that the amplitude in the seasonal fluctuations are very variable across the data set with those boreholes located above the quarry appearing to have little or even no fluctuations. A number of separate graphs covering groups of boreholes have been plotted on a variety of vertical scales in order to understand the fluctuations in greater detail.

Figure 10 shows the hydrographs for the borehole located below the quarry (A, D, E, F and G plus Borehole N which is also included on Figure 11) from which it can be seen that the three-year record for Boreholes A, D, and E show the same pattern although the seasonal fluctuations have different amplitudes. The hydrographs for Boreholes F, G and N that cover almost a full 12 months also have a similar seasonal pattern but again with different amplitudes.

Figure 11 shows the hydrographs for the other boreholes (J, K, L, M and Old that are above the quarry and Boreholes H, I and N that are lie to the side of the quarry void). The hydrographs in Boreholes J and L rise over the period of record although the other hydrographs appear to have a muted seasonal response. The piezometer construction records show that Boreholes H, I and Old have response zones spanning both the Ousel Nest Grit and deeper sandstones that lie below the shales associated with the Margery Mine coal seam. Although it is unlikely that there will be great difference in the groundwater heads between the individual sandstone aquifers the data need to be viewed with caution. Borehole J lies on the downthrow side of the fault that runs along the northern side of the quarry and has its response zone in a thick shale sequence. The hydrograph shows a slow rise of some 7 m over the period of the record which is assumed reflects slow leakage through the shales from the overlying aquifer. Borehole L is only 21.5 m deep and is close to Borehole M that has a water table about 36 m below ground and a response zone from a depth of 56.5 m. However, the water levels in Borehole L are typically about 7 m below ground from which it is assumed they represent a perched water table, perhaps on a shale layer not identified in the borehole log.

Figure 12 compares hydrographs for Boreholes K, M and Old that lie above the quarry with Borehole E that is below the quarry and also has the largest seasonal amplitude. It can be seen that all three upstream boreholes generally follow the same patterns of seasonal fluctuations, although the fluctuations are extremely muted compared with Borehole E. For example, Borehole K has about 10% of the range of Borehole E,

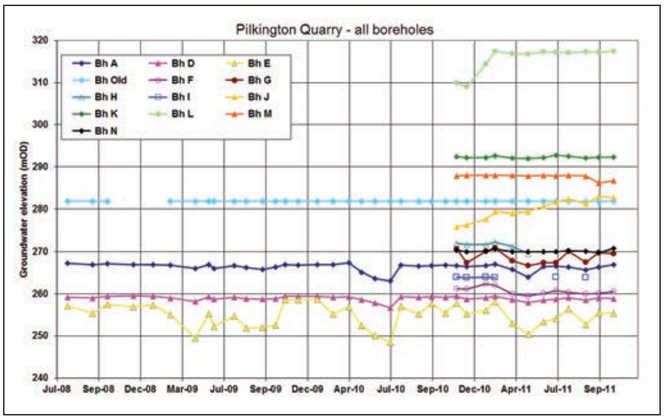


Figure 9. *Hydrographs of the full groundwater levels data set collected from July 2008 to August 2011 shown to Ordnance Datum. Note measurements in Boreholes A, D, E and Old commenced on 24th July 2008 with those for the remaining boreholes commencing on 22nd November 2010.*

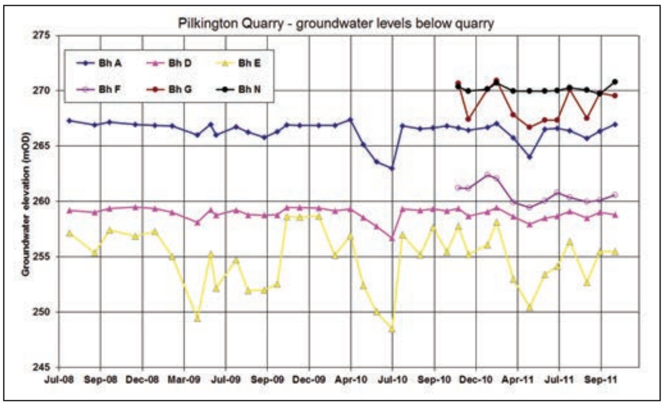


Figure 10. *Hydrographs for the monitoring boreholes that lie below (both down dip and down the hillside from) the quarry void (shown to Ordnance Datum). Note that all the hydrographs follow the same overall pattern reflecting the recharge events that occurred during the period of the record. However, the amplitude of the fluctuations varies from location to location with the possible causes discussed in the text. The diagram includes the record for Borehole N that is also included in Figure 11.*

