ARE YOUR GROUNDWATER MONITORING BOREHOLES DEEP ENOUGH? – WATER IMPACT ASSESSMENT IN KARSTIC LIMESTONES AT CAULDON QUARRY

S. Barnes[1], J. Elvins[2] and N. White[3]

[1] Golder Associates Ltd, 16820 107 Avenue, Edmonton, Alberta, Canada, T5P 4C3.

[2] British Gypsum, East Leake, Loughborough, Leicestershire, England, LE12 6HX. Previously at Lafarge Tarmac.

[3] Golder Associates (UK) Ltd, Attenborough House, Browns Lane Business Park, Stanton-on-the-Wolds, Nottinghamshire, England, NG12 5BL.

ABSTRACT

Lafarge Cement's Cauldon Quarry is situated within a karstic limestone aquifer less than 2km from the Peak District National Park and amongst a series of Sites of Special Scientific Interest (SSSIs). The hydrogeology of the quarry area was poorly understood, and a thorough review has been undertaken as part of the preparation to develop a new phased working scheme to extend the footprint and deepen the extraction area.

The findings of the review are presented, including clarification on the necessity to examine regional scale geology and hydrogeology when seeking to interpret site specific water level and quality data in a limestone terrain. A determination of catchment scale hydraulics and water balances has been used to help constrain potential receptors and sensitivities associated with the proposed scheme and the nature of karstic features present. Water table fluctuations in excess of 65m have been observed, and potential impacts associated with alterations to the local groundwater regime assessed and mitigation measures derived accordingly. Ultimately it has been concluded that in karstic limestone environments groundwater can do the unexpected.

Barnes, S., Elvins, J. and White, N., 2014. Are your groundwater monitoring boreholes deep enough? –
Water Impact Assessment in karstic limestones at Cauldon Quarry.
Pp. 87-99 in Hunger, E., Brown, T. J. and Lucas, G. (Eds.)
Proceedings of the 17th Extractive Industry Geology Conference, EIG Conferences Ltd. 202pp.
e-mail: sbarnes@golder.com

INTRODUCTION

The Lafarge Cement UK (LCUK) (from 7 January 2014, Lafarge Tarmac) Cauldon Quarry site is situated in Staffordshire about 1km to the south of the village of Waterhouses in an upland area predominantly comprising pasture land and woodland copses (Figure 1).

The new working scheme at the site includes an extension to the south east. This will expand the existing extraction area from 48ha to 72ha (with 4 new phases), and will deepen parts of the existing quarry floor by up to three benches, from approximately 260mAOD to 215mAOD (Figure 2). Whilst the proposed development is within the existing planning permission area, approval is required from Staffordshire County Council ahead of each new working scheme. The site is situated in Carboniferous Limestone, which is classified as a Principal Aquifer, and consultation with the Environment Agency is also appropriate ahead of such development.

REGIONAL GEOLOGY

Carboniferous sedimentary rocks reported in the direct vicinity of Cauldon Quarry range from Lower Carboniferous (Dinantian) limestones through to Upper Carboniferous Namurian sandstone, mudstone and grits (Figure 3). The Dinantian deposits consist mainly of marine limestones, with Cauldon Quarry situated within the 'Staffordshire Shelf Province' where the strata have been separated chronologically into the Rue Hill Dolomites, Milldale Limestones and Kevin Limestones (Chisholm et al., 1988). The quarry extracts material from the Milldale Limestones, which are well-bedded, mid grey, finely bioclastic limestones (medium to high purity (>93.5% to <98.5% $CaCO_3$)) (Harrison and Adlam, 1985) with some darker and thinner bedded bands.

The axis to a broad complex upfold, the Cauldon anticline, runs in a north northwest to south southeast orientation approximately several hundred metres to the west of the quarry (shown on the line of section in Figure 3). This axis orientation is similar to most of the faults and folds throughout the southern portion of the Peak District (Bridge and Kneebone, 1983). The limestones at the quarry outcrop as an inlier, with the site located about 1.5km to the east of the shales/limestone boundary which represents the transition between the Lower and Upper Carboniferous.

