British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Hydrogeological notes for the Sheffield district (sheet 100)

Groundwater Systems and Water Quality Programme
Internal Report IR/05/045

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/05/045

Hydrogeological notes for the Sheffield district (sheet 100)

B L Morris

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Ordnance Survey licence number GD 272191/1999

Key words

Groundwater, Sheffield UK, aquifer properties,.

Bibliographical reference

B L MORRIS 2005.
Hydrogeological notes for the Sheffield district (sheet 100)
British Geological Survey Internal Report, IR/05/045. 21pp.

© *NERC 2005*

Keyworth, Nottingham British Geological Survey 2005

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham and Edinburgh; see contact details below or shop online at www.thebgs.co.uk

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

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

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

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

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.thebgs.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

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

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Parent Body

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

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Acknowledgements

With acknowledgements to the Centre for Ecology and Hydrology (NERC-CEH) and the Environment Agency for England and Wales (EA) for the provision of data used in this report. The author thanks Felicity Sanderson (NERC-CEH), Khalid Karmali (EA Midlands Region) and James Senior (EA Northeast Region) and especially Mrs Melinda Lewis (NERC-BGS), for assistance in this respect. Other BGS staff who contributed to the production of this report include; Mrs Melinda Lewis, Ms Rosemary Hargreaves, Dr Helen Rutter, Mr John Talbot and Dr John Carney.

Contents

FIGURES

TABLES

1 Introduction

1.1 PURPOSE OF REPORT

This report provides a compilation of hydrogeological information as part of the 1:10,000 scale re-survey of the Sheffield geological sheet. The resulting published products will comprise a revised 1:50,000 scale map and a Sheet Explanation. The latter will be published as a booklet to accompany the folded 1:50 000-scale map.

1.2 BACKGROUND

The district relating to Geological Sheet 100 comprises the conurbation of Sheffield and Rotherham with its suburbs and dormitory villages to the south and southwest, the towns of Maltby, Dronfield, and Staveley, the northern edge of Chesterfield, and intervening rural and periurban areas. About 26% of the 600 km^2 quadrangle's area is urbanised.

Topography in the district is varied, with the high ground of the gritstone moors falling away eastwards towards undulating ground either side of the River Rother then rising again along the low but noticeable ridge line of the Permian Limestone either side of North and South Anston. Elevations range from a maximum of c. 420m on the Hallam Moors west of Sheffield down to about 60m in the Ryton valley on the line of the former Chesterfield Canal. The high moor also dominates drainage, with streams like the Barlow Brook and Rivers Sheaf, Rivelin and Loxley flowing eastwards off the dip slopes of the gritstone scarps. To the east of Sheffield, this predominantly dendritic drainage form becomes more rectilinear, with pronounced NE-SW and NW-SE components. Further east again the low scarp of the Permian Limestone marks a change back to eastward-draining dip-slope streams (Fig 1).

