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The hydrogeology of the Chesterfield, Matlock and Mansfield district (Geological Map Sheet 112)

Groundwater Management Programme

Internal Report OR/07/039

BRITISH GEOLOGICAL SURVEY

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INTERNAL REPORT OR/07/039

The hydrogeology of the Chesterfield, Matlock and Mansfield district (Geological Map Sheet 112)

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1 Introduction

1.1 PURPOSE OF THE REPORT

This report provides a compilation of hydrogeological information as part of the 1:10 000 scale re-survey of the Chesterfield, Matlock and Mansfield geological sheet (112). The resulting published products will comprise a revised 1:50 000 scale map. A Sheet Explanation including a summary of this report would normally be published as a booklet to accompany the folded 1:50 000 scale map; however, reorganisation of budget allocations within BGS may prevent production of such a booklet.

1.2 BACKGROUND

The district covered by Geological Sheet 112 extends from Chesterfield in the north, to Matlock in the south-west and the towns of Mansfield, Sutton in Ashfield and Kirkby in Ashfield in the south-east. The district is rural in nature, particularly in the western part, which is underlain by the Peak Limestone Group (formerly part of the Carboniferous Limestone) and Millstone Grit strata. There, moorland, hill farms and scattered small settlements predominate with the only large town being the spa town of Matlock. The central section of the district, underlain by the Coal Measures strata, although largely rural with widespread farming, is more densely populated with numerous larger villages, many of which were formerly associated with coal mining. Much of the eastern section of the district is underlain by Permian carbonates of the Zechstein Group, the northern section of which is largely rural with numerous farms and small colliery towns. In the south the larger towns of Mansfield, Sutton in Ashfield and Kirkby in Ashfield provide a more urban aspect. The extreme south-western corner of the district, underlain by Triassic sandstones, are rural being widely farmed or wooded.

Topography in the district is very varied, with the higher ground being located in the west, where moorland developed on Millstone Grit rises to a maximum elevation of about 367 m aOD at Beeley Moor [SK 3009 6816]. Much of this western area is drained to the south by the River Derwent. Ground elevations generally decline to the east. The north-central section of the district is drained to the north by the River Rother and its tributaries the River Hipper, Calow Brook, the River Doe Lea, with the south-central section draining to the south via the River Amber and its tributaries the Alfreton, Normanton and Westwood brooks. The river Amber a tributary of the River Derwent, the confluence being to the south of the district. A major surface water divide is located to the east, running sinuously in a generally southerly direction. It passes to the east of Bolsover before bending westward around the headwaters of the River Meden near Tibshelf and then south-eastwards to the west of Sutton in Ashfield. Farther to the south-west this watershed can be traced to the south-east of Alfreton. To the east, drainage is predominantly eastward via the Rivers Poulter and Meden, which flow in steep sided valleys cut into the Permian limestones, and the River Maun. The extreme south-western edge of the district is drained by the headwaters of the river Erewash that flows to the west before turning to the south (Figure 1).

In general, annual average rainfall declines from southwest to northeast. Rainfall attains a maximum in excess of 1000 mm/a (millimetres per year) over the high ground of the Peak District in the south-west, with the higher areas of the moors to the north of Matlock averaging between 900 and 1000 mm/a. The minima of less than 700 mm/a is recorded to the north-east of Bolsover and Shirebrook (1961-2000 long-term average) (Figure 1).

The district lies within the MORECS 40 X 40 km squares 107 and 116 for which average annual potential and actual evapotranspiration values (1971 to 2000) are available (Meteorological Office 1977, Thompson et al. 1981). Much of the north of the area is covered by square 107, with the area to the south of northing ^{3}600 lying within square 116. The average annual potential and actual evapotranspiration values were about 570 and 518 mm respectively for square 107 and 592 and about 516 mm for square 116, with soil moisture deficits typically at their maximum during May-August and minimum during December-February. In consequence, average effective rainfall (the amount available for runoff and recharge to the subsurface) is likely to be in excess of 500 mm/a over much of the Peak District and higher parts of the moorlands to the north of Matlock, but may be as little as 125 mm/a in the north-eastern corner of the district.

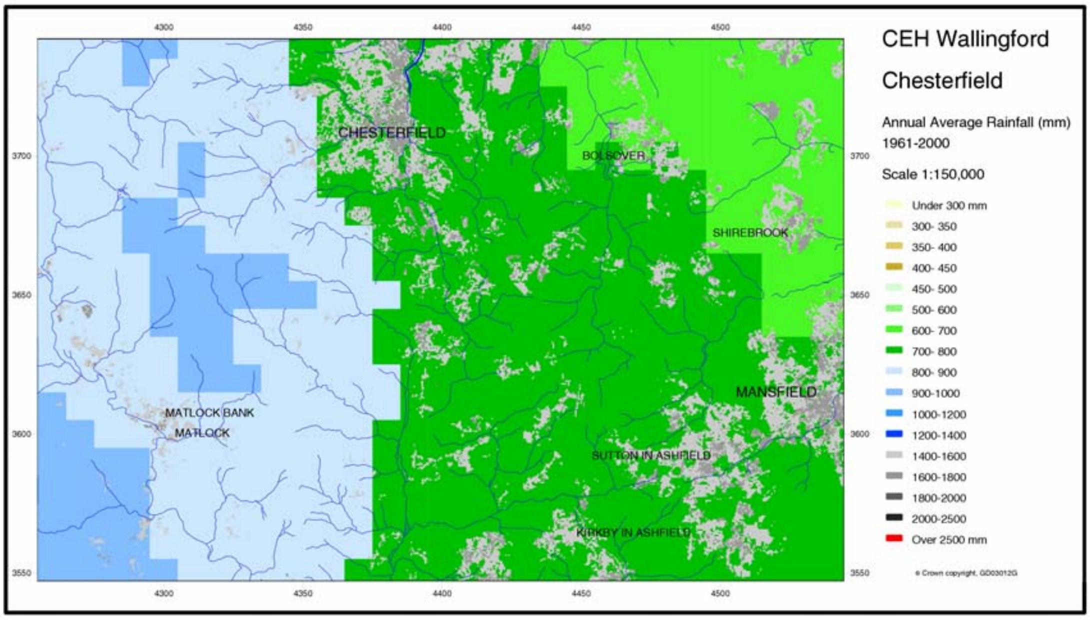


Figure 1. Drainage and mean annual precipitation 1961-2000 for the Chesterfield, Matlock and Mansfield district (provided by CEH Wallingford).

2 Hydrogeology

2.1 GENERAL

A simplified geological map (from BGS 1:625 000 edition, 1979) for the Chesterfield, Matlock and Mansfield district is provided in Figure 2 and stratigraphy listed in Table 1.

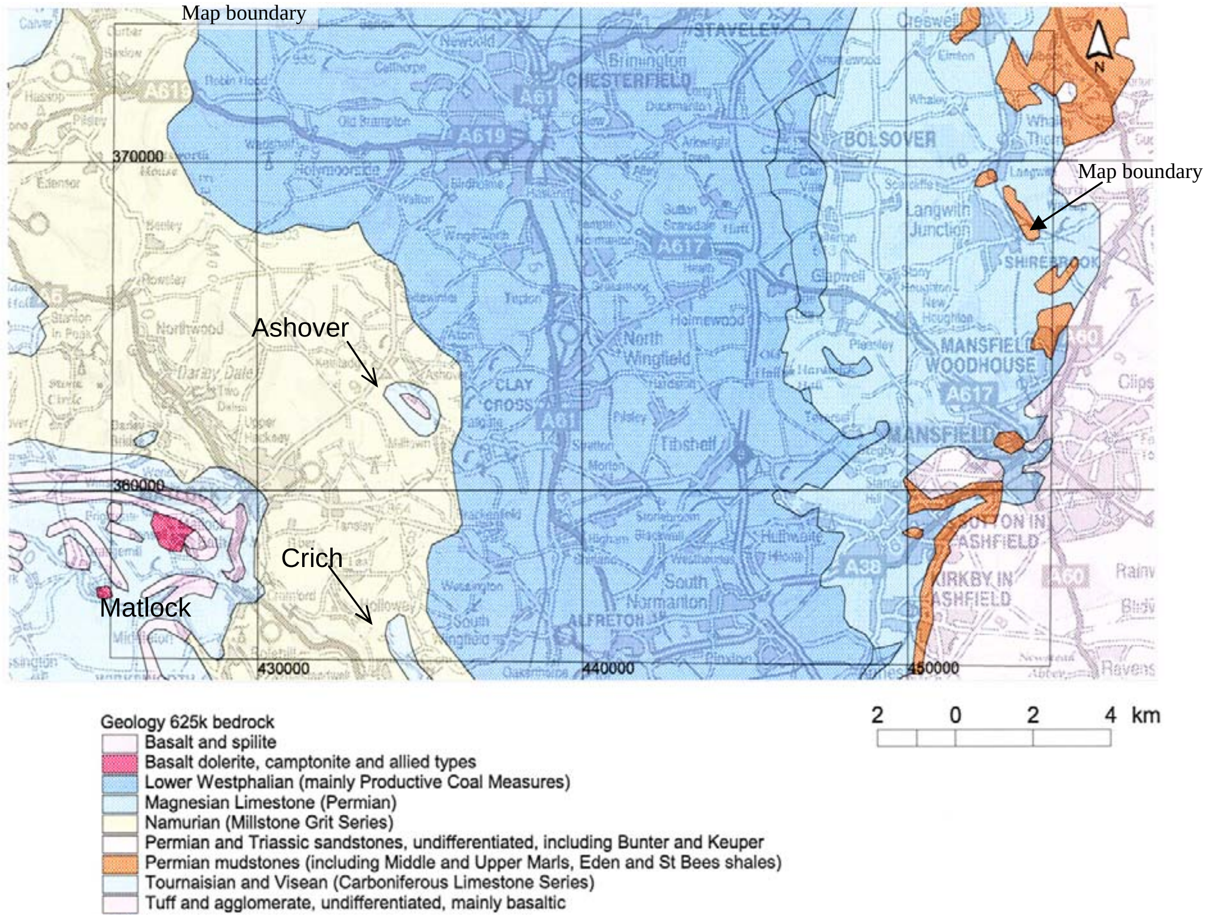


Figure 2. Simplified geological map of Chesterfield, Matlock and Mansfield district

(extract from 3rd Ed. Solid 1:625 000 scale Geological Map of the United Kingdom [south] 1979)

Table 1. Simplified stratigraphy of the Chesterfield, Matlock and Mansfield district.
(compiled from Smith et al 1967 with updates by R D Lake, and from Allen et al (1997); Jones et al (2000). NB: the names of some units may change following final publication of the map (Sheet 112)

Group	Formation	Former Name	Lithology	Thickness (m)	Hydrogeological Charectoristics
	Hill peat; alluvium; river terrace deposits; solifluction and glaciofluvial deposits, till.(Holocene & Pleistocene age)		Peat, clay, silt, sand, gravel	largely absent; up to c. 5 m;	Highly variable
Permo-Trias					
Sherwood Sandstone	Nottingham Castle Sandstone	Bunter Pebble Beds	sandstone with pebbles	up to 30 m	Major aquifer
	Lenton Sandstone	Lower Mottled Sandstone	fine-grained sandstone	up to 30 m	
Zechstein	Edlington	Middle Permian Marl	mudstone and siltstone	0 to 36.5 m (Note 1)	Aquiclude
	Cadeby	Lower Magnesian Limestone	dolomitic limestone	9 to 45 m (Note 2)	Major aquifer
		Lower Permian Marl	mudstone with carbonate beds	17 to 33 m (Note 3)	Aquitard
Carboniferous					
Pennine Coal Measures	Pennine Middle Coal Measures	Middle Coal Measures	cyclic packages of mudstone, siltstone, sandstone, seatearth and coals.	c.533 m	Multi-layered; sandstones minor aquifers.
	Pennine Lower Coal Measures	Lower Coal Measures		c.550 m	Multi-layered; sandstones minor aquifers.
Millstone Grit		Millstone Grit	Mudstones with thick, massive to cross-bedded sandstones and grits.	c. 1075 m	Mudstones: aquicludes Sandstones & grits : minor aquifers
Peak Limestone		Carboniferous Limestone	Massive limestones, bedded limestones with mudstone and basic volcanic rocks	>250 m	Limestones: major aquifers mudstones: aquicludes

Note 1: Edlington Formation – attains a maximum thickness of 36.6 m near the north east corner of the area but thins southward and although absent in the vicinity of Mansfield Woodhouse, is up to 12 m thick to the south of Mansfield.