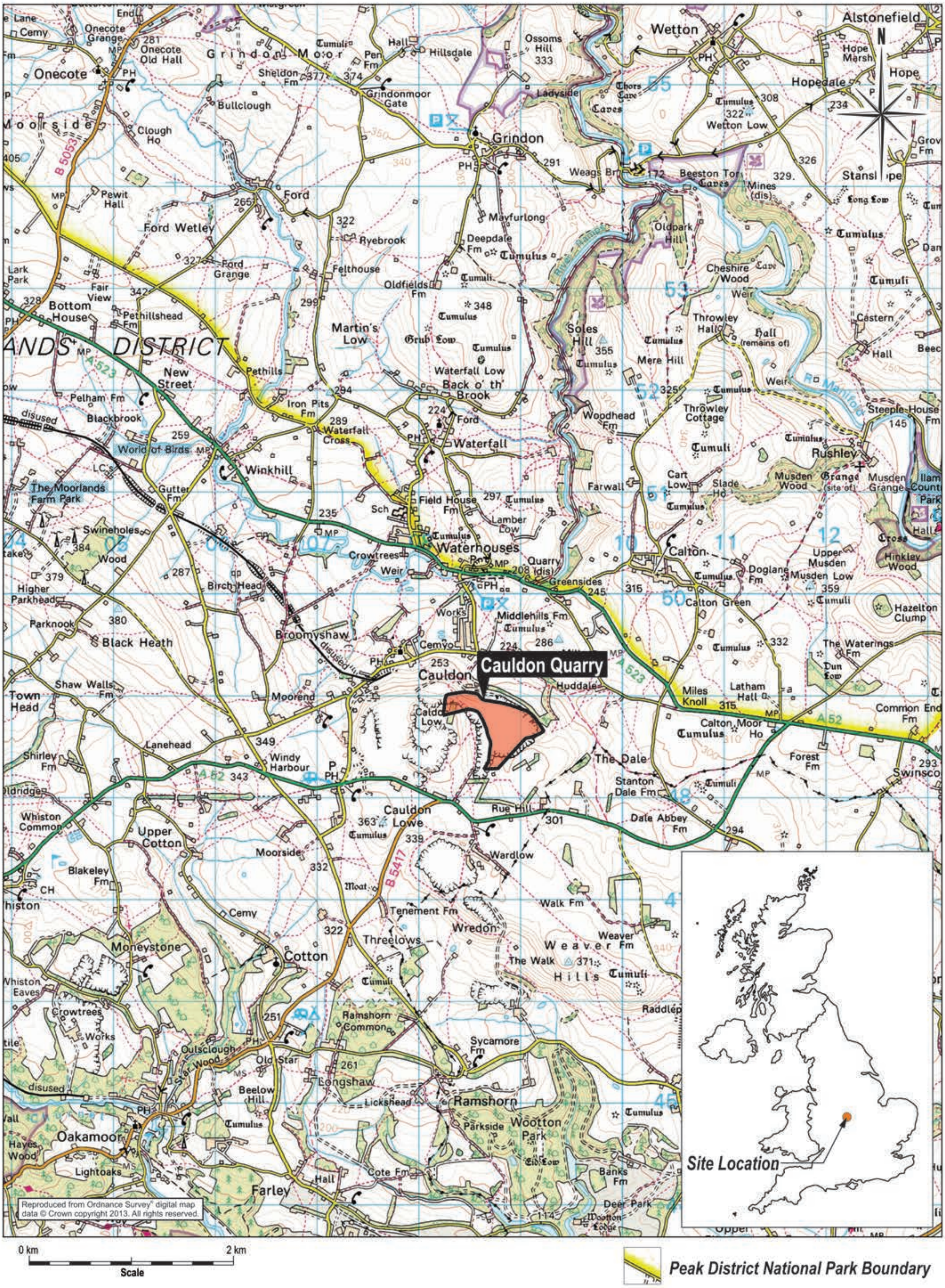


Figure 1. *Site location plan for Cauldon Quarry.*

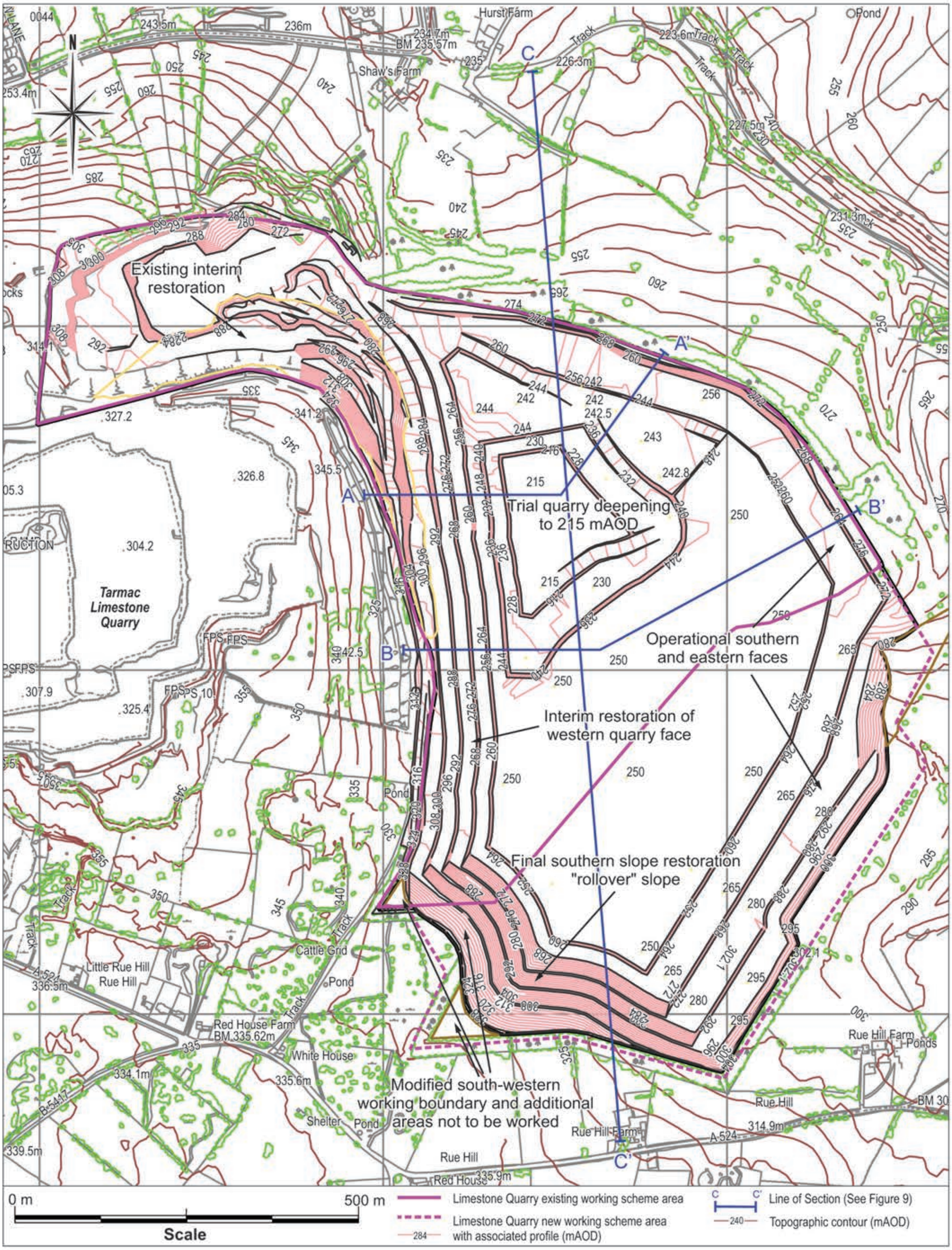
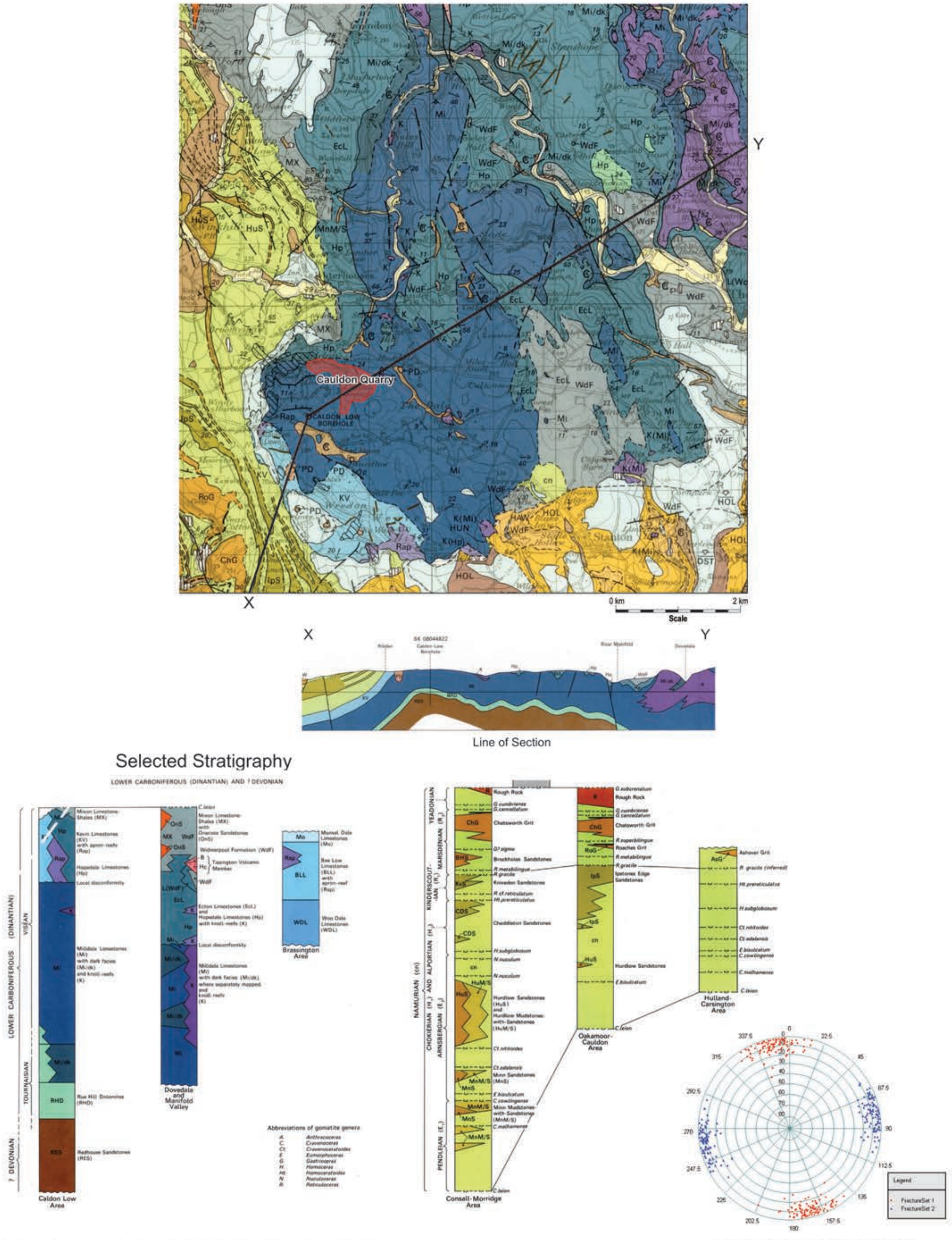


Figure 2. Cauldon Quarry design at end of proposed working scheme.