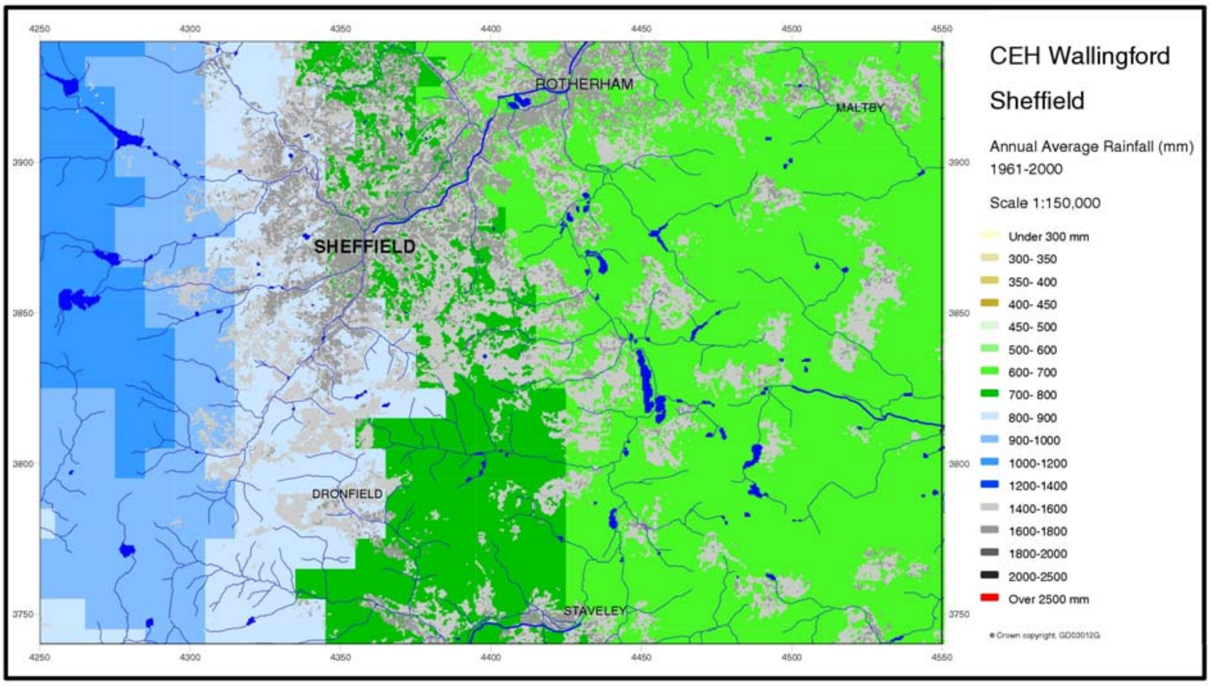


Figure 1 Drainage and mean annual precipitation 1961-2000 in Sheffield district (with acknowledgements to CEH Wallingford)

Rainfall distribution divides the area into two halves along a north-south axis between Rotherham and Staveley. To the east mean annual rainfall is less than 700 mm (1961-2000 long-term average), but to the west this rises steeply with elevation to exceed 1000 mm on the high moors beyond Sheffield. The quadrangle is located within the MORECS 40 X 40 km square 107 for which average annual potential and actual evapotranspiration values (1971 to 2000) are available (Meteorological Office 1977, Thompson et al. 1981). These were about 570 and 518 mm respectively,with soil moisture deficits typically at their maximum during May-August and minimum during December-February. Therefore effective rainfall (the amount available for runoff and recharge to the subsurface) is typically c.175-500 mm/a

2 Hydrogeology

A simplified geological map (from 1:625,000 edition. 1979) for the Sheffield district is shown in Figure 2 and a stratigraphy as Table 1.