Note 2: Cadeby Formation - attains a maximum thickness of about 46 m in the north, thinning fairly regularly southward to between 6 and 12 m in the south.

Note 3: 'Lower Permian Marl' – generally 24 to 27 m thick, with thinnest known section of 17.2 m at Sutton Colliery and thickest (33.6m) at Cross Hills borehole; up to 36.6 m may be present in Langwith Colliery shaft and Top Farm borehole

2.2 PEAK LIMESTONE GROUP (DINANTIAN)

2.2.1 Geology

The main limestone outcrop is located in the south-western corner of the district, with smaller outcrops located on the southern border to the north of Crich and in the core of an anticlinal structure around Ashover.

The Peak Limestone Group (formerly ‘Carboniferous Limestone’ in the Peak District) consists predominantly of commonly thin bedded, cherty limestones with reef knolls in the uppermost part of the sequence but more massive, cherty and often porcellaneous limestone below the uppermost 60 m. The limestones in the district are capped by up to 15 m of mudstones. The limestones are interbedded with considerable thicknesses of basic volcanic strata, particularly in the Matlock area where two discrete basalt lava horizons, the upper being up to 37 m thick and the lower ranging up to 45 m (exceptionally up to 115 m). In the Ashover area, brecciated lavas (often referred to locally as ‘toadstone’), tuffs and basalt lavas predominate, the greatest thickness of limestone (up to 55 m thick) occurring in the upper part of the sequence.

Large parts of the limestones have been intensively dolomitised, the contact between limestone and dolomite commonly being sharp, cutting across bedding at many locations. Silicification of the limestones is also widespread. Much of the Peak Limestone has also been subject to intense mineralisation, giving rise to the presence of ore bodies and mineral veins, such as fluorspar, calcite, barites, galena and sphalerite of economic importance. Mining for lead, zinc and silver goes back to the Roman period but reached a peak in the eighteenth century. The mining of these metals has occurred in each of three outcrop areas in the district (Matlock, Ashover and Crich) (Figure 2), as has the extraction of fluorspar.

2.2.2 Hydrogeology

The matrix of the Peak Limestone Group has very low values of porosity and permeability and, in consequence, groundwater is stored within and flows through a secondary network of solution-enlarged fractures (commonly termed conduits). These conduits often form complex branching systems ranging in scale from microfractures to extensive cave systems. The Peak Limestone Group is commonly considered to exhibit ‘karstic’ hydrogeological behaviour. The term ‘karst’ is not precisely defined but is associated with terrain that has distinctive landforms and hydrology by virtue of a combination of high rock solubility and well-developed secondary (fracture) porosity. Typical karst features are sinking streams, caves, enclosed depressions, fluted rock outcrops and springs (sometimes with large flows), together with a general absence of surface water features. Dry valleys are present over most of the limestone outcrop in the district and karst features are widespread. Natural groundwater drainage has been substantially affected as a result of mining activities. Large quantities of ore and gangue have been removed along veins, which commonly follow the principal vertical fractures and bedding planes. Such workings may provide additional ‘conduits’ through which groundwater can infiltrate and flow through the rock mass.

In addition tunnels (locally termed ‘soughs’) were constructed during the course of mining to drain water from the lowest level in the mine to a suitable point at the surface in a neighboring valley, in particular the River Derwent in the Chesterfield district. As the mines were deepened fresh soughs were constructed, resulting in a complex system of tunnels. Sough discharges can be substantial, with three soughs in the area of interest (Meerbrook Sough, Yatestoop Sough and Hillcarr Sough) having discharges in excess of 40 000 m^3/d (Edmunds, 1971). Meerbrook Sough has reached a maximum recorded discharge of around 85 000 m^3/d (cubic metres per day), draining water from the Peak Limestone and the Millstone Grit (Stephens, 1929). These are the largest discharge points for groundwater from the Peak Limestone aquifer. By comparison, the largest recorded discharge from a spring within the district (Fountain Bath, Matlock [SK294 584]) does not exceed 1040 m^3/d (Edmunds 1971). Details for each of the soughs located within the district, including discharge rates recorded at the time these sources were sampled for chemical analysis in the late 1960's, and analyses are provided in Table 2. Former mining activities, in particular the drainage of mineral workings by the construction of soughs has had a major impact on water table levels within the Peak Limestone aquifer, in places giving a water level many tens of metres lower than that before mining commenced.

Table 2. Soughs in the Matlock area of the Chesterfield district (after Edmunds, 1971)

Sough Name	**Grid Reference**	**Geology penetrated**	**Discharge (m^3/d)**
Meerbrook	SK 327 552	Peak Limestone & Millstone Grit	68,260
Hillcarr	SK 259 637	Peak Limestone & Millstone Grit	21,600
Ridgeway	SK 332 549	Peak Limestone & Millstone Grit	345
Cromford	SK 296 569	Peak Limestone	2,070
Yatestoop	SK 264 626	Peak Limestone & Millstone Grit	No record
Snitterton	SK 282 608	Peak Limestone	345
Oxenclose	SK 289 606	Peak Limestone	24,500

In addition, the upper section of the limestones in the Ashover area is drained by the Cockwell (or Gregory) Sough and Hogsland Sough, whilst workings at near Crich are drained by the Fritchley and Ridgeway Levels (Smith et al., 1967).

Edmunds (1971) provided tentative water table contours for the limestone region, using water level data from boreholes, mineshafts, caves and soughs and data from a number of earlier publications. He concluded that, in general, a water table could be identified (although this was very variable locally) and that this indicated the development of branched fracture systems. Groundwater levels were of the order of 180 m aOD in the centre of the limestone outcrop to the south west of Matlock, declining to below 120 m aOD towards the northern, eastern and southern edges of the outcrop. The magnitude of seasonal water level fluctuations have been only infrequently recorded but fluctuations of up to 27 m have been observed in boreholes located near Tideswell to the west of the area of interest (Rafferty et al. 1953).

Thermal springs issuing from the Peak Limestone occur at a number of locations in the Peak District. Their occurrence and groundwater chemistry were described in detail by Edmunds (1971) and their genesis by Brassington (2007). Within the Chesterfield district, thermal springs occur in the vicinity of Matlock, where temperatures of up to 19.8^{o}C have been recorded (Edmunds, 1971). Details regarding the main Matlock thermal springs have been provided by Stephens (1929). The origin and chemistry of the thermal groundwater is discussed in more detail below.

2.2.3 Aquifer Properties

The Peak Limestone in Derbyshire is classified by the Environment Agency as a major aquifer. The limestone rock matrix has a very low porosity and permeability and, in consequence, does not contribute significantly to the water-bearing properties of the aquifer. Laboratory measurements of porosity, contained within the BGS Aquifer Properties Database, are only available for samples obtained from four outcrop locations and three boreholes across the Pennines as a whole. None are available from the Chesterfield, Matlock and Mansfield district. Average porosity for the outcrop samples was 1.3% and for borehole samples 1%. No permeability measurements are available.

Groundwater storage and flow occurs within fractures and joints that are present within the rock mass, particularly those that have been enlarged as a result of karstification. The natural aquifer properties of the area (i.e. those unaffected by mining) are, therefore, dominated by solution enlarged fractures, as is often the case elsewhere in the Peak Limestone. Five main factors have influenced the development of underground drainage, namely removal of impermeable cover, structure, lateral discontinuities, vertical discontinuities, and lithology. Initially the impermeable cover overlying the Peak Limestone was removed by erosion, triggering the episodic development of conduits that has continued since the early Pleistocene (Ford et al 1983) or possibly the Pliocene (Walsh et al., 1972). Bedding planes form the main routes for lateral flow in the aquifer, with flow below the water table generally occurring along bedding plane strike, particularly in areas of shallow dip. The vertical movement of groundwater occurs via joints, faults and mineral veins and more rarely provide conduits for horizontal flows if they form a low angle with the hydraulic gradient (Gunn, 1992). Although the above factors determine the position of the conduits within the aquifer, their size and form is more a function of limestone lithology. Gunn suggested (on the basis of an unpublished study) that the greatest degree of cavern enlargement takes place in massive, generally fine-grained limestones, particularly where pseudobrecciated horizons are present, as these strata may be more readily dissolved than the surrounding homogeneous limestone. The weathering of pyrite in lavas may also produce an acidic aggressive solution, which can enhance conduit development.

A detailed assessment of the flow hydrograph for the Meerbrook Sough was carried out to determine the large-scale hydraulic behavior of the artificially drained aquifer (Shepley, 2007). Available hydrogeological and hydrological data was utilized to construct a conceptual model that was in turn used to carry out numerical modelling. Analysis indicated that the limestone aquifer at a large scale can behave as a dominantly diffuse flow system, in which storage processes are important. Bulk estimates obtained from numerical modelling suggested an equivalent saturated specific yield of the order of 5%, some of which was attributed to the mine workings with limestones affected by dolomitisation being suggested as a potential secondary source. It was concluded that the dominant diffuse flow response could be attributed to disconnection of a significant proportion of the natural conduit flow system due to large scale dewatering of the aquifer below the base level of drainage.

Yields obtainable from the Peak Limestone are highly variable and unpredictable; they are dependant on the penetration of enlarged interconnected fractures, joints and bedding planes. The very highest yields may be obtained from boreholes that penetrate enlarged discontinuities (such as caves or passageways) or mine workings, but the aquifer may be low yielding or effectively dry if no enlarged discontinuities are encountered. Yield records are available for only four boreholes penetrating the Peak Limestone in the area, three of which are located in close proximity, at Ball Eye Quarries [SK 428 357]. Yields range widely, ranging from a minimum of 21.6 m^3/d, with the three boreholes at Ball Eye Quarries ranging from 132 and 864 m^3/h. Specific capacity values are only available for the three boreholes at Ball Eye Quarries and range from 0.35 to 4 m^3/h/m, again illustrating the highly variable nature of the Peak Limestone aquifer.

Very few pumping test results are available from the Peak Limestone in the Peak District, and the BGS Aquifer Properties Database has details of only six tests (at six sites) over the whole outcrop area. Test transmissivities for the whole area vary from 0.1 to 770 m^2/d; however, all but one are less than 60 m^2/d and the geometric mean is 10 m^2/d. No values of storage coefficient are available. As with the other areas of Peak Limestone examined, transmissivity values are likely to be dominated by the unpredictable presence or absence of local fractures. Transmissivity values are available for only two boreholes located within the section of the Peak Limestone in the Chesterfield district. These values were 18 and 0.1 m^2/d. Collectively, the wide range of values for the Peak District as a whole, including the parts that fall within the Chesterfield district, is indicative of the highly variable nature of the aquifer.