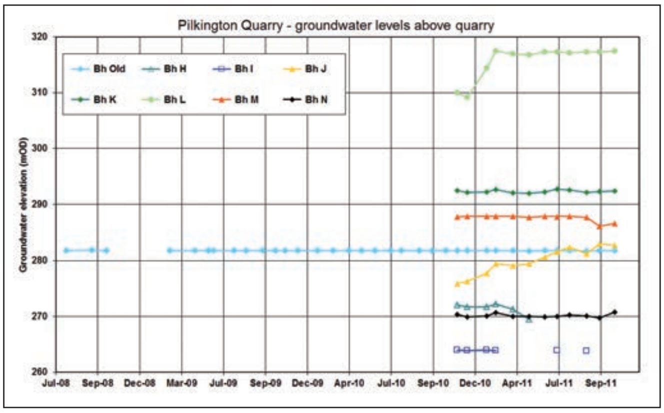


Figure 11. *Hydrographs of the monitoring boreholes that lie above (at a higher elevation and up-dip from) the quarry void to Ordnance Datum and including Borehole N. The hydrograph for Borehole Old appears to be featureless. The others follow the same overall pattern reflecting the recharge events that occurred during the period of the record. However, the amplitude of the fluctuations varies from location to location with the possible causes discussed in the text.*

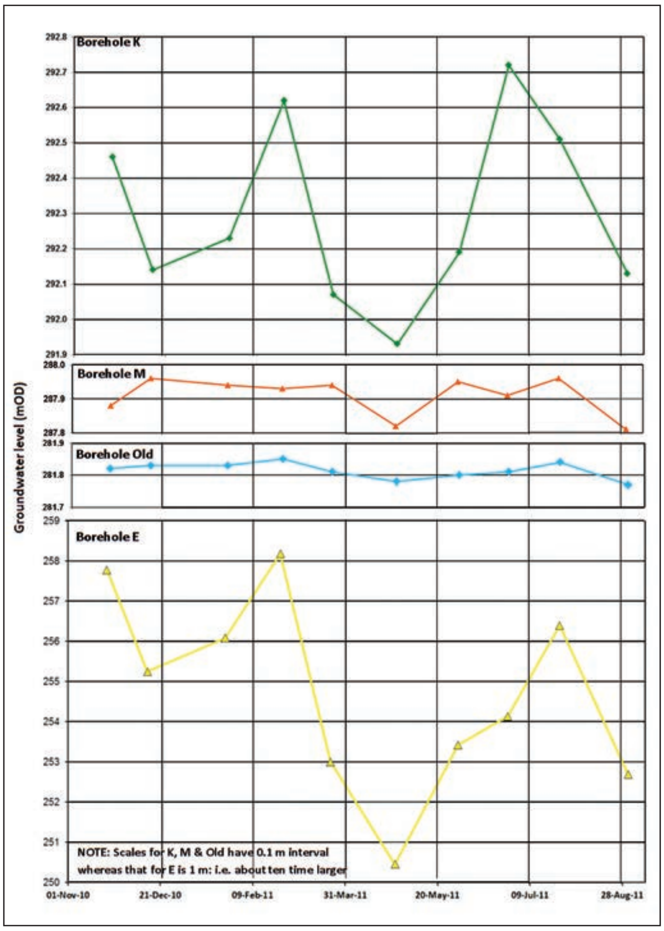


Figure 12. *Groundwater level records for three boreholes above the quarry (K, M and Old) are shown here to Ordnance datum and to the same vertical scale of 0.1m intervals. The vertical scale for Borehole E (located below the quarry) however, is at 1m intervals and therefore some ten times bigger.*

whereas Borehole M has about 2% of this range and Borehole Old only about 1.3%.

It has been assumed that the seasonal fluctuations are in response to variations in rainfall recharge and to test this theory the hydrograph for Borehole E has been compared with monthly rainfall figures. Rainfall data for the Horwich area are not readily available. The Meteorological Office (Met Office) web page provides information on some long-term weather stations with the closest to Horwich being in Lister Park in Bradford (The Meteorological Office, 2013) Although the annual average rainfall at Bradford is about 84% of that at Horwich it can be expected that the overall patterns of monthly rainfall totals is broadly similar. Figure 13 shows the hydrograph for Borehole E with the monthly rainfall from which it can be seen that there is a general rise in the groundwater levels after wet periods and conversely the levels fall following periods with relatively small amounts of rain. The rise in groundwater levels following the high rainfall in November 2009 was followed by a steady recession to the end of June 2010 other than a rise in groundwater levels caused by heavy rainfall in March 2010. Similarly the recession from February to April 2011 resulted from the dry Winter and Spring.