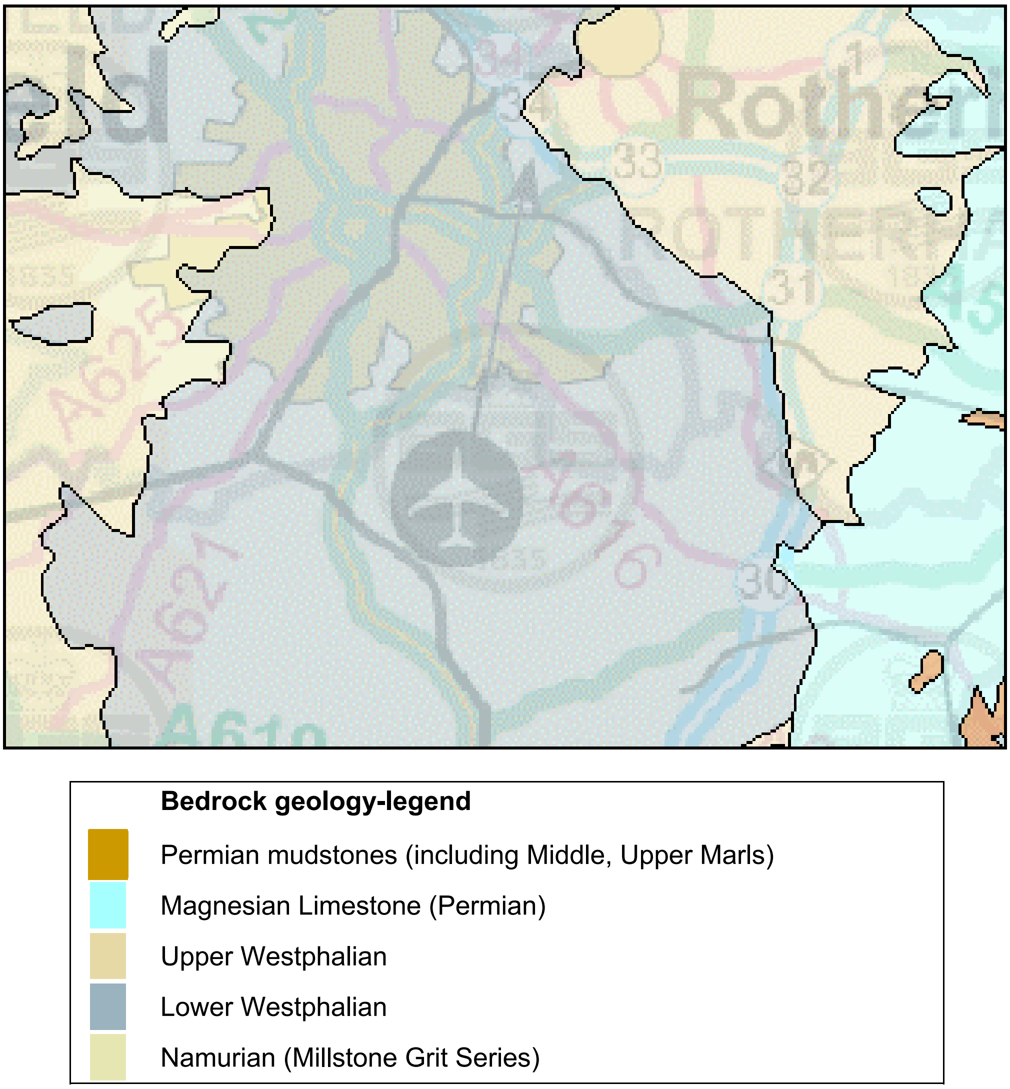


Figure 2 Simplified geological map of Sheffield district (extract from 3rd Ed. Solid 1:625,000 scale Geological Map of the United Kingdom [south] 1979)

Table 1 The stratigraphy of the Sheffield district (compiled from Eden et al 1957 with updates by R D Lake, and from Allen et al 1997 and Jones et al 2000) Table to be updated by memoir field geologist authors with any changes in strata thicknesses or preferred nomenclature

Geological Unit		Previous and revised lithostratigraphy with main lithologies		Hydrogeological significance
Quaternary	Artificial	Worked ground, Made ground, Infilled ground		Variable
	Pleistocene and Holocene	Hill peat; alluvium; river terrace deposits; solifluction and glaciofluvial deposits, till.		Variable
Permian	Upper Permian	Middle Permian Marl	Edlington Formation (~3 m); calcareous clays and sand	Leaky aquitard
		Lower Magnesian Limestone	Cadeby Formation; dolomitic limestone (37 m) overlying calcareous clays (15 m)	Aquifer
		Lower Permian Marl		Aquitard
	Lower Permian	Basal Permian Sands	Basal Permian Sands Fmn (0-6 m) medium to fine sands	Aquifer
Upper Carboniferous	Westphalian A,B,C,?D	Pennine Upper Coal Measures Fmn	(1340 m); cyclic sediments with c120 cyclothems of shales, siltstones, sandy shales, clay palaeosols and coals.	Highly variable; thin sandstones are aquifers separated by the argillaceous strata, but mining-induced structural deformation may secondarily increase permeability
		Pennine Middle Coal Measures Fmn		
		Pennine Lower Coal Measures Fmn		
	Namurian	Millstone Grit Group	(up to 640 m); cyclic sediments comprising mudstones, prominent medium to coarse sandstones and occasional clay palaeosols with thin coal bands.	Aquifers (coarse sandstones), Aquitards (mudstones,palaeosols)

2.1 NAMURIAN (MILLSTONE GRIT GROUP)

2.1.1 Geology

The Millstone Grit Group refers to Namurian strata of the Millstone Grit facies; older Namurian strata (which are present at depth throughout the district) are composed of predominantly argillaceous strata and are not generally water-bearing. As a whole, the cyclic sediments of the upper part of this group mainly comprise mudstones and prominent medium- to coarse-grained sandstones. It is the latter which are the principal water-bearing strata. The group has been formally subdivided into formations, but individual sandstones are typically given informal names.

The Millstone Grit typically comprises coarsening-upward cycles with dark grey carbonaceous shales, 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 proportion of sandstone to mudstone broadly increases upwards within the group as a whole and gives it topographic expression. It is the uppermost part of the Group which crops out in the Sheffield district. The sandstones can range from coarse-grained and cross-bedded or massive to fine-grained, micaceous and thinly planar laminated. The Rough Rock is typically a coarse-grained, pebbly, cross-bedded sandstone, the lower beds of which are flaggy. The Chatsworth Grit is lithologically similar to the Rough Rock.

Millstone Grit 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.

2.1.2 Hydrogeology

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 obtainable from shale horizons although small quantities may be present in thin interleaved sandstone beds. The grit and sandstone horizons, being separated by impermeable shales and mudstones, effectively act as independent aquifer horizons, although faulting may locally juxtapose them into hydraulic connection. The more important aquifer horizons in the Sheffield area include the Chatsworth Grit (up to 60m thick), and to a lesser extent the Redmires Flags, the Rough Rock (each about 15m thick) and the Heyden Rock. Springs issue from these at points along the base of the outcrop. The Kinderscout Grit, which is productive elsewhere, is also present at depth. Borehole yields are dependent on the number and size of fractures encountered in any particular productive horizon. These are quite variable and it is often difficult to predict actual yields. Additionally, initial productivity of the Millstone Grit is not always sustainable, sometimes declining with time as pumping depletes storage.