The only available groundwater hydrograph for the district (Rider Point observation borehole [SK 2615 5641]) is shown in Figure 3. Large annual seasonal water level fluctuations are a dominant feature of the hydrograph, the largest being a 37 m variation between September 1976 and February 1977.

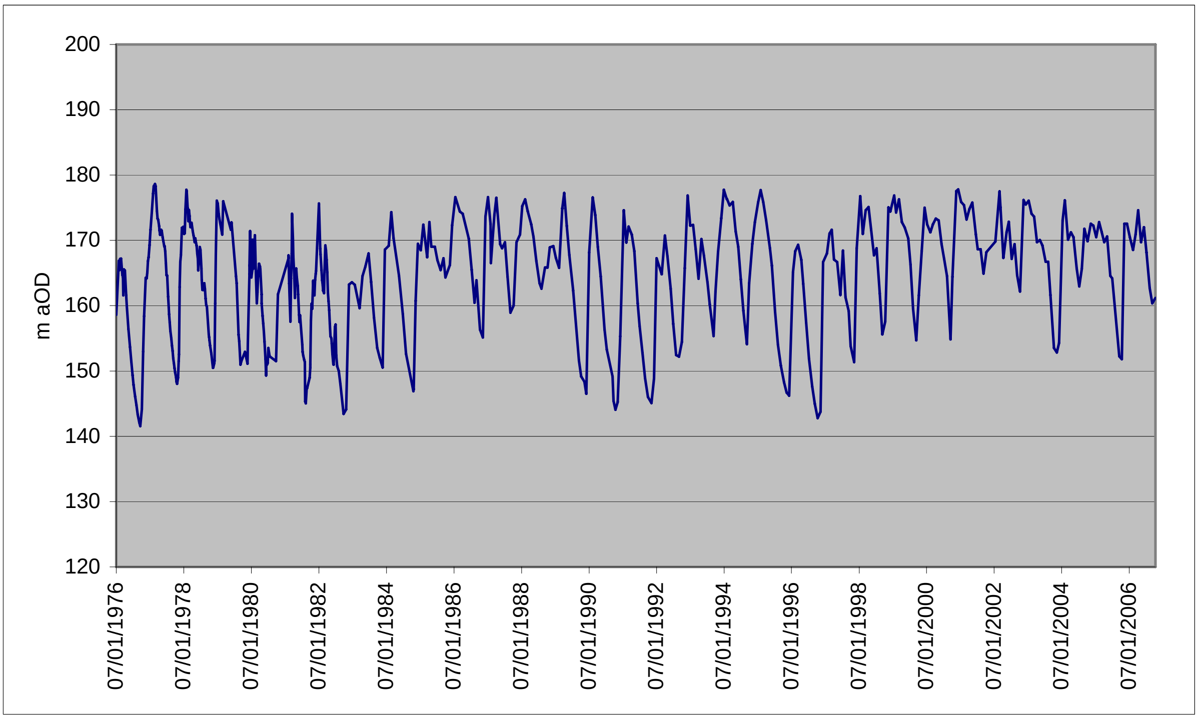


Figure 3. Peak Limestone groundwater hydrograph: Rider Point observation borehole [SK 2615 5641].(Data provided by the Environment Agency, Midlands Region).

2.2.4 Groundwater Chemistry

Peak Limestone groundwaters are almost invariably of a calcium/magnesium bicarbonate type (Edmunds, 1971). The thermal waters at Matlock, although more mineralised than 'normal' Peak Limestone groundwater, are of the same type. Examples of the groundwater chemistry for a non-thermal water (Cromford Sough) and a thermal water (Fountain Bath, Matlock) are provided in Table 3. Edmunds (1971) provided a detailed discussion of the major and trace element hydrogeochemistry of the Peak Limestone groundwaters.

As part of Edmunds' overall study into the hydrogeochemical characteristics of the Peak Limestone in the Derbyshire Dome, six samples of thermal waters were submitted for the determination for thermo-nuclear tritium in order to assess if there was a contribution from recent water. Two of these samples were obtained from sources within the Chesterfield district; namely from New Bath Hotel, Matlock [SK 299 579] and Ball Eye Quarry borehole [SK 289 573]. Edmunds (1971) reported that the Matlock sample contained 4.4 tritium units (TU) indicating that either the groundwater contained small amounts of tritium from the time of infiltration and was therefore around 15 to 20 years old (ie dating from the late 1950s), or that they were ‘waters of that age or older admixed with a few percent of recent water’. The Ball Eye Quarry borehole groundwater contained a value of 103.4 TU, considered by Edmunds to strongly imply that this thermal water had been considerably diluted with recent water, possibly drawn in via shallow fractures from an adjacent stream whilst pumping.

Brassington (2007) utilised available hydrogeochemical and hydrogeological information to develop a conceptual model for the genesis of the Derbyshire thermal springs and concluded that the water could be up to 5000 years old, being heated by deep circulation ranging up to 1 km below surface.

Table 3. Groundwater analyses

BH No.	SK25/21	SK25/17c	SK35/59	SK36/25A	SK46/85	SK47/56	SK56/17	SK55/71
Location	Cromford Sough*	Fountain Bath, Matlock*	Meerbrook Sough*	Hunger Hill	Ashton Corrugated	Markham Colliery	Gildwell P.S.#	New Dairy, Berry Hill
Grid Ref.	SK 296 569	SK 294 584	SK 327 552	SK 330 679	SK 404 630	SK 449 719	SK 541 369	SK 5647 5953
Aquifer	Peak Limestone	Peak Limestone. (thermal)	Peak. Lstn. & Millstone Grit	Millstone Grit	Coal Measures	Coal Measures (mine drainage)	Permian Cadeby Formation	Sherwood Sandstone Group
pH	8.25	7.77	7.32	7.3	7.2	7.2	na	na
Calcium (mg/l^{-1})	99	103	75	36	192	5280	102	23.4
Magnesium (mg/l^{-1})	9	38	29	22	16	1091	51	10.7
Sodium (mg/l^{-1})	14	29	10	31	na	24	12	6.8
Potassium (mg/l^{-1})	2	0.8	0.9	na	na	na	na	na
Chloride (mg/l^{-1})	29	52	22	13	204	49,560	33	19.0
Sulphate (mg/l^{-1})	56	192	54	45	24	202	150	40.1
Iron (mg/l^{-1})	na	17	27	1	2	0.3	0.1	trace
Temp. Hardness (mg/l^{-1})(as $CaCO^3$)	na	na	na	171	40	13,200	262	12
Perm. Hardness (mg/l^{-1})(as $CaCO^3$)	na	na	na	10	505	4,500	202	68
Total Hardness (mg/l^{-1})(as $CaCO^3$)	286	511	307	181	545	17,700	464	80
TDS (mg/l^{-1})	454	700	500	259	na	81,000	590	150

* Anaylses from Edmunds 1971. # Analysis from Smith et al. 1967

2.3 MILSTONE GRIT GROUP (NAMURIAN)

2.3.1 Geology

The Millstone Grit Group forms a broad outcrop extending from the southern central border to the north-eastern corner of the district. It typically consists of coarsening-upward cycles of dark grey carbonaceous mudstones, grey silty mudstones and siltstones, and fine- to very coarse-grained feldspathic sandstones (formerly referred to as ‘grits’). Subordinate coals and residual soil horizons typically cap the cycles in the upper part of the group (Jones et al., 2000). The sandstones can range from coarse-grained and cross-bedded or massive, to fine-grained, micaceous and thinly laminated types.

The sandstone beds constitute the principal water-bearing strata. The group has been formally subdivided into formations, but individual sandstones are typically given individual local names that may vary from area to area. In the Chesterfield district, four major named sandstone successions are present; the Rough Rock and Redmires Flags near the top of the sequence, underlain by the Chatsworth Grits and, in turn, the Ashover Grit. The Kinderscout Grit, commonly positioned towards the base of the sequence in areas farther north, is not present at outcrop in the district, the lower section of the Millstone Grit below the Ashover Grit consisting predominantly of mudstones between 60 and 90 m thick.

The Rough Rock has a composition that varies from siltstone with sandstone bands to a hard flaggy sandstone. It is laterally impersistent within the district and does not attain a thickness greater than about 12 m. The Rough Rock is separated from the underlying Redmires Flags by strata that predominantly consist of mudstones and are between 25 and 40 thick.

The Redmires Flags are thickest in the north, where they are about 14 m thick but are not laterally continuous across the district, thinning and occurring only locally to the south of Ashover where their maximum thickness is only about 3.7 m. They consist predominantly of medium- to fine-grained sandstones, although some grits are present in the north. The Redmires Flags and the Chatsworth Grit are separated by up to 26 m of predominantly mudstone strata.

In the north west, in the type area around Chatsworth House, the Chatsworth Grit sequence thickness totals about 150m, consisting of two main sandstones separated by up to 60m of mudstone with additional local sandstone beds. The lower main sandstone horizon dies out to the south of Chatsworth House although thin sandstones may constitute its equivalent further to the south. The upper sandstone persists southward, varying in thickness from 20 to 38 m (Smith et al. 1967).

The beds between the Ashover and Chatsworth Grits consist of between 15 and 60 m (average about 40 m) of grey to dark grey mudstones and siltstones, with sporadic ironstone bands and two coal horizons.

The Ashover Grit is the equivalent to the Roaches Grit to the west of the Pennines. In the south of the district, it consists of up to 60 m of massive medium- to coarse-grained sandstone with bands of pebbles but thins to the north, passing into finer-grained sandstone with interbedded siltstone and mudstone. In the Chesterfield district the Ashover Grit may consist of up to four laterally discontinuous sandstone ‘leaves’ separated by argillaceous horizons.

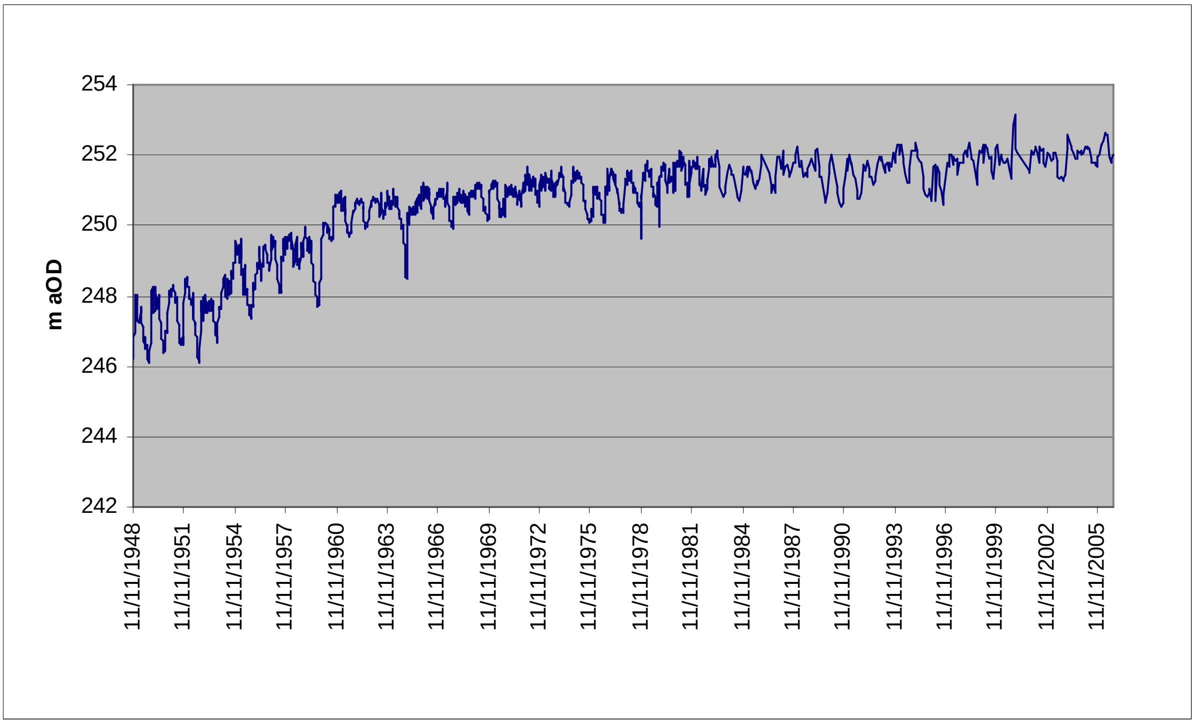
Millstone Grit Group sandstones are typically cemented by quartz overgrowths. The resultant sandstone fabrics are closely packed and the combined effect of quartz overgrowths and pressure welding results in low intergranular porosity. The finer grained sandstones generally display more authigenic quartz. Intergranular authigenic clays are variably developed with kaolinite and illite or sericite being the common components. These clays typically result from the alteration of feldspar grains, which may produce a grain dissolution porosity. The development of secondary porosity can occur where the sandstones are coarse-grained and arkosic, especially near surface in the zone of weathering.