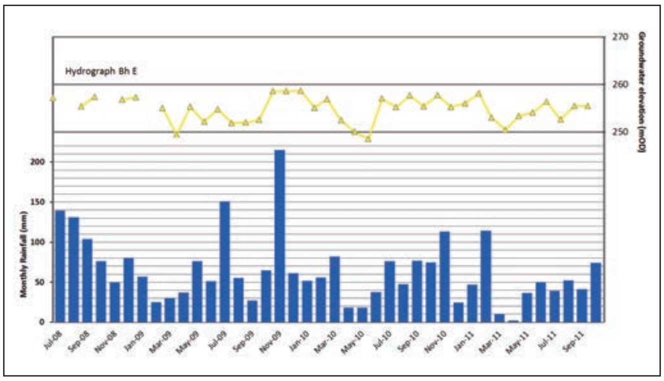


Figure 13. *The groundwater level data for Borehole E is shown above the rainfall data from which it can be seen the changes in groundwater level generally follow the rainfall pattern with a short delay.*

The maximum change in the groundwater levels during the period when data was being collected from all the boreholes occurred between February and April 2011. This period followed a dry Winter and Spring when there was only some 65% of long-term average rainfall (as measured at Bradford). The total changes over this period recorded in each borehole have been plotted on Figure 14 (except for Borehole I which was not measured in March or April 2011). This generally reflects the earlier observation that groundwater changes above the quarry void are much less than those below it and its significance is discussed below.

The lagoon located on the southwest part of the quarry floor is formed by ponding of groundwater that has flowed across the quarry floor from a seepage area along the base of the northern face together with rainfall runoff from within the quarry area. The water level in the lagoon lies at about 275mOD with an estimated one metre fluctuation based on informal observations of "tide-marks" left by floating debris as the water level fell.

The groundwater level record has been used to construct a water table elevation map for February 2011 that is presented in Figure 14. These contours confirm that the groundwater flow direction is to the southwest and follows the topographical slope. This groundwater flow appears to discharge along the spring line indicated on the Ordnance Survey map (Figure 14) as springs or the start of blue lines that indicate water courses. This spring line is downhill from George's Lane/Matchmoor Lane at an elevation of about 230 – 250mAOD possibly influenced by the faults shown in Figures 2 and 3.

DISCUSSION

The hydrographs from those monitoring boreholes with response zones in the Ousel Nest Grit aquifer and those that are in both the Ousel Nest Grit and Margery Flags aquifers show a similar general pattern of seasonal fluctuations although there are major differences in the amplitude in these fluctuations. These differences are illustrated by the period February to April 2011 shown in both Figure 14 and Table 3.

In general terms, the seasonal changes are the greatest in the area below the quarry whereas those above the quarry have very small fluctuations although there are also relatively large differences between boreholes that have similar relationships to the quarry. Groundwater level changes that represent the same recharge pattern may be influenced by a number of factors that may give