2.1.3 Aquifer properties

There are few aquifer properties data for the Namurian strata within the area covered by Sheet 100. Yields ranging from 28.5 to 1309 m^3/d are recorded from nine sites in the NWRA[1] , four of which also have rest and pumping water level information enabling specific capacities to be estimated. These range from 2 to 56 m^3/d/m and a number of records suggest that the Chatsworth Grit, the Redmires Flags and the Rough Rock are productive horizons. Well yields can also be assessed from licensed daily quantities and these lie generally in the range 1.6 - 31.8 m^3/d. The large difference between yield ranges reported from archived well records and current licences is striking. The reason could be because licences cite daily abstraction quantities while the archive reports are hourly rates that may not be sustainable 24 hours per day. However the number of records in both cases is small and it could just be that

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

present uses of water from the Namurian no longer require the volumes that were needed in the past e.g.for industrial process water. For instance, a single industrial abstraction at Wadsley Bridge (at SK 323919) , which penetrates the Lower Coal Measures into the Millstone Grit, is licensed for 1000 m^3/d and this suggests that higher yields may be possible.

Table 2A summarises what is available from the core records in the National Aquifer Properties database. The data from the two localities in the table are samples from the Chatsworth Grit and they are considered to typify water movement in the coarser sandstone members of the Namurian. 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. Namurian strata over a much larger Pennines province were characterised for assessment purposes for the Minor Aquifers Physical Properties manual (Jones at al. 2000). This province extends from the south of the Peak district to Barnard Castle in Co. Durham (see Fig 3). In the absence of local field data, Table 2B, based on this much larger Millstone Grit outcrop, provides indicative information on transmissivity, storage coefficient and specific capacity.