2.3.2 Hydrogeology

The Millstone Grit Group constitutes a multilayered aquifer in which the thick, massive grit and sandstone horizons effectively act as separate aquifers with the intervening mudstones and mudstones acting as aquicludes or aquitards, although faulting may locally juxtapose them into hydraulic connection. Groundwater storage and movement in the well-cemented grits and sandstones is predominantly through fractures and joints with only minor contributions from the rock matrix. Little or no water is normally obtainable from mudstone horizons although small quantities may be present in thin interbedded sandstones. The groundwater potential of the main water-bearing horizons is very variable and some horizons may only be of local importance. Yields are in consequence highly variable even over short distances. Initial yields are not however always sustainable, sometimes declining with time as storage is depleted by pumping. Abundant springs are frequently located at junctions between sandstone and mudstone horizons

The more important aquifer horizons in the Chesterfield, Matlock and Mansfield district include the Chatsworth Grit and Ashover Grit, and, to a lesser extent, the Redmires Flags and Rough Rock. Springs issue from these at points along the base of the outcrop. The Kinderscout Grit, which is productive elsewhere, is not present at outcrop in the district, being represented by almost entirely argillaceous rocks. The Kinderscout Grit has only been proven to occur in the northern sections of the district at considerable depth beneath Coal Measures strata (Smith et al., 1967) but no significant thickness of sandstone or grit appears to be present beneath Coal Measures further to the south.

Seasonal water level changes are quite site-specific and only one long-term hydrograph is available; a 44-year water level record from the borehole at Big Moor Longshaw (Fig 4), located just outside the northern edge of the Chesterfield district [SK 2808 7460]. This 99.1 m deep borehole penetrates the uppermost sandstone members of the Millstone Grit Group (Rough Rock, Redmires Flags and Chatsworth Grit) and shows typical annual fluctuations of about 1.3 m. The hydrograph also shows a gradual water level recovery from about 247 m aOD in 1948 to about 252 m aOD by 1998, after which the water level (apart from seasonal variations) appears to have stabilised. The cause of this recovery or rather the drawdown prior to the period of recovery is not known.



(from data provided by the Environment Agency)

Figure 4. Millstone Grit Group groundwater hydrograph: Big Moor observation well [SK 2808 7460].

2.3.3 Aquifer properties

There are only limited aquifer properties data for Millstone Grit Group strata within the Chesterfield, Matlock and Mansfield district. The BGS Aquifer Properties Database contains porosity and intergranular permeability measurements from 16 outcrop localities in the Pennines area as a whole. Porosity values range from 6 to 23%, with arithmetic mean and median values of about 14%. Permeability values range from 3 x 10^{-4} to 0.7m/d (0.7 to 1061mD), with arithmetic mean and median values of 5 x 10^{-3} to 4 x 10^{-2} m/d (10 and 66mD). These values, obtained from samples of weathered outcrops, are likely to be higher than those applicable to unweathered strata at depth (Jones et al., 2000). Flow in the Millstone Grit aquifers tends to decrease rapidly with depth and sandstones, which are soft and decalcified at outcrop, are commonly well cemented, hard and compact down-dip. Although interconnected porosity can exceed 10% of the rock volume, the cementation of grains reduces pore-neck diameters. The resultant adverse effect both on intergranular permeability and on the ability of the rock mass to drain (reducing available storage or specific yield) means that permeability of, and storage in, the fracture systems control water flow in this aquifer.

The National Aquifer Properties database contains aquifer test data for only two sites in the Chesterfield, Matlock and Mansfield district. One borehole at Spitewinter Camp [SK 3425 6646] is thought to have penetrated the Chatsworth Grit whilst that at Two Dales [SK 3050 6520] penetrated the Ashworth Grit. Transmissivity values of 40 and 8.5 m^2/d respectively were obtained from analyses of the test data. Namurian Millstone Grit Group strata extend from the south of the Peak District to Barnard Castle in Co. Durham and physical properties data from the whole of this area were assessed for inclusion in the Minor Aquifers Physical Properties manual (Jones at al., 2000). As the availability of local field data is limited, Table 4, based on the Millstone Grit Group outcrop as a whole, provides indicative information on transmissivity, storage coefficient and specific capacity likely to occur in the district.

Table 4. Aquifer properties data for Millstone Grit Group of the Pennines (from Jones et al., 2000)

	Transmissivity (m^2/d)	**Storage coefficient**	**Specific capacity (m^3/d/m)**
No. of records	81	3	123
Maximum	1059	0.013	9092
Minimum	0.6	0.0001	0.54
Arithmetic Mean	93	-	140
Geometric mean	25	-	23
Median	26	-	21
25/75 percentile range	7 to 80	-	8 to 76

Borehole yields ranging from 33 to 9536 m^3/d are available from the records for twenty nine sites held in the NWRA[1] . In addition, an exceptional yield of 22 257 m^3/d was recorded from Mill Close Mine, South Darley [SK 2600 6250] but as this source is almost certainly a large diameter shaft and not representative of yields obtainable from boreholes, this data has been excluded from the statistical analysis. A total of thirteen of the borehole records also contain rest and pumping water level information that allow specific capacities to be calculated. These values range from 3 to 136 m^3/d/m. Statistical values for both yield and specific capacity for boreholes penetrating the Millstone Grit Group in the district are contained in Table 5.

Available yield data suggests that the Rough Rock and Chatsworth Grit are particularly productive horizons compared to the Ashover Grit. The maximum and minimum yields for the Rough Rock in the district are 9536 and 23 m^3/d and for the Chatsworth Grit, 9600 and 44 m^3/d. In contrast the Ashover Grit maximum and minimum yields are 139 and 33 m^3/d.

The majority of boreholes penetrating the Millstone Grit in the district have been completed at a diameter of 152 mm, with a few being completed at diameters up to 305 mm, for example the former public supply borehole at Hunger Hill, Walton [SK 3296 6790]. In general, the higher yields have been obtained from boreholes that have been completed at larger diameters. It is also probable that many of the lower recorded yields are a reflection of the pump capacity and/or the small quantities abstracted from these sources to meet limited demand, rather than the maximum yield that could have been obtained.

Table 5. Yield and specific capacity data for the Millstone Grit Group.

	Yield (m^3/d)	**Specific capacity (m^3/d/m)**
No. of records in category	30	13
Maximum value	9536	136
Minimum value	33	3
Geometric mean value	129	15
Median value	79	12
25%ile	45.8	6.7
75%ile	139.2	26.8

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[1] NWRA: National Well Record Archive, maintained by the BGS.

A number of boreholes in the district penetrate the basal section of the Pennine Coal Measures and upper section of the Millstone Grit Group, abstracting groundwater from sandstones and grit horizons in both aquifers. Whispering Well at Holymoorside [SK 3322 6946], completed at a depth of 261 m, penetrated the Crawshaw Sandstone at the base of the Pennine Coal Measures Group and the underlying Chatsworth and Ashover Grits, to produce a yield of over 2100 m^3/d. In comparison, a nearby borehole located at Hunger Hill [SK 3296 6790], penetrated the base of the Chatsworth and Ashover Grits to a total depth of 141 m, producing a yield of 1140 m^3/d; somewhat over half that obtained from Whispering Well (Smith et al 1967).

2.3.4 Groundwater quality

The Millstone Grit Group groundwater quality is generally acceptable, with a hardness of about 150 to 250 mg/l (as $CaCO3$) and a chloride ion concentration generally less than 50 mg/l. An analysis for a groundwater sample obtained from the former public supply borehole at Hunger Moor is provided in Table 3. Occasionally iron concentrations can locally exceed 0.5 mg/l, which may impart a taste and cause staining of laundry and bathroom fittings. At Long Lane Farm, Alton [SK3537 6469] a 37 m deep borehole that penetrated the Rough Rock was reported to have produced ochreous water but this would appear to have been a rare occurrence.

2.4 PENNINE COAL MEASURES GROUP (WESTPHALIAN)

2.4.1 Geology

The Pennine Coal Measures Group comprises grey mudstones and siltstones, with alternations of pale grey sandstone, the latter typically well cemented, fine-grained and often ochreous when weathered, together with frequent coal seams, palaeosol horizons and ironstones (Jones et al., 2000). These strata have been deposited in a cyclic manner, which when fully developed comprise a basal dark grey marine mudstone passing up to grey mudstone that becomes increasingly silty, succeeded by siltstone or sandstone, seatearth and coal. One or more phases may be absent but seatearth and grey mudstone are usually present (Smith et al., 1967). Sandstones are rarely present in many cycles but occasionally are more persistent. The development of sandstone horizons are very variable, most consisting of a flattened lensoid shape, commonly passing laterally as well as vertically into siltstones and mudstones, or wedging out. There are, however, some individual sandstone beds that are laterally extensive (>100 km^2) and can exceed 20m in thickness, such as the Wingfield Flags and Crawshaw Sandstone in the Chesterfield district.

In contrast to the numerous named coal seams, only those sandstones that are particularly thick and/or laterally persistent tend to be individually named. Several significant sandstone horizons occur in the lower section of the Pennine Lower Coal Measures in the Chesterfield District, namely the Crawshaw Sandstone (up to 55 m thick) close to the base; a sandstone immediately below the Forty-Yards Coal (the local equivalent to the Loxley Edge Rock of the Sheffield district); and the Wingfield Flags (up to 75 m thick). Sandstones are relatively common throughout the Pennine Lower Coal Measures above the Wingfield Flags but are normally thin and of only local development; thicker sandstones of wider lateral extent are found above the Tupton and Deep Hard Coals (Smith et al., 1967).

In common with the underlying Millstone Grit Group rocks, the Pennine Coal Measures strata are strongly dislocated by faults, which dominantly trend to the north-northwest with a subsidiary north-easterly trending system. The strata have also been gently folded about NW-SE trending axes (Smith et al., 1967).