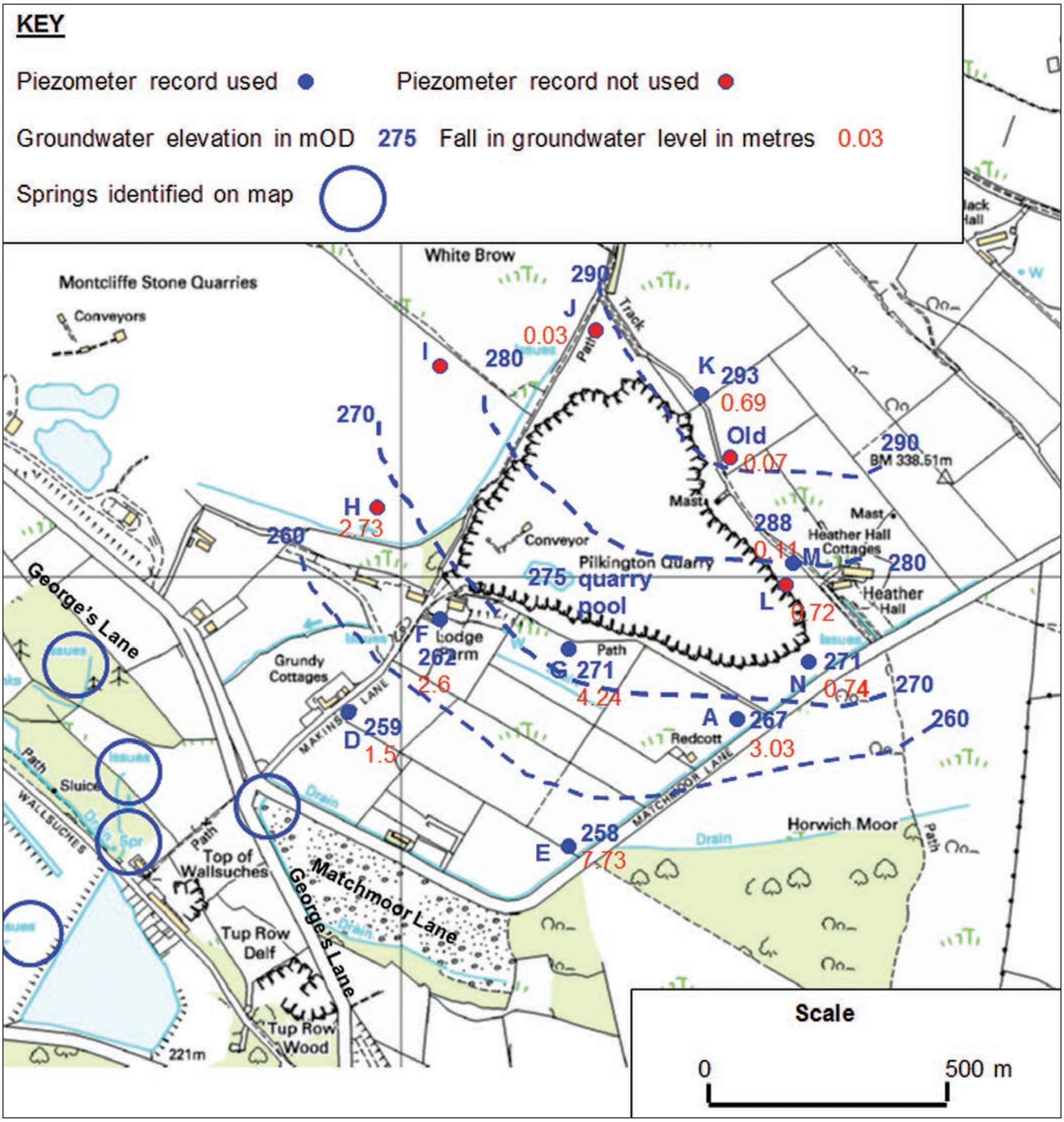


Figure 14. Contours on the water table in the Ousel Nest Grit aquifer across the Pilkington Quarry have been constructed for the data for February 2011. Data from Boreholes H, I, J, L and Old (marked in red) have not been used as these are judged to be unrepresentative of the Ousel Nest Grit for reasons discussed in the text. The reduction in groundwater levels from February to June 2011 (see Table 3) is also shown in red as values in metres. This was the greatest lowering in the water table elevations during the period when all 13 boreholes were monitored. The greatest changes are below the quarry void although there is no clear relationship between the amount of change and the distance from the quarry.

rise to differences. These factors include construction features of the boreholes, their proximity to the quarry void and local variations in the hydraulic properties of the aquifer.

Jones *et al* (2000) indicate that the aquifer properties of Namurian and Coal Measures sandstone aquifers are largely dependent on the degree of fracturing and consequently it may be concluded that this provides the most likely explanation for the variations in the amount of groundwater level changes between borehole locations. The possible influence of fractures on storativity is likely to be complex such that if the degree of fracturing varies with depth the amount of change in groundwater levels may vary with its elevation for any given rate of flux through the system.

Boreholes A – F inclusive (including B and C that were not used for water level readings) were drilled by using rotary coring techniques. The cores in all boreholes showed that the sandstone has vertical and horizontal fractures that are variable between the boreholes.

However the available information is not in sufficient detail to identify any variations in fracture size or density that can account for the observed differences in water levels. The postulated fault shown on Figure 3 passes close to the boreholes in this group except for Borehole E where the seasonal amplitude is the greatest. It is likely that fracturing associated with the fault has increased the storativity in the aquifer rock close-by leaving the aquifer near the more distant Borehole E relatively unaffected.