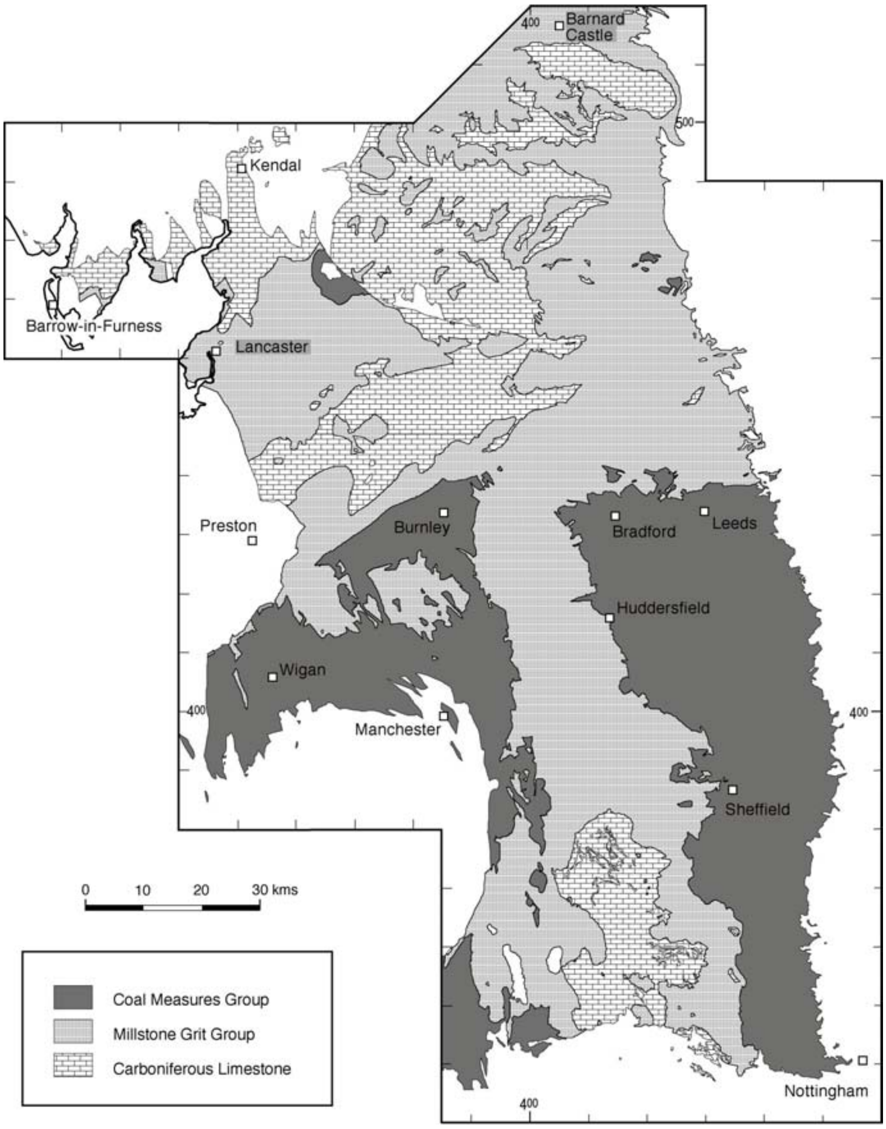


Figure 3 Pennines area Carboniferous outcrops used for comparative purposes in this report (from Jones et al. 2000)

Table 2 (A) NAPD* aquifer properties data for the Namurian of the Sheffield district (B) comparison with data from east and west Pennines (from Jones et al, 2000)

Area	Statistic	Porosity %	Liq. Permeability mD	Hyd. conductivity m/d
(A) Sheffield district	No. of localities	2	2	2
	No.of samples	18	18	18
	Max	16.4	116.0	0.0743
	Min	11.5	2.0	0.0012
	Mean	13.7	12.7	0.0081
	Median	13.6	4.2	0.0026
(B) Pennines province	No. of localities	16	16	16
	Max	23	1061	0.7
	Min	6	0.7	.0003
	Mean	14	10	.005
	Median	14	66	.04
		Transmissivity m^2/d	Storage coefficient	Specific capacity $m^3/d/m$
	No. of records	81	3	123
	Max	1059	.013	9092
	Min	0.6	.0001	0.54
	Mean	93	-	140
	Median	26	-	67

* National Aquifer Properties Database, maintained by the BGS

Seasonal water level changes are quite site-specific and only one long-term hydrograph is available; this is the 44-year water level record at Big Moor Longshaw (Fig 4). This 99.1 m deep borehole penetrates the uppermost sandstone members of the Millstone Grit (Rough Rock, Redmires Flags, Chatsworth Grit) and shows typical annual fluctuations of about 1.3m.

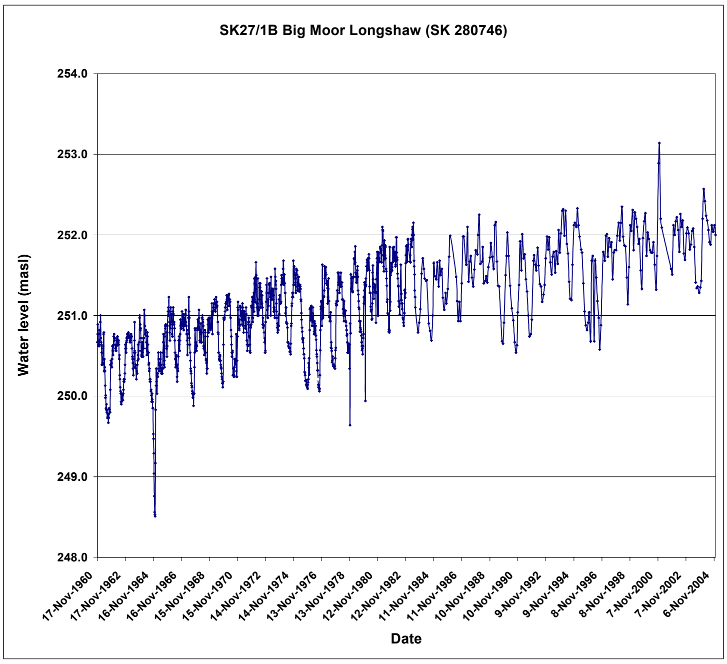
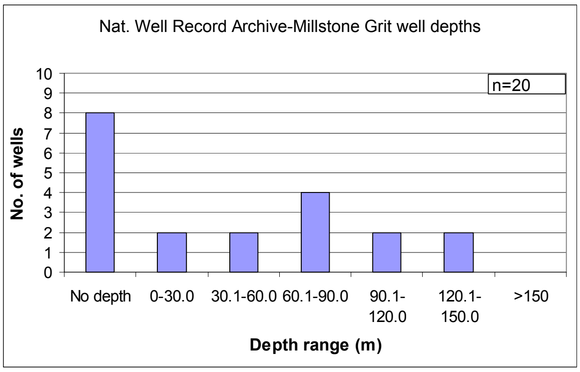


Figure 4 Water level hydrograph for Millstone Grit observation well: Big Moor Longshaw (with acknowledgements to the Environment Agency)

It could be inferred that seasonal water level changes in the Namurian are muted; however, the borehole is located on the edge of Big Moor and Ramsley Moor, suggesting that significant peat cover may be damping seasonal water level response.