Fracture set data from Cauldon Quarry

Reference: Figure is produced after the British Geological Survey, Sheet 124, Ashbourne.

***Figure 3.** Regional geological setting.*

Although limestone pavement is not prevalent in the vicinity, Downing et al. (1970) report that on a regional scale, for all practical purposes, the limestone can be reported as being ‘drift free’.

SITE SPECIFIC GEOLOGY AND FINDINGS FROM MINERAL EXPLORATION BOREHOLES

The geology at Cauldon Quarry has been constrained primarily from observations and measurements made within the quarry and from a dedicated programme of borehole and geophysical logging carried out over a 20 year period. Two perpendicular fractures sets (Figure 3) have been noted; striking at north northwest to south southeast (parallel to the fold axis and faults in the area) and east northeast to west southwest orientations (Edge and Pritchard Limited, 2002).

None of the sixty nine borehole logs available from the site suggest that rock head is greater than 3.3m from the ground surface.

In 2000/2001 six mineral exploration boreholes (CW1/2000 to CW6/2001) were drilled and installed to depths of 127m (basal elevations between 167mAOD (CW1/2000) and 218mAOD (CW3A/2000)) to support initial investigations of the proposed working scheme area. Each of these boreholes has a 30m slotted response zone at the base with plain pipe and associated bentonite cement seal to the surface. Borehole locations are presented on Figure 4. Core recovery, sample testing and gamma logging typically demonstrated a fractured limestone with occasional massive horizons and containing a number of minor distributed clay and argillaceous layers.

Spot groundwater elevations were measured in boreholes CW1/2000 to CW6/2001 every two weeks during 2002. Including information from the Environment Agency’s Wardlow borehole to the south, data from December 2002 suggest a fairly consistent groundwater table gradient (of approximately 0.035) across the site, varying from about 240mAOD to 215mAOD and sloping towards the north northeast in the direction of the River Hamps (at approximately 210mAOD) about 1km to the north (Figure 4). Regional groundwater head contours presented for Peak District limestones by both Downing et al. (1970) and Edmunds (1971) are in the order of 210mAOD to 240mAOD in the vicinity of Cauldon Quarry and are therefore consistent with these site specific data. However, groundwater elevations recorded by LCUK in the mineral exploration boreholes remained fairly static during summer months and were judged to possibly reflect either the damp base of the borehole or to be representative of trapped perched water in the base of the hole (<5m water depth was recorded in the boreholes, in all cases).

WATER IMPACT ASSESSMENT

In order to better understand the nature of the groundwater table and to confirm summer groundwater elevations, during June/July 2003 an additional six dedicated and deeper groundwater monitoring boreholes (2003-A to 2003-F presented on Figure 5) were installed to depths of 160m (basal elevations between 103mAOD and 173mAOD) over an increased geographical area. The response zone in these boreholes is typically 60m in length from the base. This drilling programme was completed in parallel with commencement of an associated Water Impact Assessment to support the development.

Meteorology

Long term average rainfall (1941-1970) for the quarry area is 840mm per annum, and the potential transpiration for grassland is 474mm per annum (Smith, 1976). The estimated effective rainfall for the site is 416mm per annum based upon the monthly difference between precipitation and the potential transpiration. The nearest Environment Agency rain gauge at Cauldon Low, 2.25km to the west southwest of the quarry (see Figure 6), reports an average annual rainfall (between 1986 and 2002) of 888mm per annum (range 687mm to 1,187mm per annum). The figures from Cauldon Low are considered to be consistent with the longer term regional data set.

Hydrology

The area is regionally part of the River Dove drainage basin (1,018km^2) and is locally drained by the River Manifold and the River Hamps.

About 6km to the north of Cauldon Quarry the River Manifold sinks upon leaving the overlying Namurian grits and shales and reaching the limestones at Wetton Mill (Figure 6). The stream bed is thereafter dry for much of its course during summer months; before rising again at the springs at Ilam.

The River Hamps behaves similarly to the Manifold, sinking at the village of Waterhouses at Cotton Swallet about 1km to the north of the quarry. Cotton Swallet is also known to be connected to the River Manifold, and again to specific risings in the Ilam area (Gill and Beck, 1991).

Figure 7 presents catchments associated with three identified gauging stations in the area. The ‘Manifold at Hulme End’ is a gauging site situated on the River Manifold just upstream of the sink at Wetton Mill, and the ‘Hamps at Waterhouses’ is a gauging site situated on the River Hamps just upstream of Cotton Swallet. In addition, a gauging site is situated just downstream of the collective risings at Ilam on the River Manifold (Manifold at Ilam) (Figure 6).

A summary of flow data (Natural Environment Research Council, 2012) for each of the three gauging stations are provided in Table 1.

Considering the Q50 flow data (most likely flow rate), the rivers supplying sinks at Wetton Mill and Cotton Swallet alone account for 37% of the flow (incorporating spring output) in the River Manifold at Ilam. The remainder is inferred to derive from further input from more minor river sinks known to exist in the area (see Figure 6) and from diffuse recharge to the limestone outcrop.

If a similar comparison is undertaken for flow in the River Manifold at Ilam using the Q10 (high flow) and Q95 (low flow) data, the rivers supplying the sinks after Hulme End and at Waterhouses provide 55% and 24% of this flow respectively. The inferred reducing relative