All of the boreholes (with the exception of Borehole Old where no construction details are available) have a similar design containing a piezometer installation that comprises a string of plastic pipe and screen, with the screen surrounded by gravel and the pipe sealed with bentonite pellets above which there is backfill. Table 3 shows the length and depths of the response zones in each borehole that are generally 15m or more in length. There are no clear differences between the boreholes to explain the contrasts between the groundwater hydrographs.

Similarly, the proximity to the quarry void which is listed in Table 3 does not show any pattern linking proximity to the amount of change. The presence of a large excavation in an aquifer can be expected to modify the hydrogeological conditions in its immediate vicinity particularly the water table elevations and the hydraulic gradients that drive groundwater flow. The principal hydraulic properties of permeable rocks are the specific yield (or storage) which is the volume water that will drain from saturated rock as a percentage of its total volume and the hydraulic conductivity (i.e. permeability with respect to water). The main contrast between an aquifer rock and an excavated void is that the specific yield of the void is 100% which contrasts with aquifers that typically have specific yield values in a range of 0.5 – 35%. Similarly the hydraulic conductivity of a void is also extremely large compared with that of the rock mass. It is also possible that the presence of the quarry void may cause movement of the adjacent rock face either creating or enhancing existing fractures on a local basis. Such effects can be expected to reduce away from the quarry face.

Where the volume of the quarry void is large compared with the annual groundwater flux (i.e. the groundwater flow resulting from rainfall recharge) the water level in the quarry can be expected to be at a significantly lower elevation than the original water table provided that the aquifer is sufficiently permeable to allow the groundwater flux to enter the downstream part of the aquifer under the resulting reduced hydraulic gradient.

The main change that quarrying has on an aquifer is caused by the removal of large rock volumes which, when the workings extend below the original water table the aquifer system will be altered in two ways. The replacement of the aquifer rock by the quarry void means that the original flow paths through the aquifer that were controlled by the rock permeability has been replaced by a large capacity, low resistance flow path. In effect, the permeability of the original block of rock has been dramatically increased.

Some of the possible ways that quarrying can impact on groundwater systems were discussed by Brassington (1982), recognising the implications of the contrast between the hydraulic properties of the rock and the quarry void. Figure 15 has been redrawn from Brassington (1982) and shows the changes to a water table envisaged when quarrying has taken place. In that example the water level in the flooded quarry is below the original water table elevation on the upstream side on the quarry. The groundwater flux is sufficiently high compared with the quarry void and /or the original hydraulic gradient was relatively low so that the flow out of the quarry on the downstream side has maintained a water level in the quarry above that of the original water table in that location. Such low hydraulic gradients are likely to be found in areas with small topographical relief such as broad river floodplain areas.

The excavation of the Pilkington Quarry took place in phases over a long period approaching 150 years and no information is available of the groundwater conditions before quarrying started. With one exception the monitoring boreholes were all installed by the present owner and consequently the hydrogeological regime that is being monitored is one where the impacts of quarrying are long established. Consequently, any deductions regarding the changes brought about by the quarrying must be based on the existing groundwater and geological information.

Jones *et al* (2000) provide limited information on the specific yield in terms of the storage co-efficient suggesting that the specific yield for the Ousel nest Grit is likely to be at the lower end of the range given above and it has been assumed to be 5%. To deduce the significance of the effect of quarrying the volume of water stored in the rock before quarrying would have been 1% of the rock that was removed. Consequently the water table would have fallen by 95% of the height above the base of the quarry; for example, from an elevation of 295 mOD to 275 mOD (the elevation of the quarry pool).