12 NWRA well records for the Namurian in the Sheffield district have recorded depths: these are evenly distributed over the range 0-120 m with the majority drilled pre-WWII (Fig. 5). Occasionally boreholes require a sand screen to prevent spalling, but generally stand unsupported.



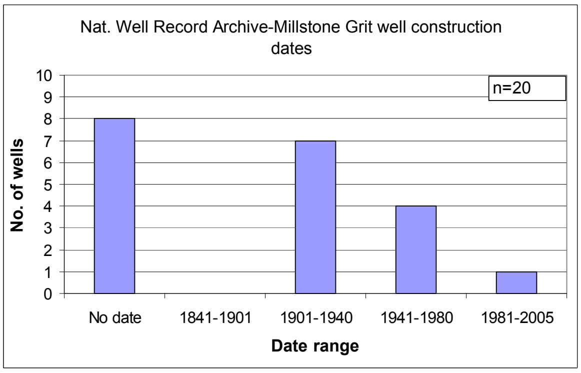


Figure 5 NWRA summaries for Namurian wells in Sheffield district showing distribution of well depths and construction dates

The water quality is generally acceptable, with a hardness of about 150 to 250 mg/l (as $CaCO_3$) and a chloride ion concentration generally less than 50 mg/l. A single partial analysis from the first Rod Moor rural supply borehole (142 m deep, drilled 1933, SK269892) had a total dissolved solids content of 270 mg/l with a total hardness of 200 mg/l as $CaCO_3$ and a chloride content of 13 mg/l (see Table 5). Occasionally iron concentrations can locally exceed 0.5 mg/l, which may impart a taste and cause staining of laundry and bathroom fittings.

2.2 WESTPHALIAN (PENNINE LOWER, MIDDLE AND UPPER COAL MEASURES FORMATIONS)

2.2.1 Geology

The Westphalian strata can be considered together in groundwater terms because stratigraphic subdivisions are based upon laterally extensive marine bands and coal seams which in general have little hydrogeological significance. The Pennine Coal Measures Group comprises alternations of pale grey sandstone, typically fine-grained and often ochreous when weathered, grey siltstones and grey mudstones, with frequent coal seams, residual soil horizons and ironstones (Jones et al, 2000). Although argillaceous rocks predominate throughout the Coal Measures, it is to the east of the Pennines and in the Yorkshire Coalfield where the sandstones are thickest. There is a broad transition between the greater abundance of marine bands in the lower strata, and of coal seams in the upper strata.

While the thinner sandstones are generally lenticular, passing laterally as well as vertically into siltstones and mudstones, there are some individual sandy members that are laterally extensive (>100 km^2) and exceed 20m in thickness. These include the Crawshaw Sandstone, the Silkstone Rock, the Deep Hard Rock, the Oaks Rock and the Mexborough Rock.

A number of other sandstone beds attain or exceed this thickness locally but laterally thin to a few metres thick (see Eden et al. 1957). In common with the underlying Namurian rocks, the Westphalian strata are strongly dislocated by faults, typically with a northwest-southeast trend, and a system of WNW-ESE-trending folds (Eden et al 1957).

2.2.2 Hydrogeology

As with the underlying Namurian, the argillaceous strata in the Coal Measures Group act as aquitards or aquicludes that isolate the occasional thicker sandstone horizons which, under natural conditions, would act as separate aquifers. Water may therefore rise above the level at which it is struck. The effects of faulting and post-mining subsidence can hydraulically interconnect different producing horizons in the multiaquifer array. Coal Measures sandstones are generally fine to medium grained, very well cemented, extremely hard and dense and in consequence possess little primary porosity or intergranular permeability. Groundwater storage and movement occurs predominantly within and through fractures in the sandstones. Potentially any of the thicker and more widely-found sandstones can be water-bearing e.g the Crawshaw and Grenoside Sandstones, the Penistone Flags, the Silkstone and Greenmoor Rocks, 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 sandstone horizons), have potential, with borehole yields depending on the number, size and degree of interconnection of fractures encountered in a productive horizon.