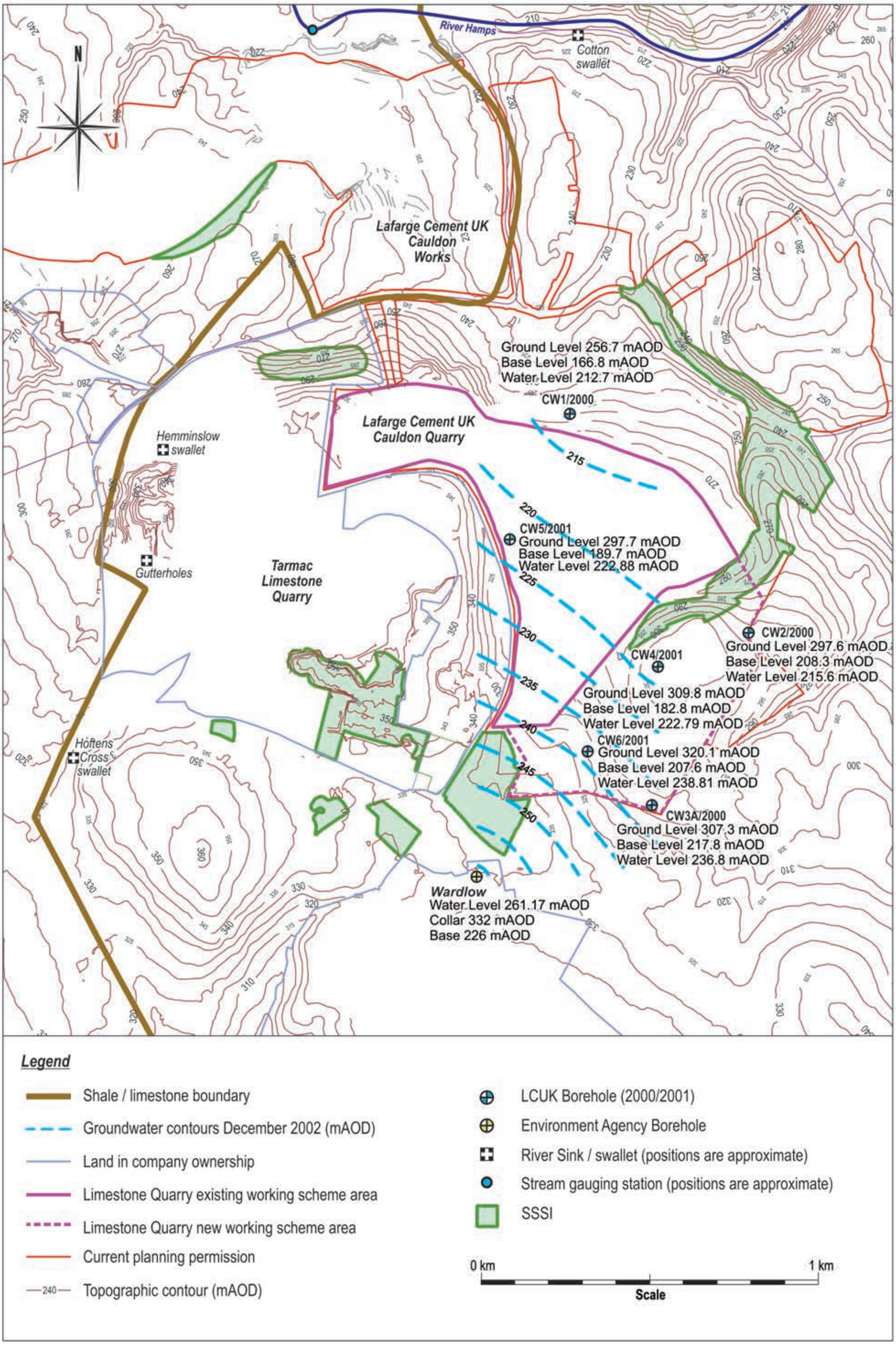


Figure 4. *Groundwater table contour plot generated from elevations determined in mineral exploration boreholes (CW1/2000 to CW6/2001) during December 2002. Drainage was inferred to occur towards the River Hamps located about 1 km to the north.*

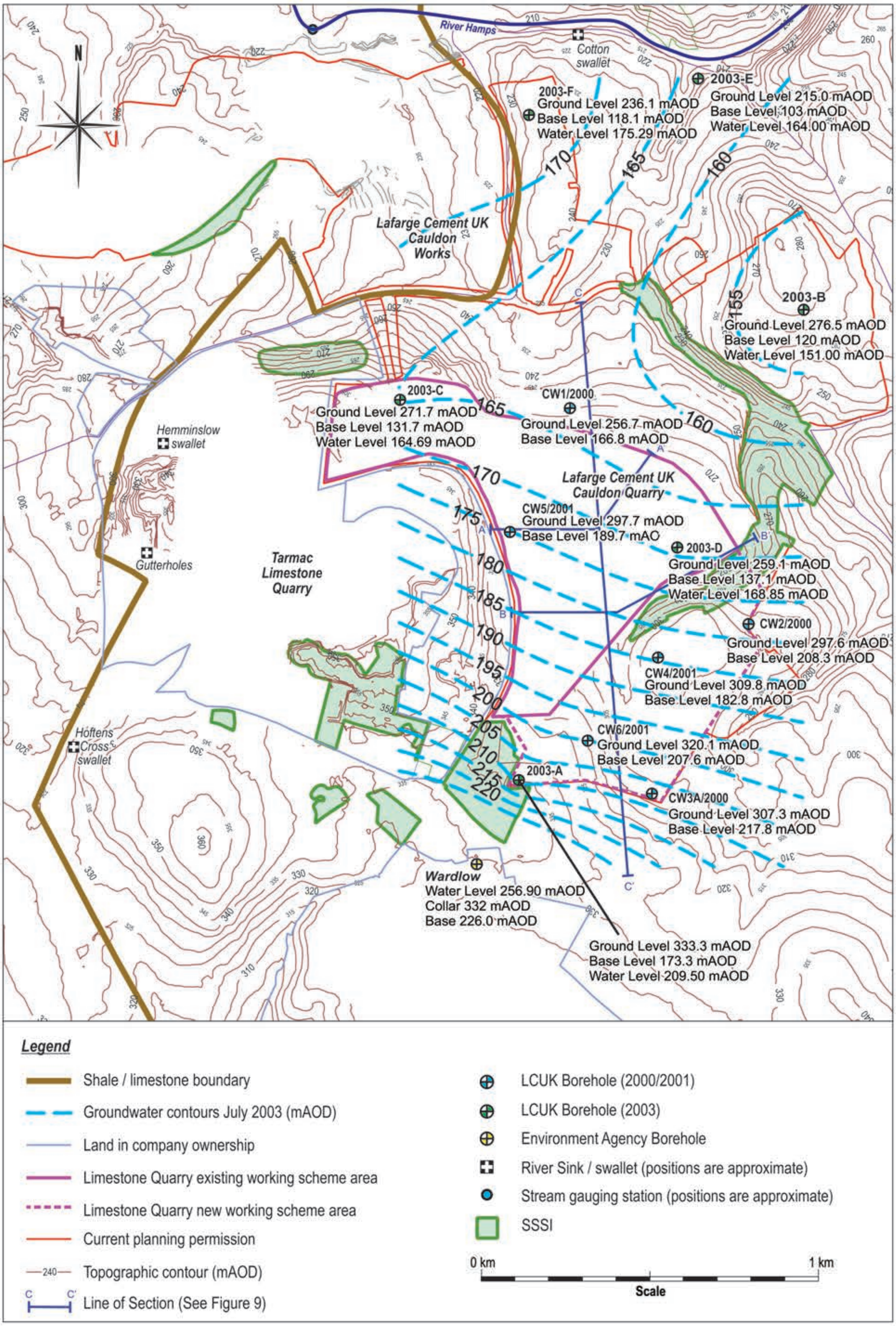


Figure 5. *Groundwater table contour plot utilising elevations recorded in July 2003 from dedicated groundwater monitoring boreholes at Cauldon Quarry. Components of flow can be observed to derive from the high ground to the south southwest of the quarry footprint, and from north of the quarry and the sink/losing section on the River Hamps. Hydraulic head contours and thus flow converges to the north and east of the quarry which is anticipated to mark the approximate orientation of a conduit system.*