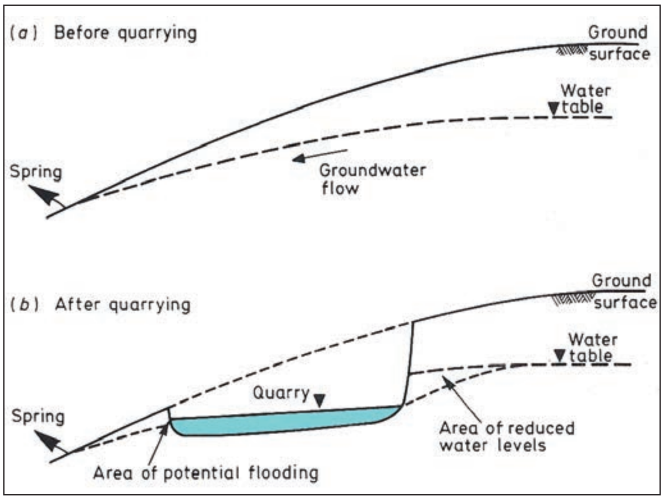


Figure 15. *The theoretical changes to local groundwater levels caused by a quarry that is excavated below the water table and allowed to flood is illustrated here. The water level in the quarry represents the local water table and because there is no resistance to flow through the quarry the level on the downstream side is higher than the original water table and on the upstream side it is lower. As a result the water table downstream is raised and consequently may present potential flooding problems. The lowering of the water table on the upstream side is similar to that seen at the Pilkington Quarry as illustrated in Figure 16. (Reproduced from Brassington 1982 by permission of the Institute of Materials, Minerals and Mining).*

Figure 16 summarizes a conceptual model of the changes caused by the workings at the Pilkington Quarry. The groundwater level record shows that the water table is close to the quarry floor on the upstream side of the quarry and the presence of a seepage face has been deduced. Groundwater from the upstream side of the quarry will flow across the floor and collects along with any rainfall runoff to form the lagoon. The water in the lagoon will flow through the sandstone in its base and the adjacent rock face to the south to add to the groundwater flow through the sandstone on the southern side of the quarry. The contrasts in the storativity means that it is logical to assume that the water table has been significantly lowered in the rock adjacent to the quarry with the greatest affect being on the upstream side. The field evidence supports that deduction.

It is likely that the original water table in the Ousel Nest Grit stood at a much higher elevation than that of the present groundwater levels near the quarry. The significance of this deduction is that should the quarry be restored the water table would rise above the present levels with the final elevations depending on the hydraulic properties of the infill materials. It would be possible to manage the final groundwater conditions by engineering flow paths through the infill materials as proposed by Edwards (oral presentation given at the 17th EIG conference, Edge Hill 2012) at the Rookery Quarry in karstic limestone in Ireland.

In order to design such drainage systems it is necessary to obtain a sufficient understanding of the local hydrogeology to be able to define both the current (i.e. pre-backfill) groundwater flow system and the original groundwater flow system as well as the conditions that are necessary to be achieved after backfilling to prevent contamination and groundwater flooding problems. There are many potential options for the detail design of such groundwater control systems although all will depend on gravity flow, and the water will either discharge through pipes buried at appropriate depths in the fill material or possibly through highly permeable backfill. Pipe systems are more likely to be practical as they will make long-term maintenance more simple. Important features of all designs are the inclusion of a method to capture the inflowing groundwater on the upstream side and the design of the discharge at the downstream end.

CONCLUSIONS

The data set of groundwater levels around the Pilkington Quarry shows that an old pre-existing, large quarry void can be expected to have had a significant impact on the groundwater levels in the adjacent rock. These effects include lowering the water table on a scale similar to that of the quarry void and also reduce the amount of water table fluctuations as measured in monitoring boreholes located on the upstream side of the quarry in relation to the direction of groundwater flow.

Detailed groundwater monitoring is required to identify the seasonal fluctuations in the water table "upstream" of the quarry void.

Any changes to the quarry may have further impacts that the regulator can be expected to require the operator to predict and where necessary take appropriate action.

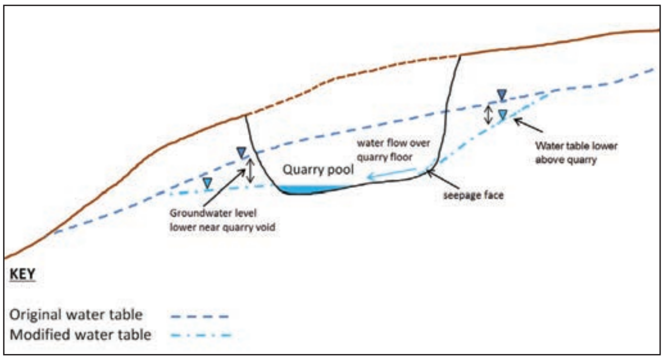


Figure 16. *The groundwater changes in the Pilkington Quarry are illustrated here. In contrast to the situation illustrated in Figure 15, the water body in this quarry lies significantly below the original water table and consequently has caused the water table elevation downstream of the quarry to fall.*

Backfilling will result in further changes in the groundwater conditions that are likely to include a significant rise in the water table elevation. In most cases such changes can be expected to require an engineered drainage system that will control the groundwater elevations and prevent possible problems of contamination and groundwater flooding.

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