There are a number of conflicting processes that make borehole productivity in the Coal Measures difficult to predict. On the one hand, sandstone outcrop areas are often small, limiting the amount of recharge that can infiltrate directly to individual sandstone units. Extensive faulting has frequently split previously continuous sandstone horizons into disconnected and isolated fault-bounded blocks, to which little or no direct recharge can occur. Where these processes dominate, initial borehole yields may decline substantially due to the depletion of aquifer storage by abstraction. On the other hand, the district has been mined for coal, refractory clays and ironstone for c.300 years, with improved technology since the mid-19th century allowing collieries to progressively extend to greater depths and penetrate further east into the concealed coalfield below the Permian. The natural hydrogeological conditions of the Coal Measures Group have therefore been disrupted over wide areas and in places to depths in excess of 300 m below ground level. Where undermining of coal has occurred, the collapse of strata behind worked faces and the creation of open shafts, roadways and galleries not only induces fractures but also can create hydraulic continuity between layers that were previously isolated, in some places linking previously separate aquifer horizons to flooded, disused workings.

The coal mining processes causing dislocation of overlying strata are well described in a review of the effect of colliery closure on water resources by Dumpleton and Glover in 1995. Adits and bell pits, although they seldom reached depths of more than 10 metres, create disturbed ground in the unsaturated zone as workings collapse and this creates conditions for enhanced infiltration. Recharge can increase when the workings extend downdip into the pillar and stall workings that developed from the 18th century onwards, which themselves became deeper as dewatering and drainage technology developed. The introduction of longwall mining methods in the early 20th century increased the lateral extent of the collapse area behind workings. As Dumpleton and Glover indicate, the degree of upward migration of subsidence and the associated extent of bed separation voids is strongly influenced by the competence of the roof rocks; mudstones collapse rapidly and become compacted, leaving little void space while sandstones, especially if they are thick-bedded, can break into large blocks or even remain uncollapsed.

The hydrogeological consequences of this process are locally important; in the former case, even if mudstone or shale roof rocks are compacted as roof-fall and ground heave close the worked out panel or stall, more competent overlying sandstones near the workings are likely to develop subsidence induced fracture patterns that can propagate upwards and outwards. These can link different sandstone members, especially where the sequence is thin-bedded or already structurally dislocated by faults. Where a sandstone roof rock stands, the vertical extent of enhanced transmissivity propagation may be more limited, but the workings provide significant increases in storage capacity, available when the mine is abandoned and water levels rise as dewatering ceases. This effect is enhanced by the presence of underground access and ventilation roadways that can total tens of kilometres in length in a single colliery. Where these 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 for minewater/groundwater movement of very high hydraulic conductivity, analogous to mature karst systems in limestone.

Over a dozen separate seams have been worked in the South Yorkshire coalfield and Dumpleton and Glover suggest that the net effect 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 metres thick. They postulate a conceptual model similar to that described for the Durham coalfield (Younger and Bradley 1994) in which groups of collieries (many were linked underground during operation) behave as discrete leaky reservoirs, each having its own independent water level, controlled by pumping at working or closed collieries. Two such leaky reservoirs are proposed for the Sheffield area, the northernmost one extending from Elsecar north of Steetley and Kiveton Park towards the Rossington and Harworth mines east of Maltby. Isolated interconnection occurs between this unit and a more southerly reservoir extending southeastwards from Hartington through Creswell towards Bilsthorpe. It is considered likely that the eventual cessation of pumping may result in uncontrolled minewater discharge into surface water courses such as the Rother as well as posing a rebound hazard in the concealed coalfield, which is overlain not only by the Magnesian Limestone but also by the important Sherwood Sandstone Permo-Triassic aquifer to the east of this quadrangle.

Yields from licensed abstraction returns are very variable; domestic and agricultural supplies typically have spray irrigation permits in the range 0.2-20 m^3/d, but there are a number of mine drainage boreholes licensed to pump up to 100-1200 m^3/d, their productivity illustrating the processes described in the previous paragraphs. When coal mining was active, withdrawals from the Coal Measures were significant; Rae (1978), referring to the Yorkshire Coalfield as a whole extending north as far as Leeds, estimated that the abstraction of 15 Mm^3/a from boreholes and wells in 1972 for water supply purposes was dwarfed by that from active mines at 41 Mm^3/a, as well as a possible 24 Mm^3/a from then-disused mines. Thus in the early 1970s, groundwater pumped from the 98 coalmines then working in the Yorkshire coalfield was about four times abstractions for all other purposes.

Table 3 summarises yield and specific capacity information from 97 records in the NWRA categorized as tapping Coal Measures strata. These comprise mainly industrial, commercial and food/beverage processing water supply boreholes with three shafts (two of which are mine drainage shafts) and a spring source. The statistics indicate that yields are typically in the range 75-850 m^3/d with the mean of c. 500 m^3/d reflecting the dozen or so supplies abstracting >850 m^3/d but the median indicating that most supplies typically yield less than 250 m^3/d.