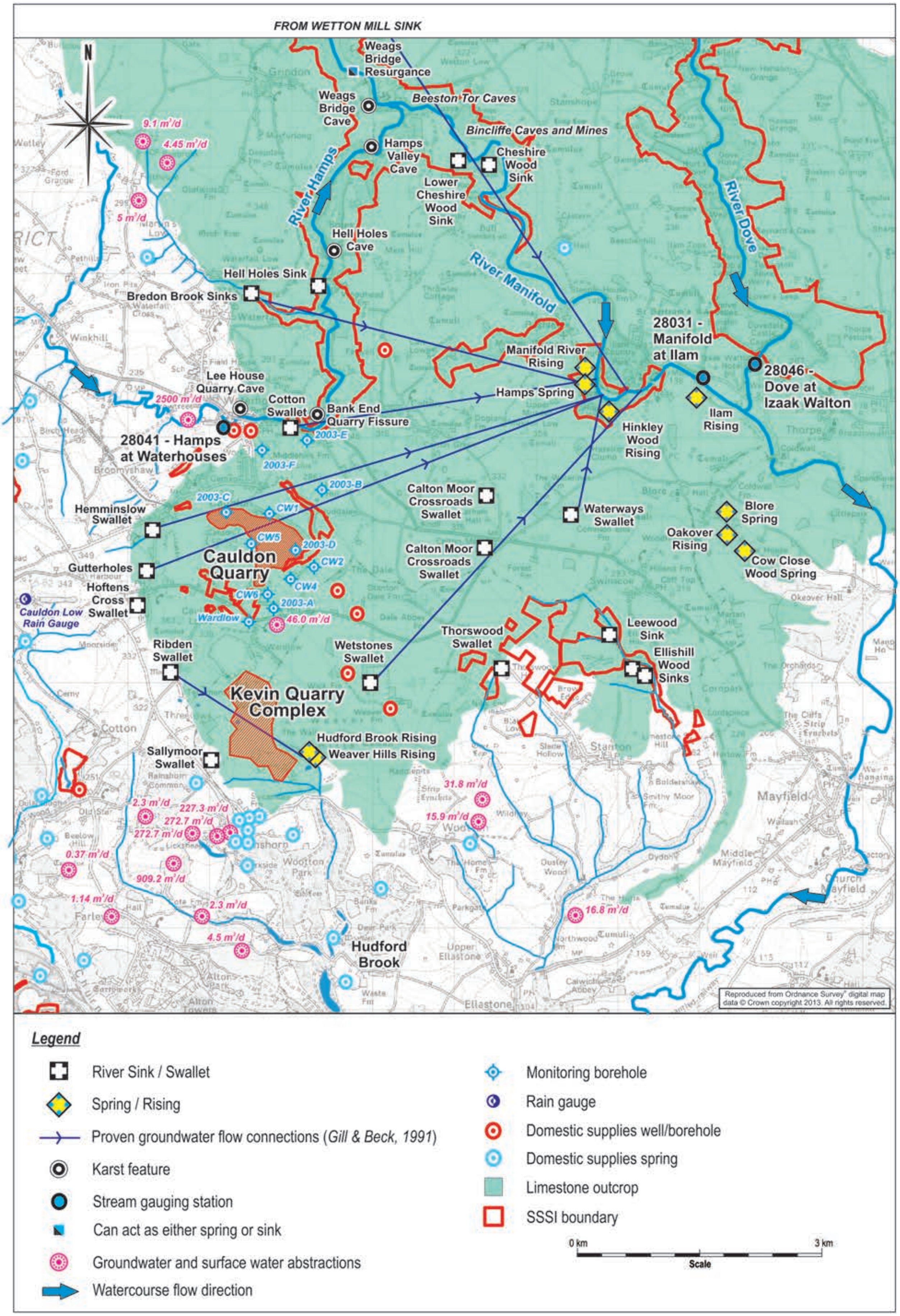


Figure 6. *Hydrological and hydrogeological setting of Cauldon Quarry. The limestone outcrop area is presented, together with surface watercourses and known karstic features including river sinks, springs and established flow connections. Much of the rivers shown over the limestone outcrop are ephemeral in nature. The bulk of spring risings in the area are located just upstream of the stream gauging station on the River Manifold at Ilam.*

contribution from these river-sinks to the spring flow output under lower flow conditions is expected to reflect an increasing proportion of output at Ilam being received from a more consistent diffuse recharge/groundwater input or baseflow during summer months. During flood conditions, indicative of the Q10 results, the surface flow expected to occur over previously dry stream beds in the Manifold and Hamps, and the increased karstic river sink throughput envisaged in the aquifer accounts for a greater proportion of the flow at Ilam.

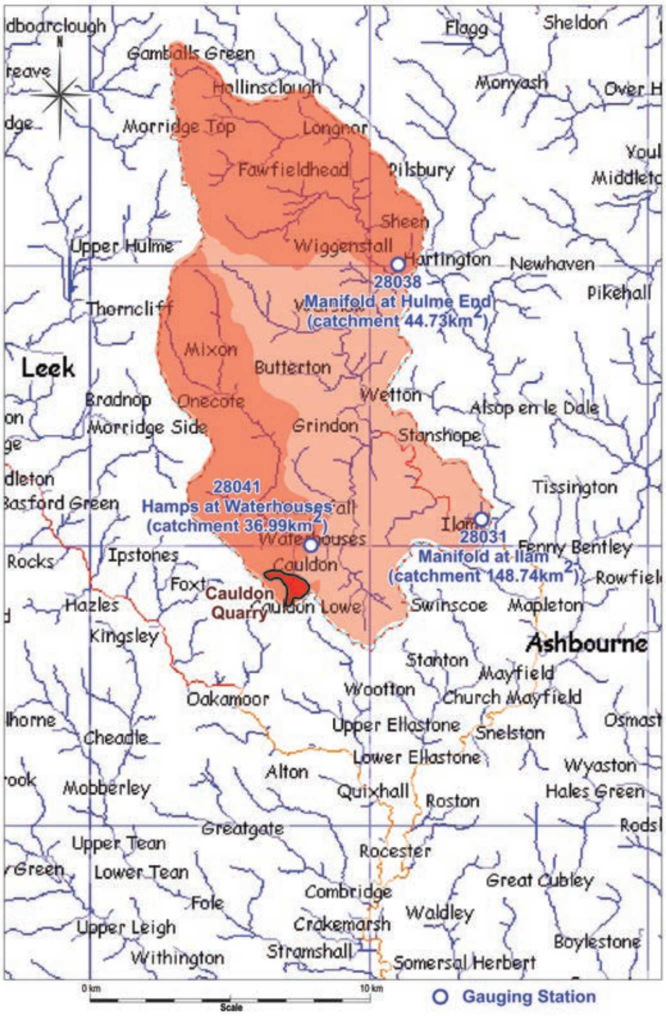


Figure 7. *Map generated by Flood Estimation Handbook (FEH) Software and showing catchment boundaries and areas (coloured) associated with three stream gauging sites in the vicinity of Cauldon Quarry. The quarry can be observed to be present towards the south of the defined catchments.*

Hydrogeology

The Carboniferous Limestone is an aquifer commonly considered to exhibit karstic hydrogeological behaviour. The term karst can be summarised as a terrain which has distinctive landforms and hydrogeology as a result of its high rock solubility and well developed secondary fracture porosity. Such systems can be viewed as dynamic, with solution processes being influenced by head gradient and water chemistry controls. In general karst systems tend to evolve downward to include a simplified network of a few main pathways.

The matrix of the limestone has a low porosity and hydraulic conductivity, with values ranging from between 0.18% and 5.9% (Drew, 1968, and Nirex, 1993) and 1.2×10^{-8} m/s and 1.2×10^{-7} m/s (Gunn, 1992) respectively. Nirex (1993) report a median hydraulic conductivity of 3.3×10^{-11} m/s. These data are consistent with the matrix not contributing significantly to the water bearing properties of the rock (flow and storage). Permeability testing using the slug approach on six boreholes at Cauldon Quarry was undertaken as part of the Water Impact Assessment and interpretation was completed using the Bouwer-Rice method (Kruseman and de Ridder, 1991). This produced hydraulic conductivities ranging between 9.2×10^{-10} m/s to 4.3×10^{-8} m/s. The lower values, in particular, are not dissimilar to those published for the limestone matrix and limited fissure occurrence is inferred in the sections tested.