2.4.2 Hydrogeology

In the Pennine Coal Measures Group, argillaceous strata predominate, acting as aquitards or aquicludes, and isolating the thicker sandstone horizons that effectively act as separate aquifers. Coal Measures sandstones are generally fine-grained, very well cemented, extremely hard and dense and in consequence possess very little primary porosity or intergranular permeability. Groundwater storage and movement occurs predominantly within and through fractures in the sandstones. Under natural conditions the sandstones act as individual aquifers separated by the intervening impermeable argillaceous horizons, and thus constitute a complex multi-layered aquifer. Confined conditions are, therefore, common and groundwater often rises above the level at which it is struck.

Sandstone outcrop areas are generally small, limiting the amount of recharge that can infiltrate to individual sandstone beds. Extensive faulting has frequently split previously continuous sandstone beds into disconnected, isolated fault-bounded blocks, to which no direct recharge can occur. Initial high yields frequently decline due to the depletion of aquifer storage caused by abstraction. Sandstone beds are frequently jointed but interconnection of the joints is often poor and sandstones at depth can be effectively dry despite the presence of joints (Holliday, 1986). Potentially, any of the thicker and more widely-found sandstones can be water-bearing; for example, the Crawshaw and Grenoside sandstones, the Penistone Flags, the Silkstone Rock, Greenmoor Rock, the Deep Hard Rock, the Oaks Rock and the Mexborough Rock. However, even the thinner more localized sandstone members, such as the Ravenfield, Wickersley and Ackworth rocks (and other unnamed sandstones), have some potential and borehole yields depend on the number, size and degree of interconnection of fractures encountered in a given productive horizon.

Underground mining has been widespread over virtually the whole of the East Midlands coalfield. Exploitation has concentrated on the extraction of coal, refractory clays and ironstone for about 300 years, initially over the outcrop area of the Coal Measures Group. Improved technology since the mid-19th century allowed collieries to progressively extend to greater depths and penetrate further east into the concealed coalfield below the Permian and Triassic strata. The natural hydrogeological conditions of the Coal Measures Group have, therefore, been disrupted over wide areas, in places to depths in excess of 300 m below surface. This disruption has involved the creation of open shafts, roadways and galleries, as well as collapsed, disused workings, and by the formation of subsidence-induced fractures. These features have created hydraulic continuity between layers which were previously isolated and, in some places, between aquifer horizons and flooded disused workings. Where underground access and ventilation roadways remain open (e.g. if steel supports were left in place or there is a strong sandstone roof) the resultant linked conduit system can provide pathways, potentially up to tens of kilometres in length, for groundwater movement of very high hydraulic conductivity, analogous to mature karst systems in limestone.

The early widespread development of coal mining and attendant mine drainage pumping has made development of groundwater resources in the Coal Measures difficult due to the lowering of water levels, and widespread contamination from the mining process itself and associated industrial activities. In addition large quantities of water were readily available for industrial use from pumped mine drainage. Relatively few water supply boreholes have, therefore, been drilled into the Pennines Coal Measures Group.

The coal mining processes causing dislocation of overlying strata are well described in detail in a review of the effect of colliery closure on groundwater resources by Dumpleton et al. (1995). Over a dozen separate coal seams have been worked in the Derbyshire and Nottinghamshire coalfield, the Top Hard/Barnsley seam being the most important and extensively worked. In many collieries the Top Hard was worked to exhaustion, frequently creating underground connections between adjacent collieries. At many collieries, several seams were worked and in places a given working may have overlapped with deeper and shallower workings in adjacent collieries.

Dumpleton et al. suggest that the net effect of the dislocation of strata could be an enhanced transmissivity throughout the worked sequence (several hundred metres thick) and also in an overlying zone thought to be at least 150 m thick. They postulated a conceptual model similar to that described for the Durham coalfield (Younger and Bradley, 1994) in which groups of collieries (many linked underground during operation) behave as discrete leaky reservoirs (or ‘ponds’), each having its own independent water level, controlled by pumping at working or closed collieries. The individual reservoirs were considered to be separated by barriers or dams consisting of unworked strata, although in many places these may have been weakened by the effects of subsidence. Two such leaky reservoirs were proposed for the Chesterfield, Matlock and Mansfield district.

The northern reservoir was considered to extend south-eastwards from Blacks and Hartington collieries (located just outside the northern boundary of the district), through Oxcroft, Creswell and Langwith towards the collieries of Welbeck, Thoresby, Clipstone and Bilsthorpe. All four of these collieries were active in 1995 but Bilsthorpe closed in 1997 and Clipstone in 2003, whilst the other two were still operational in 2007. A second flow path from Williamthorpe colliery via abandoned colliery workings at Pleasley, Shirebrook and Warsop towards Clipstone was also postulated. In 1991, only small quantities of water were being abstracted at Blacks and Hartington with an average rate of 0.17 Ml/d at Oxcroft, 1.68 Ml/d at Creswell, 0.35 Ml/d at Langwith (winter only). Pumping only occurred at Williamthorpe, on the southern flow path (at an average rate of 6.55 Ml/d in 1994). Pumping at the six pumping stations indicated above was designed to protect the four active collieries located down gradient to the east of the district, in the concealed section of the coalfield. Isolated interconnection was thought to occur between this reservoir and another located to the north in the Sheffield area. Dumpleton and Glover considered it likely that the eventual cessation of pumping could result in uncontrolled minewater discharge into surface watercourses, such as the River Rother, as well as posing a rebound hazard in the concealed coalfield, which is overlain not only by carbonate rocks of the Zechstein Group but also by the important Sherwood Sandstone Permo-Triassic aquifer.

The second, southerly reservoir was considered to extend south eastwards from Morton via ‘A’ Winning and Bentinck/Annesley towards Calverton Colliery (located beyond the eastern margin of the district). A second flow path was postulated as running from Woodside (located outside and to the south of the district) in a north-easterly direction towards the old Bentinck/Annesley workings. In 1994, the average abstraction rate at Morton was 4.25 Ml/d, at ‘A’ Winning 6.09 Ml/d and at Bentinck/Annesley 7.86 Ml/d. At Woodside the average pumping rate was 13.09 Ml/d in 1994. Interconnection was considered to occur between this reservoir and that located to the north via the old colliery workings in the Clay Cross area. Abstraction at the four pumping stations was to protect workings at Calverton Colliery, which was active in 1995 but closed in 1999. No information is available regarding the current status of the four pumping stations in this reservoir. Dumpleton and Glover considered that if pumping were to cease, this reservoir would experience complete water table rebound and minewater would travel northwards into a further reservoir via the disused Clay Cross colliery workings.

Table 6. Yield and specific capacity data for the Pennine Coal Measures Group

	Yield (m^3/d)	**Specific capacity ($m^3/d/m$)**
No. of records in category	26	6
Maximum value	6546	56
Minimum value	0.23	1.5
Geometric mean	132	10
Median value	184	14
25%ile	48	5
75%ile	655	19

Borehole yields ranging from 0.23 to 6546 m^3/d are available from the records (held in the NWRA) for twenty six boreholes that penetrate the Pennines Coal Measures Group in the district. Two yields are available for one of the sites whilst three are available for a second site; only the higher yields have been included when calculating the statistical values. The majority of yields range between about 50 and 650 m^3/d. Only six of the borehole records also contain rest and pumping water level information that allow specific capacities to be calculated. These values range from 1.5 to 56 $m^3/d/m$. Statistical values for both yield and specific capacity for boreholes penetrating the Pennine Coal Measures Group in the district are contained in Table 6..

Yields of those boreholes penetrating the Pennines Coal Measures Group are highly variable, at times even over relatively short distances. This is well illustrated by a group of water supply boreholes drilled at the Chesterfield Tube Co. The initial 254 mm completed diameter borehole [at SK 3831 70250], drilled to a depth of 61.3 m, produced 6546 $m^{3/}d$ (75.8 l/s), the largest yield obtained from the Coal Measures in the district. This borehole was reported to have initially provided an artesian supply in excess of 7300 m^3/d, probably from old workings in the Tupton Coal (Smith et al., 1967). Subsequent boreholes drilled in the mid 1960s [at SK3830 7026 and SK3834 7037], completed at diameters of 254 mm and 305 mm and penetrating to depths of 43.6 and 45.7 m respectively, produced yields of only 655 $m^{3/}d$ (6.2 l/s) and 393 $m^{3/}d$ (4.6 l/s). A final 380 mm diameter borehole drilled in 1976 to a depth of 119.3 m, obtained a yield of 872 m^3/d (10.1 l/s).

Groundwater abstraction for mine drainage massively exceeded abstractions for all other purposes in the 1950s when mining in the district was at a peak. BGS archives contain annual abstraction records for a total of 82 mine shafts penetrating the Coal Measures Group. These abstraction records have been categorised into those shafts that penetrate the outcrop section of the coalfield and those that penetrate the concealed section to produce the total annual abstractions in graphical form (Figure 5). Abstraction from mine shafts located within the district peaked in 1958 at over 20.5 Mm^3/a (about 55 000 m^3/d), of which 19.6 Mm^3/a was abstracted from the outcropping coalfield. By comparison, abstractions in 1958 from major water supply boreholes that penetrated the Coal Measures Group totalled about 157,000 m^3/a from three sources for public supply, about 136,00 m^3/a from a single source for colliery supply and about 132 000 m^3/a from four sources for industrial use; a total of 302 600 m^3/a.

By 1965, only 47 shafts were being used for mine drainage abstraction. The total abstraction had fallen to 9.8 Mm^3/a (about 27 000 m^3/d), of which 8.9 Mm^3/a were being abstracted from the outcrop section of the coalfield. This steep decline in abstractions is a reflection of extensive mine closures across the district during the early 1960s. Abstractions from the concealed section peaked at a little over 1 Mm^3/a (about 274 m^3/d) in 1953, and following a reduction over the following two years thereafter varied between 0.7 and 0.9 Mm^3/a, the latter in 1965 (the last year for which such records are available). By comparison, abstractions in

1965 from the major water supply boreholes were about 180 000 m^3/a for public supply and about 110,000 m^3/a for industrial use; a total of 302 600 m^3/a. Abstraction for colliery use had ceased.

By the early 1900s, mine drainage abstraction was concentrated at only five locations in the outcrop section of the coalfield (at Oxcroft, Williamthorpe, Morton, 'A' Winning and Bentinck) and a further two in the concealed section (Creswell and Langwith). In the early 1990s, average abstraction from the outcrop section was reported by Dumpleton et al. (1995) to be about 15.3 Mm^3/a (about 42 000 m^3/d) and from the concealed section about 0.8 Mm^3/a (c.2200 m^3/d). By the early all 1990s, abstraction from the Coal Measures Group boreholes for public supply had ceased and industrial usage had declined to less than 58 000 m^3/a, although limited quantities of water were still used for agricultural purposes.