Based on data from six pumping tests in Carboniferous Limestones in the Peak District, the British Geological Survey (Allen et al., 1997) report a range of transmissivities from 0.1 m^2/d to 770 m^2/d (geometric mean 10 m^2/d). Downing et al. (1970) presented yield information from four wells in the Peak District which ranges from 163.7 m^3/d with a drawdown of 50.6m, to 1,283 m^3/d with a drawdown of 35.7m. From these data specific capacities have been calculated and used as a proxy to estimate transmissivities (Batu, 1998) of between 3.4 m^2/d and 37.5 m^2/d. The range of performances presented will in part reflect the presence or absence of local karstic features or flow routes.

Groundwater recharge

Identified recharge mechanisms to the limestone in the area around Cauldon Quarry can include the following:

- Infiltration directly to the limestone outcrop area;
- Surface runoff water draining from the overlying cap

Setting	Gauging Station (and reference)	Grid Reference	Daily Flow (m^3/s)		
			Q10	Q50	Q95
Upstream of River sink	Manifold at Hulme End (28038)	SK 106 595	2.57	0.52	0.09
	Hamps at Waterhouses (28041)	SK 082 502	1.64	0.36	0.06
Downstream of Spring	Manifold at Ilam (28031)	SK140 507	7.59	2.35	0.63

Q95 represents value below 95% of the data and above 5% of the data
Q50 represents value below and above 50% of the data
Q10 represents value above 90% of the data and below 10% of the data

Table 1. *Long-term daily river flow rates*

rock and flowing into the limestone via sinks in stream beds; and

- Leakage from the overlying Namurian cap rock.

Infiltration to the limestone outcrop can be considered to approximate effective rainfall rates (416mm per annum) since the soil cover is known to be thin and observed dry valleys and closed depressions suggest that runoff from the limestone will be limited. The mechanism of leakage from the overlying Namurian cap rock is considered to be comparatively negligible due to the anticipated low permeability of the cap rock. In addition, the groundwater quality in the limestone confined at depth at subcrop is understood to be saline and not potable (Downing et al., 1970) suggesting limited movement or flushing within the aquifer in this area.

Groundwater levels and circulation

Groundwater elevations have been recorded hourly by electronic loggers placed in each of the six groundwater monitoring boreholes installed in 2003 (Figure 5) around Cauldon Quarry. Scrutinising the resulting and available data set from early 2006 to mid 2012, a significant range (generally >50m) in groundwater elevation at individual locations is evident (between approximately 35m (2003-F) and 65m (2003-C)).

Characteristic borehole hydrographs for a single year (2008/2009), rather than the full record, are presented to show the detail of fluctuations observed (Figure 8). Groundwater elevations trend in a broadly similar manner for each of the monitoring boreholes throughout the seasonal cycle. However, the behaviour of groundwater levels in 2003-B, located to the northeast of the site, are much more responsive than the subdued variations evident in 2003-A (in particular) situated to the south. It is inferred that the former borehole is quickly and significantly influenced by recharge penetrating the aquifer and may well be situated close to a conduit system draining some of the neighbouring river sinks. 2003-A is located on comparatively high ground close to a ridge, up hydraulic gradient from the quarry, and likely close to a groundwater divide. The hydrograph from 2003-F has the smallest overall range and appears to often return to a preferred mid-range elevation of about 191mAOD (45m below ground level). This behaviour may reflect the presence of karstic void and thus storage in the aquifer in this vicinity, with water levels only varying from the specified elevation when significant recharge occurs or when the void is fully drained during drier periods. 2003-F is the borehole likely situated closest to Cotton Swallet on the River Hamps.

Groundwater elevations from winter months suggest that the proposed deeper elements of the quarry may be periodically or seasonally flooded by up to 10m. This possibility is demonstrated by the hydrogeological cross-sections presented on Figure 9 which include both the proposed quarry plan profile and projected groundwater table data. However, additional storage provided by the eventual quarried void should provide some further regulation on the actual depth of flooded workings that may be realised.

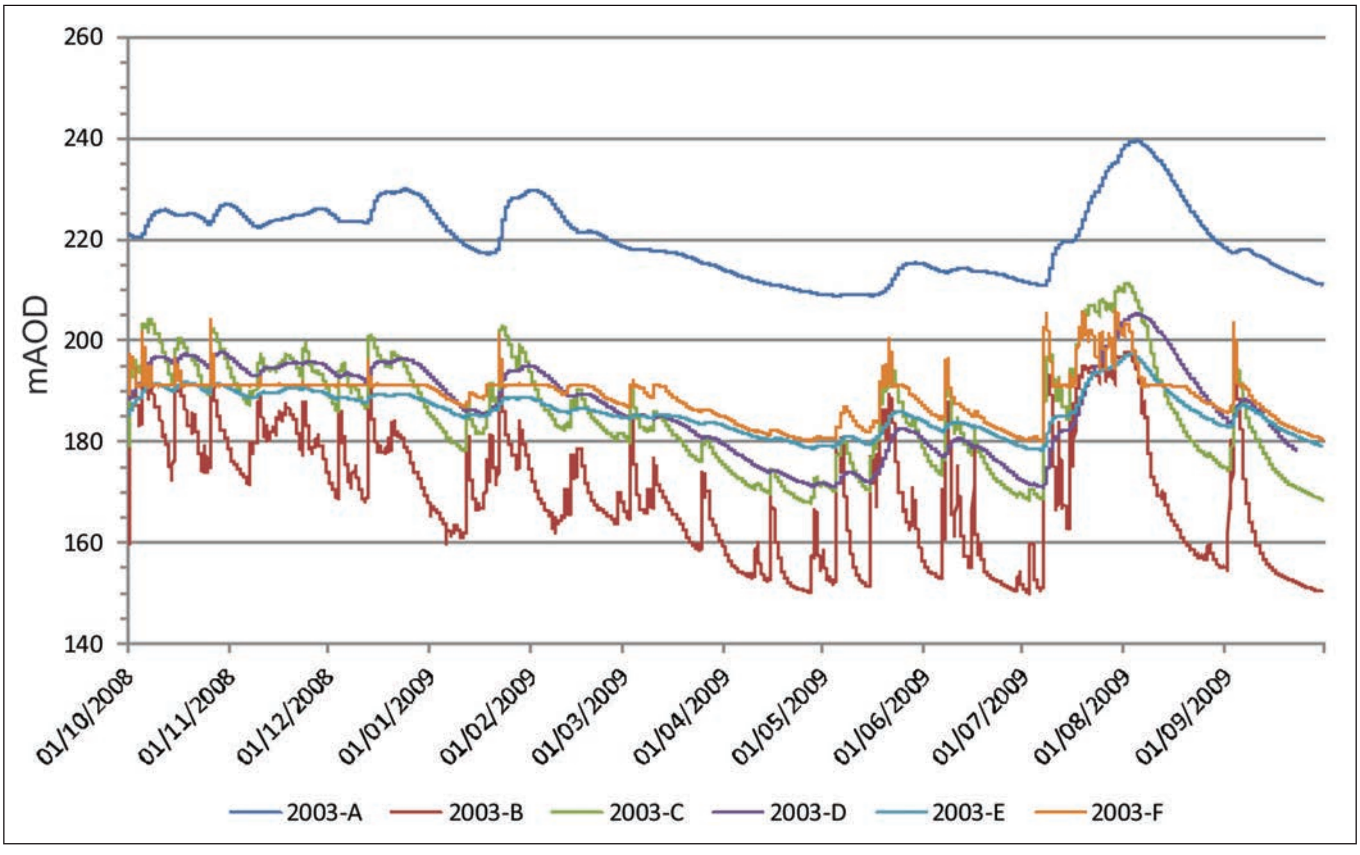


Figure 8. *Groundwater monitoring borehole hydrographs for water year 2009. Whilst water elevations in all of the boreholes have similar overall trends, 2003-B behaves in a significantly more responsive fashion than 2003-A. 2003-B is considered to be more characteristic of a portion of the aquifer influenced by karstic recharge and flow mechanisms.*