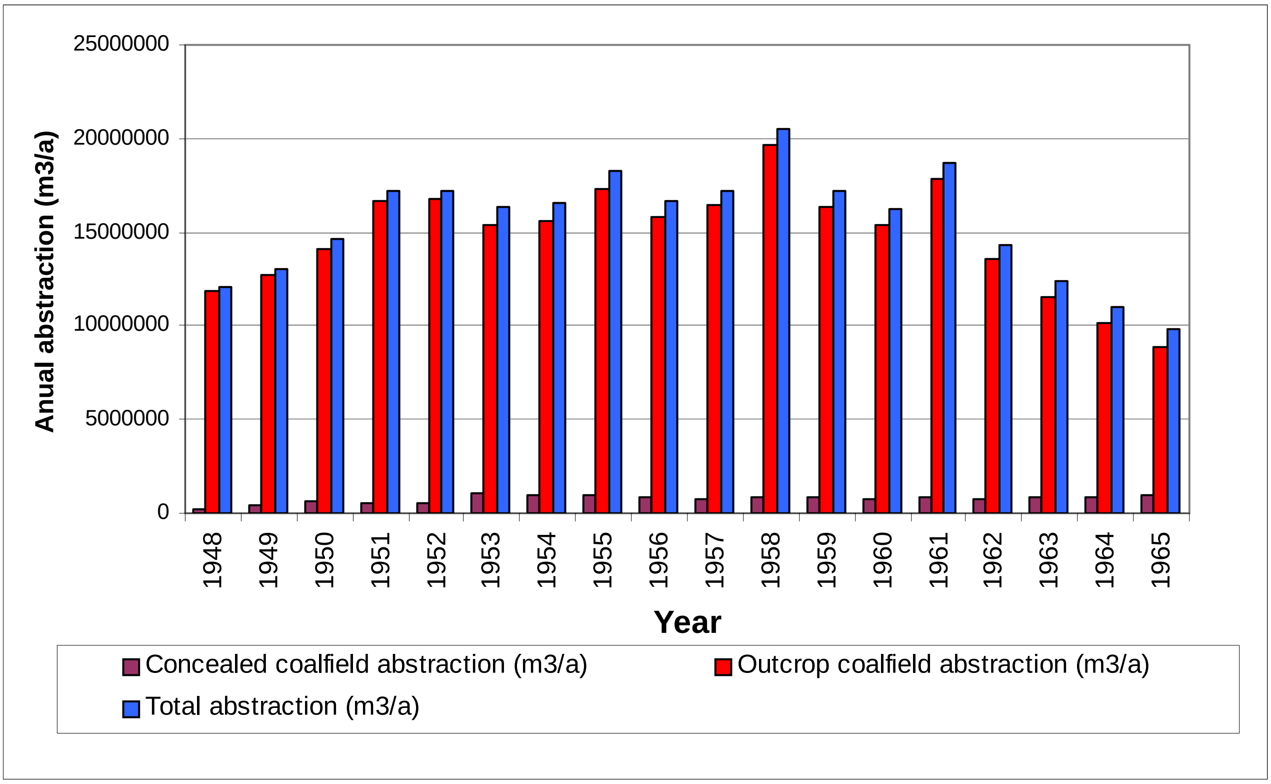

Figure 5. Groundwater abstractions from coal mines in the district between 1947 and 1964.

2.4.3 Aquifer properties

Virtually no aquifer properties data are available for the Pennines Coal Measures Group strata in the Chesterfield, Matlock and Mansfield district, with only a single transmissivity value of 10 m^2/d obtained from an aquifer test carried out on a borehole in Chesterfield [SK 383 706]. Aquifer properties values for the more general east Pennines area are, however, provided in Table 7 and are indicative of characteristics that are also likely to occur within the district.

Table 7. Aquifer properties data for the Pennines Coal Measures Group for the east Pennines (from Jones et al, 2000)

	Porosity %	**Liquid Permeability mD**	**Hydraulic Conductivity m/d**	**Transmissivity m^2/d**	**Storage coefficient**
No. of localities	15	15		-	-
No.of samples/records	450	450		65	1
Maximum	31	26529	17.0	413	-
Minimum	0.7	0.01	.0000064	0.4	-
25/75 percentiles				8 to 33	
Mean	11-17*	624-0.9	0.4-0.00058*	46	-
Median	10-18*	0.2-1.0	0.00013-.00064*	16	3.4×10^{-5}

* The ranges cover separate values cited for Lower, Middle and Upper Coal Measures, each set comprising 6 or less locations.

2.4.4 Groundwater quality

The natural quality of shallow groundwater in the Coal Measures Group at outcrop can be acceptable for many purposes; with total dissolved solids content less than 700mg/l (Table 3) and chloride less than 100 mg/l. Waters are typically hard and dominated by calcium, magnesium and bicarbonate ions. In contrast, water from deep mines may have a total hardness in excess of 1000 mg/l, sulphate in excess of 1000 mg/l, chloride ion concentration in excess of 500 mg/l and iron concentrations that may occasionally exceed 50 mg/l (Table 3). Reducing conditions are common, with the evolution of methane and hydrogen sulphide often reported.

Mining activities tend to lower water tables compared with natural conditions, particularly where the shafts are actively drained by pumping. During periods of active coal extraction, water levels could be deep if affected by the dewatering of mine workings. On the cessation of mine dewatering, water levels naturally rebound and the quality of groundwater in the Coal Measures may deteriorate. Changes in oxidation state of minerals in rocks can increase their solubility, and this can result in poor quality groundwater when the former workings flood.

2.5 PERMIAN

2.5.1 Geology

The Permian strata unconformably overlie the Pennine Coal Measures Group, occupying an area that is over 6 km wide in the north-east of the district, narrowing southward to as little as 1 km wide in the south. The Permian comprises a varied sequence of sands, calcareous clays and dolomitic limestones (Table 1).

The Basal Permian Sands Formation consists of sands only to the north of a line approximately between Bolsover and Shirebrook; it is replaced by breccia to the south (Smith et al., 1967). The sands vary from a quartzose to a marly sand; they are grey when fresh and are very variable in thickness, with up to about 3.6 m recorded at Shirebrook but as little as 2.5 cm in the Bolsover Moor borehole, and absent at other locations. The sands only occur at outcrop in the vicinity of Oxcroft in the extreme north of the district. The thickness of the breccias is also highly variable; between 3.5m and 4 cm have been recorded and they are absent in places (Smith et al., 1967). The Basal Permian Sands are not sufficiently thick to be shown on the geological map and are not considered to constitute a significant aquifer horizon within the district.

The Basal Permian Sands are overlain by strata formerly known as the Lower Permian Marl, which are now incorporated into the lower part of the Cadeby Formation. They consist of mudstone with carbonate beds, and are generally pale grey when unweathered. These beds are between 24 and 27 m thick but range from a recorded minimum of about 17 m at Sutton Colliery [SK 483 602] to over 33 m at Cross Hills borehole [SK 5086 6947]. This horizon acts as an aquitard below the overlying water-bearing Cadeby Formation.

The Cadeby Formation (formerly known as the Lower Magnesian Limestone), consists largely of bedded dolomitic limestones. Thickness of the formation varies from about 46 m in the north of the district to between 6 and 12 m in the south, although even here an exceptional 43 m was recorded at Sherwood Colliery (Smith et al., 1967). The upper part of the Cadeby Formation consists predominantly of yellow, buff or occasionally pink dolomitic limestone and forms virtually the entire outcrop. The basal part of this upper division commonly consists of a more sandy type of limestone (the Mansfield Sandstone), which can be up to 15 m thick. The lower section consists of close-grained limestones with beds of ooidal limestones, particularly in the north of the district. Mudstone beds increase in thickness and number towards the base of the Cadeby Formation, commonly giving a gradational transition into the underlying Marl Slate Formation; the boundary between the two formations commonly being somewhat arbitrary. This horizon constitutes a major aquifer in the district.

The boundary between the Cadeby Formation and overlying Edlington Formation (formerly known as the Middle Permian Marl) is in some places gradational and in others abrupt. The Edlington Formation consists of low permeability, red mudstones with occasional silty or sandy beds. This formation constitutes an aquiclude, confining the underlying Cadeby Formation aquifer and providing a base to the overlying Sherwood Sandstone Group aquifer. Thicknesses are very variable, being in excess of 36 m in the north east, almost absent in the vicinity of Mansfield Woodhouse but up to 12 m thick to the south of Mansfield.

The Permian strata are relatively little disturbed by faulting or folding, in comparison with the underlying Pennine Coal Measures Group strata. They have a gentle regional dip to the east-south-east. Fault trends are predominantly from northwest to southeast, commonly with small downthrows to the northeast.

2.5.2 Hydrogeology

The Basal Permian Sand Formation to the north of the district often contains usable quantities of groundwater but within district it is only rarely sufficiently thick to provide a sustainable supply. Boreholes constructed to abstract groundwater from the sands in the north of the district would need to be carefully designed and constructed, as the saturated sands are often poorly cemented. There are no records indicating that usable quantities of water have been obtained from the breccias in the southern part of the district.

Where present, the calcareous mudstones of the lower part of the Cadeby Formation are considered to act as an aquitard, separating the overlying limestones from the Basal Permian Sand Formations.

The Cadeby Formation limestones comprise a major aquifer in the east Midlands and Yorkshire. They are well cemented and possess little intergranular porosity or permeability. Groundwater is predominantly stored within, and flows through, fractures in the limestones. Borehole yields are unpredictable and dependent on the intersection of suitable fractures and fissures, their size and degree of interconnection. Karstification of the limestones has not been reported, due at least in part to the lower solubility of these dolomitized rocks compared with pure limestone. Springs issuing from the Cadeby Formation are common in the Bolsover area, where they maintain streamflow in the westward flowing tributaries of the River Rother (IGS, 1981).

Borehole yields available from the records for fourteen boreholes that penetrate the Cadeby Formation in the district are held in the NWRA. Values range from 11 to 5455 m^3/d, the majority of yields ranging between about 50 and 650 m^3/d. The largest yield (5455 m^3/d) was obtained from a 3.35 m diameter, 15.3 m deep shaft at Whaley Pumping Station [SK 508 718]. Yields of almost 2170 m^3/d were obtained from two boreholes of unknown diameter (one of which penetrated to a depth of 77 m) at Sherwood Colliery [SK 5371 6247 and SK 5371 6244], although a nearby [SK 5366 6244] 51 m deep, 1.5 m diameter well at the same colliery obtained a yield of only 105 m^3/d . Only seven of the borehole records contain rest and pumping water level information that allow specific capacities to be calculated. These values range from 9 to 165 m^3/d/m. Statistical values for both yield and specific capacity for boreholes penetrating the Millstone Grit Group in the district are contained in Table 8.

Table 8. Yield and specific capacity data for the Permian Cadeby Formation.

	Yield (m^3/d)	**Specific capacity** (m^3/d/m)
No. of records in category	14	7
Maximum value	5455	165
Minimum value	11	9
Geometric mean	388	44
Median value	355	45
25%ile	176	12
75%ile	1420	131

The Hydrogeological Map of the Northern East Midlands (IGS, 1981) covers an 80 km strike length of outcrop and the accompanying text suggests typical yield values of less than 90 m^3/d from 200 mm boreholes and about 650 m^3/d from 400 mm diameter boreholes, although those that intersect extensive fracture systems can yield significantly more.

The Cadeby Formation water table elevations attain a maximum along the western edge of the outcrop, being about 160 m aOD to the south of Bolsover and about 170 m aOD to the west of Ashfield in the late 1970s. Elevations decline to the east across the width of the outcrop at a gradient of about 1 in 75, attaining a minimum elevation within the district of about 70 m aOD towards the eastern edge of the outcrop to the east of Shirebrook. A lower elevation of about 60 m aOD is recorded at the outcrop edge a little further to the east, just outside of the district (IGS 1981).

Water level fluctuations can be highly variable. The average annual fluctuation for the 34 year period 1972-2007 in the long term groundwater hydrograph shown in Figure 6 is commonly of the order of 2 to 4 m but ranged up 7.84 m between September 1976 and March 1977 (following the end of a severe drought) and a little over 9 m between December and April 1978. Particularly low water levels, corresponding to drought periods, are observable in 1976, 1991 and 1996/97, with the first two giving very similar minimum water levels.

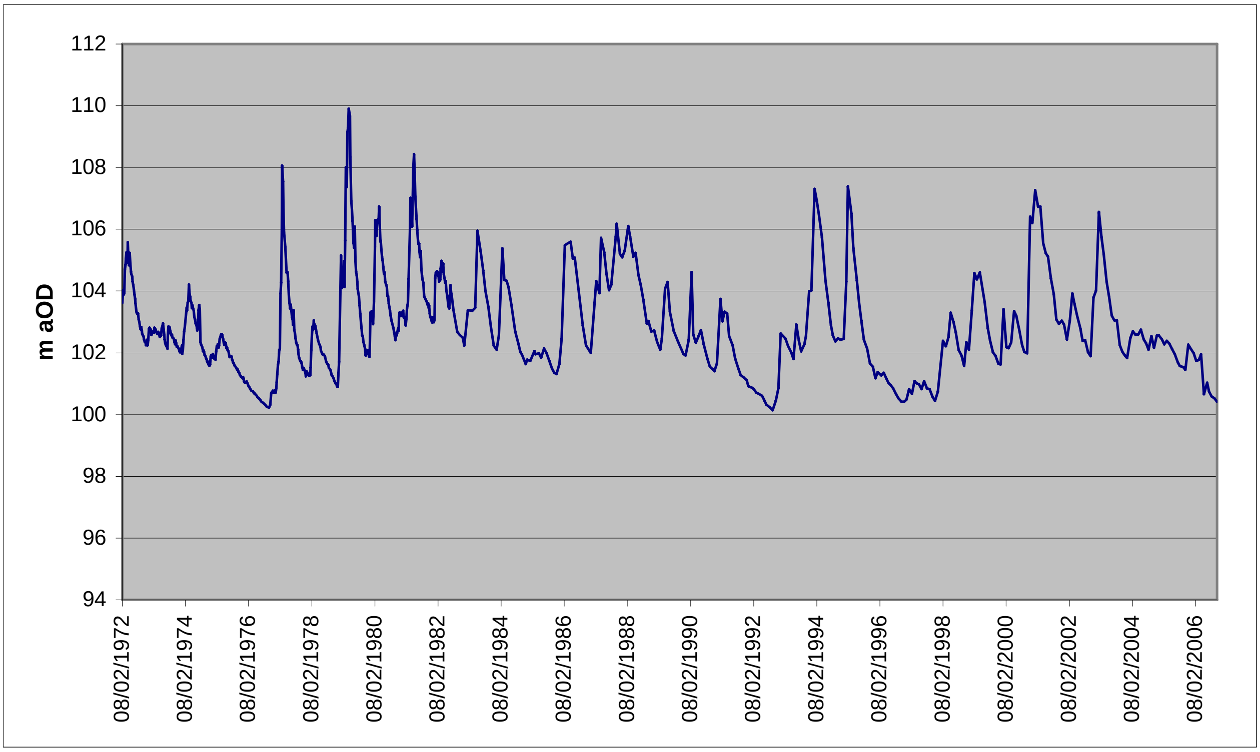

Figure 6. Permian Magnesian Limestone Group groundwater level hydrograph: Hodhill Farm observation well [SK52096634] (from data provided by the Environment Agency)

2.5.3 Aquifer properties

No porosity data are available within the district. Over the Permian outcrop as a whole, along the strike of the outcrop between Nottingham and Sunderland, a 107 sample dataset provides mean and median porosity values of 13.7% and 15% for the Cadeby Formation (Allen et al., 1997). Aquifer storage occurs both in the fracture system and in the rock matrix, as indicated in the porosity range of cores shown in Table 9. This dataset shows a trend of increasing porosity with hydraulic conductivity, although there is significant scatter in the data. No storage coefficient values are available for the district. Storage coefficient values for the whole outcrop area vary over several orders of magnitude (from 3.4 x 10^{-6} to 4 x 10^{-3}) with a median value of 5.2 x 10^{-4} (Allen et al., 1997). Statistical values for porosity and hydraulic conductivity, determined for rock core samples obtained from the overall Cadeby Formation dataset, are provided in Table 9.

Table 9. Aquifer properties statistics for the ‘Magnesian Limestone’ between Nottingham and Sunderland (from Allen et al., 1997)

	Porosity (%)	**Hydraulic conductivity (m/d)**	**Transmissivity (m^2/d)**
No. of samples/localities	107	107	80
No. of pumping tests	-	-	105
Max	30	0.85	4300
Min	1	1.9 x 10^{-6}	6
Interquartile range	8.5 to 18.7	2.9 x 10^{-4} to 0.015	131 to 763
Geometric mean/	-	-	255
Median	15.0	1.4 x 10^{-3}	229

Only a single transmissivity value is available for the Cadeby Formation within the district; testing of the borehole located at Holling Mill, Mansfield [SK 515 648] provided a transmissivity of 280 m^2/d. To the north of the district along the strike of the Cadeby Formation, the highest transmissivities are reported to be associated with fault zones and observations from pumping tests suggest that weathering-induced fracturing and dissolution may increase the permeability within the zone of water table fluctuation (Allen et al., 1997). Statistical values for transmissivity derived from the available dataset for the Cadeby Formation as a whole are provided in Table 9.

2.5.4 Groundwater quality

Groundwater from the Cadeby Formation is normally of good natural chemical quality, with total dissolved solids ranging up to about 1200 mg/l. Groundwater is commonly hard, with total hardness (as $CaCO_3$) between 400 and 650 mg/l, of which about 300 mg/l may be attributable to carbonate hardness (IGS 1981). The chloride ion concentration rarely exceeds 50 mg/l, sulphate concentrations should be less than 50 mg/l and levels of iron and manganese are generally low. At outcrop, the aquifer is prone to microbiological pollution as joints can allow rapid penetration of potentially contaminated surface water. Where confined, chloride and sulphate concentrations increase rapidly down dip and sodium concentrations increase at the expense of calcium due to the presence of halite in the confining mudstones (IGS 1981). A representative Cadeby Formation groundwater analysis for a sample obtained from Gildwell Pumping Station [SK 541 369] is provided in Table 3.

2.6 SHERWOOD SANDSTONE GROUP

2.6.1 Geology

The Sherwood Sandstone, consisting of the Nottingham Castle Sandstone and the Lenton Sandstone Formations, only occurs in the southwestern corner of the district. The Nottingham Castle Sandstone Formation (formerly known as the Bunter Pebble Beds) consists predominantly of a brown and pink, coarse pebbly sandstone whilst the Lenton Sandstone Formation (formerly the Lower Mottled Sandstone) consists of a red to red-brown, fine-grained sandstone. A maximum of up to 60 m of Sherwood Sandstone Group strata is likely to be present in the district, with each of the two formations being up to 30 m thick.

2.6.2 Hydrogeology

The two formations that constitute the Sherwood Sandstone Group outcrop within the district act as a single aquifer unit, which is an important source of groundwater for the city of Nottingham.

No physical properties data obtained from measurements carried out on core are available for the Sherwood Sandstone Group outcrop within the district. Porosity values for the outcrop area to the east of the district fall predominantly in the range of 25 to 35%, with arithmetic mean and median values of about 30%. Core hydraulic conductivity values are predominantly in the range of 0.35 to 4.7 m/d, with median and geometric mean values of 2.1 and 0.87 m/d respectively. The sandstones are predominantly anisotropic with horizontal permeability commonly double that of the vertical (Allen et al., 1997). Intergranular anisotropy within the sandstone aquifer thickness is often exacerbated by the presence of fine-grained lower permeability sandstone beds and sporadic thin intercalations of siltstone and mudstone.

There are no transmissivity values available for the Sherwood Sandstone Group in the district but an analysis of data for the nearby outcrop area suggests that values are not likely to exceed

100 m^2/d (Allen et al 1997). In general terms, hydraulic conductivity values obtained from pumping tests are on average one to two orders of magnitude higher than those determined from laboratory core measurements. There were considered to be two reasons for this phenomenon. Firstly, borehole transmissivities are likely to be dominated by high permeability horizons which, as such deposits are commonly poorly cemented and friable, are likely to be poorly represented in core sample data. Secondly, the presence of fractures can often significantly increase the effective average hydraulic conductivity of a borehole but cannot be represented in the core sample data (Allen et al., 1997).

Yield data for boreholes and wells solely penetrating the Sherwood Sandstone Group are available for only seven locations in the district. Yields vary from as little as 220 m^3/d from a 585 mm diameter borehole at Hallams Farm, Kirkby in Ashfield [SK 5314 5540], to 2180 m^2/d from a 205 mm diameter borehole at Normans Hollow [SK 5391 5551]. Considerably larger yields have been obtained from large diameter shafts; for example, that at Normans Hollow [SK54205574], which had associated headings, produced a yield of 3532 m^3/d in 1937. Kirkby Forest No.1 shaft [SK 5376 5573] produced a yield of 5455 m^3/d in the early 1900s. Collectively, the wells, boreholes and associated headings that made up the Normans Hollow Pumping Station provided a supply of 3090 m^3/d to Kirkby in Ashfield in the mid 1960s (Smith et al., 1967).

No chemical analysis of Sherwood Sandstone Group groundwater is available from within the district but a representative analysis for a location about 2.5 km to the east at New Dairy, Berry Hill [SK 5647 5953] is included in Table 3. In general, groundwater is of good quality at outcrop where total hardness varies from 80 to 200 mg/l, chlorides from 20 to 40 mg/l and nitrate commonly less that 50 mg/l (IGS 1991), Nitrate concentrations may, however, vary according to local agricultural practices. Concentrations of the various ions fluctuate seasonally in response to recharge. A partial analysis of the Kirkby in Ashfield water supply provided by Smith et al. (1967) was consistent with these values, with a total hardness of the order of 135 mg/l and a chloride ion concentration of about 21 mg/l.

Sherwood Sandstone Group water table contours are depicted on the hydrogeological map of the Northern East Midlands (IGS, 1981). Water table elevations attain a maximum of over 105 m aOD in the west of the outcrop area, declining radially towards the east and south, having an elevation of about 105 m aOD at the north eastern edge of the outcrop and about 120 m aOD in the south east. The water table contour pattern suggests that a major zone of aquifer recharge is located in the vicinity of the western edge of the sandstone outcrop, centred to the south east of Sutton in Ashfield [approximately SK 510 570].

The groundwater hydrograph for the Sherwood Sandstone Group observation borehole at Coxmoor [SK 5217 5762] is shown in Figure 7. The water levels are subject to regular seasonal variations of 1 to 2 m, the lowest levels occurring in late summer or autumn with the maximum level occurring during the early months of the year following winter recharge to the aquifer. The lowest water levels occurred in response to severe droughts in 1976 and 1992, both events being followed by a rapid rise in levels of over 3 metres in response to heavy rainfall and consequent aquifer recharge.