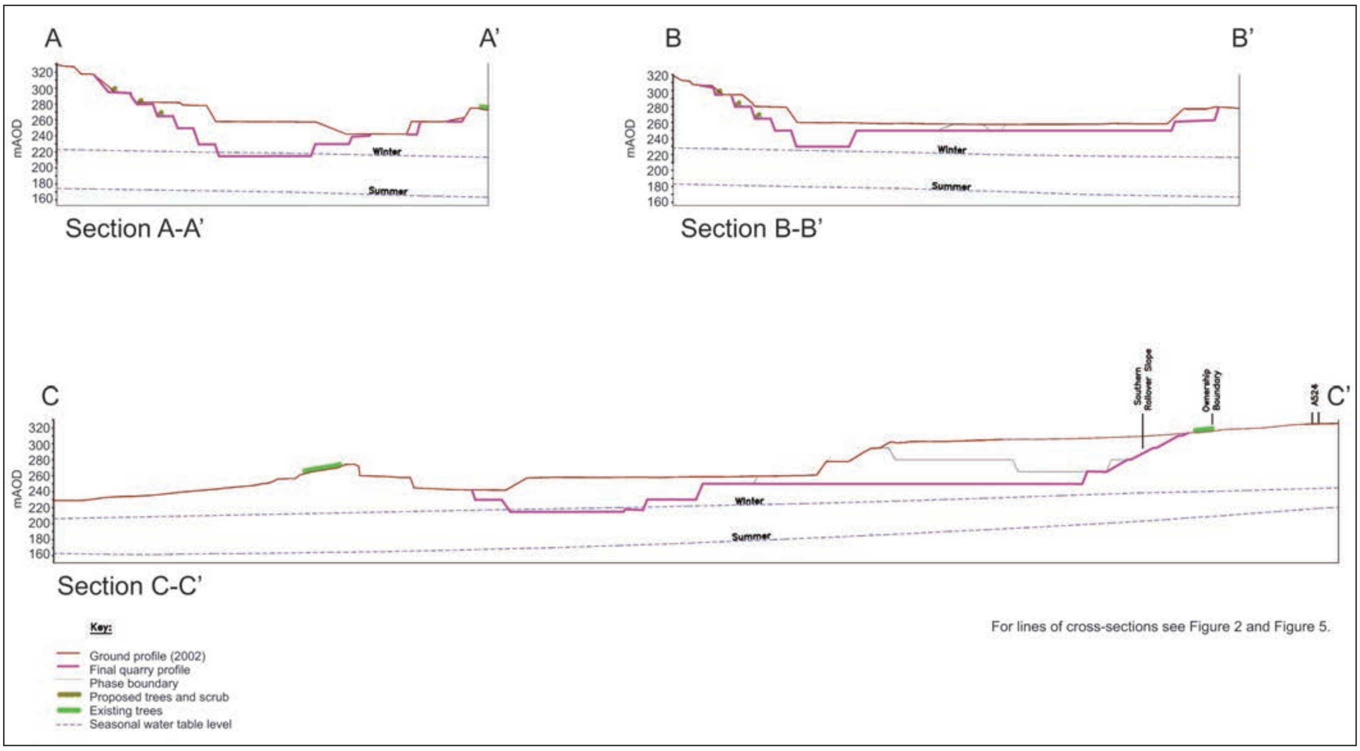


Figure 9. *Hydrogeological cross-sections through the proposed working scheme profile. The groundwater elevation range shown utilises contour data presented on Figure 4 (December 2002; winter) and Figure 5 (July 2003; summer). Based on this information it is indicated that the deepest elements of the quarry may flood during winter months.*

Figure 5 presents a groundwater table contour plot immediately surrounding the site using data from the summer of 2003. The plot is consistent with drainage from a high point of the Environment Agency's Wardlow Borehole to the south, beneath the quarry floor, and towards the north northeast. Despite the range evident in borehole hydrographs, a drop in the groundwater table in the order of 60m over this distance (about 1.5km) is fairly much maintained throughout the annual cycle. Groundwater table contours converge to the north of the quarry, also reflecting an inwards component of flow from the north and the losing section of the River Hamps. During winter months groundwater table contours also demonstrate that flow continues away from the river. Although the River Hamps may carry surface flow over the limestone outcrop during high flow conditions, it is expected to continue to lose to the aquifer at these times.

Whilst several of the borehole hydrographs on Figure 8 can overlap, the overall drainage pattern towards location 2003-B is effectively maintained. However, there are several brief exceptions to this when groundwater elevation in 2003-B can exceed corresponding levels in 2003-C, 2003-D and 2003-E. At these times hydraulic gradients can locally be reversed. These occurrences are limited in duration to several of the most pronounced peaks on the 2003-B hydrograph. Such times are interpreted to be a direct result of significant river sink recharge which impacts 2003-B more directly and rapidly than elements of the aquifer being monitored elsewhere.

The groundwater contours combined with water level variations, known sink to spring connections and field observations suggest that a significant conduit system may pass directly to the north of the quarry flowing in a broad west southwest to east northeast direction and towards the springs at Ilam. This orientation coincides with one of the major fracture trends, which have also been noted elsewhere to often correspond to drainage direction in karstic systems (Barnes, 1999). It is noteworthy that Ilam springs are approximately 3.5km from borehole 2003-B and situated at about 140mAOD. Throughout the full groundwater monitoring data set the minimum groundwater elevation recorded in 2003-B is about 5m higher than the outfall at Ilam. This potentially small hydraulic gradient of 0.0014 towards Ilam, in contrast to that routinely observed across the quarry area (between one and two orders of magnitude greater), is consistent with significantly increased hydraulic conductivity, or the presence of a conduit system, between the 2003-B area and Ilam.

Taking the reported Q50 flow rate upstream of Cotton Swallet of 0.36 m^3/s, and the fact that the traced connection to Ilam springs has been measured to have a travel time of between 3 and 6 days (Gill and Beck, 1991), if a straight line distance is assumed (3.5km) an idealised conduit radius of between 2.9m and 4.1m can be estimated based upon the volume of water underground in the system at any one time. It follows that if the route does not adopt a straight line pathway then the conduit radius may be less than this estimate.

Water features and abstractions

Licensed and unlicensed abstractions within up to 6km of Cauldon Quarry were supplied by the Environment Agency and both East Staffordshire Borough Council and Staffordshire Moorlands District Council and are presented on Figure 6. Locally the closest licensed and domestic supplies to the site are situated at approximately 600m and 225m to the south and southeast of the LCUK ownership boundary respectively.

The former licenced abstraction well is 122m deep and associated with a recorded abstraction of 46 m^3/d. No influence on groundwater head contours at the site has been observed from any abstraction in the area.

Water balance

With respect to the catchment supplying the River Manifold at Ilam, it has been assumed here that long term changes in storage are negligible and that comparatively insignificant amounts of water are abstracted from or introduced to the catchment. The latter assumption is based upon the fact that the bulk of abstractions identified in the region are located off the limestone outcrop (see Figure 6) area and comparatively remote from Ilam springs, and abstraction rates reported are all orders of magnitude lower than the spring discharge rates.