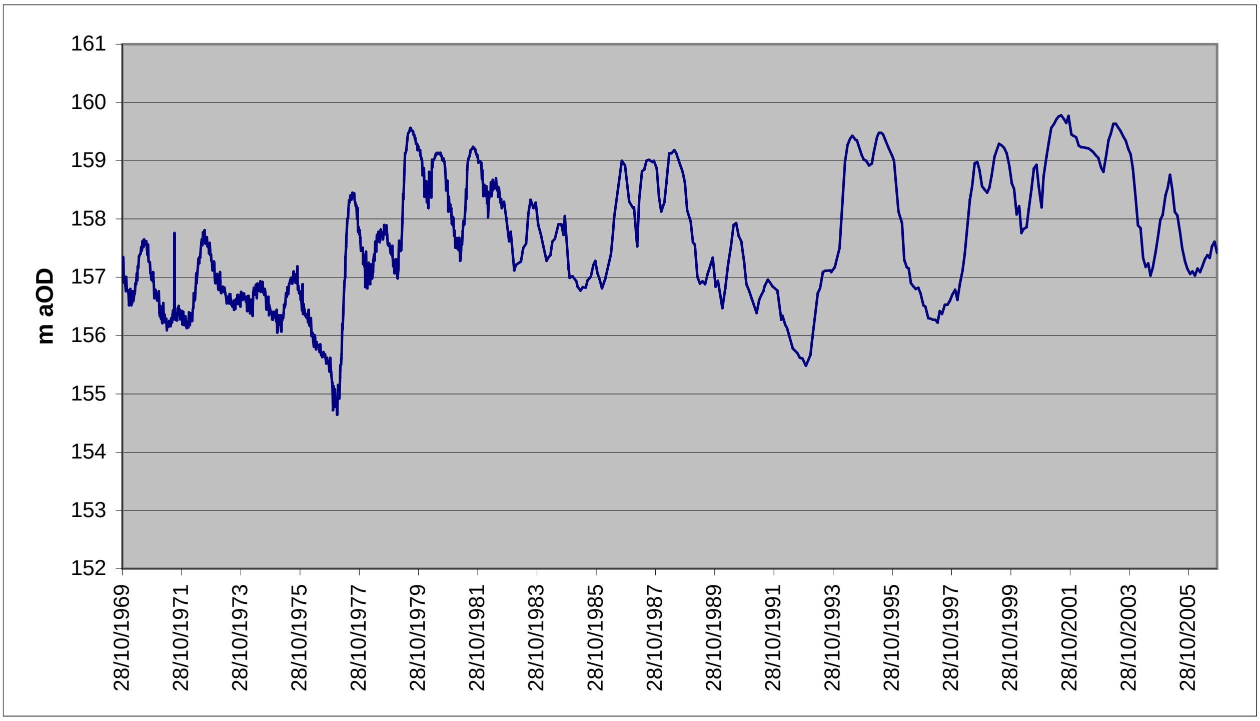

Figure 7. Sherwood Sandstone Group groundwater level hydrograph: Coxmoor observation well [SK 5217 5762] (from data provided by the Environment Agency)

3 Groundwater Resources

3.1 HISTORICAL GROUNDWATER ABSTRACTION

Much of the district, including Chesterfield, Clay Cross, Bolsover and many smaller communities, were, in the past, provided with public supplies obtained from surface water reservoirs in the Linacre and Amber valleys, together with bulk supplies originating outside of the district. They were also supplied from a number of wells and boreholes that penetrated the Millstone Grit Group, the Pennine Coal Measures Group and Permian Cadeby Formation (Smith et al 1967). The south-west regions around Matlock and Alfreton were historically supplied from boreholes and numerous springs issuing from the Millstone Grit Group, in addition to water from Meerbrook Sough. The east and south east of the district, including Mansfield, Sutton in Ashfield and Kirby in Ashfield, were supplied from wells and boreholes penetrating the Sherwood Sandstone Group, some of which were located to the east and outside of the district (Smith et al., 1967). In more rural areas numerous sources such as springs, wells and (since the late 1800s) boreholes would have been used to provide small scale agricultural and domestic supplies.

An examination of annual abstraction information for major public supply and industrial sources for the period between 1948 and 1964, held in the NWRA, show that a total of 15 Millstone Grit Group public supply sources (3 springs, 3 adits and 9 boreholes), and 3 boreholes penetrating the Pennine Coal Measures Group, were in use in the late 1940s. In addition, there were two boreholes (Whispering Well and Linacre) that penetrated both the basal section of the Coal Measures and the Millstone Grit Group and drew water from both formations, although use of the latter borehole ceased in 1949. Two sources (Whaley and Gildwell Spring) provided public supplies from the Permian Cadeby Formation and a single source (Normans Hollow) from the Sherwood Sandstone Group. Groundwater abstraction from each aquifer for selected years during the period between 1948 and 1965 is provided in Table 10.

3.2 CURRENT LICENSED GROUNDWATER ABSTRACTION

It was not possible to obtain current data for licensed abstractions and water use for the district from the Environment Agency.

An examination of an abstraction licence data set from the early 1990s shows, however, that none of the Millstone Grit Group public supply abstraction sources discussed above were still licensed for groundwater abstraction at that time. The only licensed public supply abstraction was Normans Hollow in the Sherwood Sandstone Group, a source for which no abstraction was recorded in 1965. The largest number of licences were for abstractions from the Millstone Grit Group for general agricultural use (51 borehole, well and spring sources) and private domestic supplies (7 sources, 4 of which were springs). All of the agricultural and all but one of the domestic supplies were for abstraction volumes of less than 20 m^3/d and will, in consequence, currently no longer require abstraction licences. Of the other five Millstone Grit Group abstraction licences (for industrial and agricultural spray irrigation use), only four exceeded 20 m^3/d. Of the twelve Peak Limestone Group abstraction licences, only six exceeded 20m^3/d. Of the nine Pennine Coal Measures Group licences and five Cadeby Formation abstraction licences, only three and four licences respectively exceeded 20 m^3/d. In the case of the Sherwood Sandstone Group, in addition to the public supply three agricultural groundwater abstractions (two for spray irrigation) all exceeded 20 m^3/d.

Table 10 Groundwater abstractions in the district between 1948 and 1965

	Year	**1948**		**1950**		**1955**		**1960**		**1965**	
Water use		No.	Mm^3/a	No.	Mm^3/a	No.	Mm^3/a	No.	Mm^3/a	No.	Mm^3/a
Public Supply	All sources	24	10.25	21	5.76	21	7.56	21	7.07	14	4.44
	Millstone Grit (MG)	15	7.20	15	3.13	15	3.86	15	3.75	10	2.55
	MG & CM	3	0.60	1	0.62	2	1.05	2	0.91	0	0.54
	Coal Measures (CM)	2	0.30	2	0.30	1	0.11	1	0.07	1	0.18
	Cadeby Fm.	2	1.06	2	0.87	2	1.37	2	1.24	2	1.18
	Sherwood Sandstone	1	1.08	1	0.84	1	1.18	1	1.1	0	0
Colliery	All sources	5	0.66	6	0.63	5	0.41	5	0.36	2	0.08
	Coal Measures	0	0.00	1	0.01	1	0.01	1	0.01	0	0
	Cadeby Fm. (CF)	3	0.39	3	0.33	2	0.09	2	0.07	2	0.08
	Sherwood Sandstone	2	0.27	2	0.29	2	0.30	2	0.3	0	0
Industrial	All sources	5	0.35	4	0.18	4	0.24	3	0.16	2	0.11
	Millstone Grit	1	0.04	1	0.04	1	0.04	1	0.04	0	0
	Coal Measures	3	0.10	3	0.14	3	0.20	2	0.12	2	0.11
	CF & CM.	1	0.20	0	0.00	0	0.00	0	0	0	0
Total Abstraction			11.26		6.57		8.21		7.59		4.63

In the early 1990s, abstractions of less than 20 m^3/d for domestic use did not require an abstraction licence. These small licence-exempt water supplies are not well documented and it is difficult to assess their probable number with any accuracy. A very approximate idea of their importance can be deduced from local authority (LA) environmental health returns for a national survey that was conducted in 1994 (Anon. 1994). Summary LA statistics are available for the five principal LA's that include parts of the district but unfortunately all LA's straddle the district boundaries to varying extents. Nevertheless, the figures suggest that at that time, one to two hundred properties are likely to have depended on groundwater for supply within the district, thereby forming by far the largest category in this survey in terms of source numbers if not total quantity of water abstracted. It is probable that the number of domestic sources will have declined during the intervening years as the availability of reticulated mains supplies has spread into more rural areas, but will still remain a widely used, important (and in many cases only) source of water supplies.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

ABESSER C and SMEDLEY P L. Uranium distribution in the groundwaters of the Derbyshire Dome. British Geological Survey Internal Report IR/06/072.

ANON. 1994. Private water supplies: summary of returns submitted by local authorities on numbers of supplies and populations served. Dept of the Environment Water Services Divn. London Oct 1994.

ALLEN DJ, BREWERTON LJ, COLEBY LM, GIBBS BR, LEWIS MA, MACDONALD AM, WAGSTAFF SJ and WILLIAMS AT. 1997. The Physical Properties of Major Aquifers in England and Wales. British Geological Survey Technical Report (WD/97/34). Environment Agency R&D Publication 8, Keyworth UK.

BRASSINGTON F.C. 2007. A proposed conceptual model for the genesis of the Derbyshire thermal springs. Quarterly Journal of Engineering Geology and Hydrology, Vol. 40, 35-46.

DUMPLETON, S, GLOVER, B W, BUTCHER AS, COLEBY LM and ROBINS NS. 1995. The impact of colliery closures on water resources, with particular regard to NRA Severn-Trent Region. BGS Technical Report WD/95/40, Keyworth UK.

EDMUNDS, W.M, 1971. Hydrochemistry of groundwaters in the Derbyshire Dome with special reference to trace constituents. Report No. 71/7, Institute of Geological Sciences. Pub. HMSO, London.

GUNN, J, 1992. Hydrogeological contrasts between British Carboniferous Limestone aquifers. International contributions to hydrogeology, 13, pp 25-41. Pub. Verlag Heise, Hanover, Germany.

INSTITUTE OF GEOLOGICAL SCIENCES. 1981. Hydrogeological Map of the Northern East Midlands, 1:100,000. IGS London.

JONES HK, MORRIS BL, CHENEY CS, BREWERTON LJ, MERRIN PD, LEWIS MA, MACDONALD AM, COLEBY LM, TALBOT JC, MCKENZIE AA, BIRD MJ, CUNNINGHAM J and ROBINSON VK. 2000. The physical properties of minor aquifers in England and Wales. BGS Technical Report WD/00/4, British Geological Survey, Keyworth, Nottingham, UK.

METEOROLOGICAL OFFICE. 1977, Average Annual rainfall (millimetres), International Standard Period 1941-1970, Southern Britain, 1:625 000.

RAE G.W. 1978. Groundwater Resources in the Coalfields of England and Wales - the Yorkshire Coalfield. Unpublished report of Central Water Planning Unit, Reading.

RAFERTY, S.R., SHOTTON, F.W. and THOMPSON R.W.S. 1953. Joint report on the limestone water scheme. Unpublished report, Derwent Valley water Board, 19 pp.

SHEPLEY M.G. 2007. Analysis of flows from a large Carboniferous Limestone drainage adit, Derbyshire, England. Quarterly Journal of Engineering Geology and Hydrology, Vol. 40, 123-135.

SMITH, EG, Rhy, GH and EDEN RA. 1967. Geology of the country around Chesterfield, Matlock and Mansfield. Memoirs of the Geological Survey of Great Britain (England and Wales). Institute of Geological Sciences. Pub. HMSO, London.

STEPHENS J V. 1929. Wells and springs of Derbyshire. HMSO London.

THOMPSON N, BARRIE I A and AYLES M. 1981. The Meteorological Office Rainfall and Evaporation System: MORECS, Met. Office Hydrological Memorandum No. 45, 72pp.

YOUNGER, P L and BRADLEY, K F. 1994. Application of geochemical mineral exploration techniques to the cataloguing of problematic discharges from abandoned mines in north-east England. Procs. 5th International Minewater Congress, Nottingham UK.