An indicative water balance has been produced in Table 2 to help breakdown relative recharge contributions to the limestone and to the outfall point at Ilam. The approach is aimed at characterising flow rate sensitivities within the Ilam springs catchment, now known to contain Cauldon Quarry, and with respect to the proposed development.

It can be observed that the inferred catchment areas derived from flow and effective rainfall rates correlate reasonably well with actual measured catchments areas (where available). The approach suggests that approximately 50% of the discharge at Ilam is typically derived from river-sink input, with a similar proportion from more diffuse infiltration over the limestone outcrop area. The proposed footprint of the new working scheme is considered to be insignificant within the context of the limestone outcrop area contributing a more diffuse infiltration to Ilam springs and any alterations to aquifer recharge that may result as a consequence of the development (such as reduced transpiration, evaporation etc.).

Due to the position of the quarry relative to the identified underground karst drainage connections within the aquifer, it is considered that the proposed development could have the potential to intercept some of the minor river sink (Hemminslow Swallet and Gutterholes) inputs directly to the west of the quarry (see Figure 6). According to Table 2, these will contribute to the subordinate input or recharge contribution to the catchment and therefore maintenance of the flow at Ilam. The depth of the existing excavation at Cauldon Quarry (260mAOD) together with the proximity of these river sinks (about 290mAOD) directly to the west and the lack of any current evident inward seepage to the workings suggest that point recharge descends fairly rapidly to depth and the saturated zone.

SUMMARY AND CONCLUSIONS

During the study period groundwater table fluctuations have been determined to extend up to more than 65m at individual points and can have a significant and rapid response to rainfall events. This behaviour is considered to reflect the fact that Cauldon Quarry is close

	Input/Recharge to limestone				**Output/Discharge from limestone**
	Flow upstream of Wetton Mill Sink	Flow upstream of Cotton Swallet	Total flow to other minor river sinks	Diffuse infiltration to limestone outcrop	Flow in the River Manifold at Ilam
Volume (m^3/s)	0.52[1]	0.36[1]	0.30[2]	1.16[3]	2.35[1]
% of total flow in the River Manifold at Ilam	22	15	13	49	100
Inferred contributory catchment area (km^2)[4]	39	27	23	88	178
Actual catchment area (km^2) determined from Flood Estimation Handbook Software	44.73	36.99	-	-	148.74

[1] Based on Q50 from stream gauging station – most likely flow rate

[2] Based on field study and estimated surface catchment relative to other neighbouring gauged flows and catchments

[3] Based on difference between discharge rate and total river sink recharge rates

[4] Catchment determined from 'Volume' and selected long term effective rainfall rates (416mm/year)

Table 2. *Indicative water balance for limestone in catchment containing Cauldon Quarry.*

to the top of the limestone catchment and neighbouring the shale limestone boundary where a significant proportion of focused recharge has been demonstrated to occur. The magnitude of the water table fluctuations observed is also supported by the lack of significant storage in the limestone matrix.

Under observed conditions groundwater flow beneath the quarry effectively continues towards the east and Ilam throughout the full annual cycle and not towards the River Hamps. The Ilam springs are therefore considered to be a significant and sensitive down gradient receptor associated with any impacts to the water environment in the vicinity of Cauldon Quarry. However, the quarry footprint forms a very small component (<0.2%) of the total surface drainage basin area supplying the River Manifold at Ilam.

LCUK have (subject to legal agreement) now received approval for the new working scheme. A firm understanding of the hydrology/hydrogeology at the site has assisted with the quarry development planning, and trials undertaken indicate that Cauldon Quarry can be deepened as proposed with dry working only. It is expected that this can be achieved with minimal impact by excavating deeper sections during summer months, when the groundwater table is low, and therefore avoiding the need for active dewatering. Some flooding of the deepest elements of the quarry may occur during winter months, with drainage back to the aquifer when the groundwater table lowers. The benefit of ensuring that groundwater monitoring boreholes are deep enough to confirm the full annual water table range and that in a karstic setting, in particular, the network covers a sufficiently wide area has been clearly demonstrated. Environmental monitoring and annual report production is continuing as the development progresses to help constrain and validate the findings presented.

REFERENCES

Allen, D. J., Brewerton, L. M., Coleby, B. R., Gibbs, M. A., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J., and Williams, A. T., 1997. The physical properties of major aquifers in England and Wales. British Geological Survey in Partnership with the Environment Agency. Environment Agency R&D Publication 8.

Barnes, S., 1999. Karstic groundwater flow characteristics in the Cretaceous Chalk aquifer, Northern Ireland. Quarterly Journal of Engineering Geology, 32, 55-68.

Batu, V., 1998. Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis, John Wiley & Sons, New York.

Bridge, D. Mc.C. and Kneebone, D. S., 1983. The limestone and dolomite resources of the country north and west of Ashbourne, Derbyshire. The Institute of Geological Sciences, Natural Environment Research Council, Mineral Assessment Report 129.

Chisholm, J. I., Charsley, T. J. and Aitkenhead, N., 1988. Geology of the country around Ashbourne and Cheadle. Memoir for 1:50,000 Geological Sheet 124 (England and Wales). HMSO London

Downing, R. A., Land, D. H., Allender, R., Lovelock, P. E. R., and Bridge, L. R., 1970. The Hydrogeology of the Trent River Basin. Water Supply Papers of the Institute of Geological Sciences, Hydrogeology Report No.5. The Institute of Geological Sciences, Natural Environment Research Council.

Drew, D. P., 1968. A study of the limestone hydrology of St. Dunstans Well and Ashwick drainage basins, east Mendip, Somerset. Proceedings of the University of Bristol Speleological Society, 11, 257-276.

Edge and Pritchard Limited, 2002. Cauldon Works Limestone Quarry. Quarries regulations 1999, Regulation 33 – Geotechnical Assessment of excavations and tips. Initial Geotechnical Assessment: 2001. Report ref: CD/LS/GA1/2. Volume I (Text, Table and Drawings) and Volume II (Appendices).

Edmunds, W. M. 1971. Hydrogeochemistry of groundwaters in the Derbyshire Dome with special reference to trace constituents. Natural Environment Research Council, Institute of Geological Sciences, Report No. 71/7. HMSO London.

Gill, D. W. and Beck, J. S., 1991. Caves of the Peak District. Compiled on behalf of the Derbyshire Caving Association, Dalesman Books.

Gunn, J., 1992. Hydrogeological contrasts between British Carboniferous Limestone Aquifers. International contributions to hydrogeology, Vol 13, 25-41. Verlag Heinz Heise, Hannover, Germany.

Harrison, D. J. and Adlam, K. A. Mc.l,. 1985. Limestones of the Peak: a guide to the limestone and dolomite resources of the Peak District of Derbyshire and Staffordshire. British Geological Survey, Mineral Assessment Report 144.

Kruseman, G. P. and De Ridder, N. A., 1991. Analysis and Evaluation of Pumping Test data. Second Edition (Completely Revised). International Institute for Land Reclamation and Improvement, P.O. Box 45, 6700 AA Wageningen, the Netherlands.

Natural Environment Research Council, 2012. Centre for Ecology and Hydrology. http://www.ceh.ac.uk/data/nrfal/.

Nirex., 1993. The geology and hydrogeology of the Sellafield area, Interim assessment. Volume 3 – Hydrogeology. Nirex report No. 524.

Smith, L. P., 1976. Ministry of Agriculture, Fisheries and Food. The Agricultural Climate of England and Wales, Areal Averages 1941-70. Technical Bulletin 35, Meteorological Office.