Table 3 Yield and specific capacity data for the Westphalian of the Sheffield district

Statistic	Yield (m^3/d)	Specific capacity ($m^3/d/m$)	Depth (m)
No. of records in category	97	97	97
No. of values	50	18	44
Maximum value	3272.8	382.4	321.2
Minimum value	20.7	1.8	4.9
Average value	512.2	106.3	83.5
Median value	225.9	37.1	61.0
25%ile	71.5	8.6	35.5
75%ile	845.4	187.7	93.5

The few aquifer properties data available in the Sheffield area are collated in Table 4 and again compared with the wider picture from the East Pennines, in a manner similar to Table 2. These support the view of Rae (1978) that intergranular permeability is invariably less than 0.02 m/d, and generally much less.

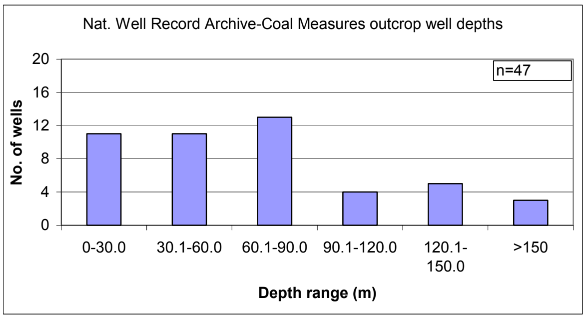
Table 4 (A) NAPD* aquifer properties data for the Westphalian of the Sheffield district (B) comparison with data from east Pennines (from Jones et al, 2000)

Area and statistic	Porosity %	Liq. Permeability mD	Hyd. Conductivity m/d	Trans-missivity m^2/d	Storage coefficient
(A) Sheffield district:					
No. of localities	1	1	1	3	-
No.of samples/records	6	6	6	3	-
Max	19.0	58.0	0.0372	55	-
Min	18.1	1.6	0.0010	2	-
Mean	18.5	23.9	0.0153	28.3	-
Median	18.5	19.7	0.0126	28	-
(B) East Pennines					
No. of localities	15	15		-	-
No.of samples/records	450	450		65	1
Max	31	26529	17.0	413	-
Min	0.7	0.01	.0000064	0.4	-
Mean	11-17**	624-0.9	0.4-0.00058**	46	-
Median	10-18**	0.2-1.0	.00013-.00064**	16	.000034

* National Aquifer Properties Database

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

The Coal Measures have been much more widely used in the past for industrial and processing water, with the greatest activity during the first half of the 20th century (Fig 6). For example, the NWRA records former boreholes or wells for 9 Sheffield breweries that used the water, latterly at least, for plant washing purposes. It also shows that a number of steel manufacturing and processing plants and other industrial users had their own boreholes for process water. Most of these wells are less than 150 m deep.



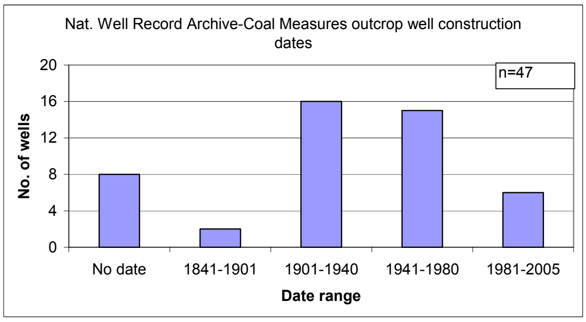


Figure 6 NWRA summaries for Coal Measures outrcrop wells in Sheffield district showing distribution of well depths and construction dates

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 5) 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 5). Reducing conditions are typical, with the evolution of methane and hydrogen sulphide not uncommonly reported. However, as Table 4 shows, the range of mineralization is broad and the nominal well depth is no guide as the mine drainage systems are usually complex and can connect zones of widely divergent depth and water quality.

Mining activities tend to lower water tables compared with natural conditions, particularly where the shafts are actively drained by pumping, and during the periods of active coal extraction up to the 1980s, water levels could be deep if affected by colliery dewatering. Once mine dewatering ceases, and water levels naturally rebound, the quality of groundwater in the Coal Measures may deteriorate. This is because the oxidation state of minerals in the rocks may have changed in the time that the strata were dewatered, increasing their solubility in water and often resulting in poor quality groundwater when the former workings flood.

2.3 PERMIAN

2.3.1 Geology

The Permian strata that unconformably overlie the Carboniferous rocks occupy the easternmost 15% of the district and comprise a varied sequence of sands, calcareous clays and dolomitic limestones. The Basal Permian Sands Formation represents a thin development of loosely coherent, medium- to fine-grained sands. Although typically up to 6 m, the thickness is variable and the sands may be absent in some marginal central areas (Eden et al. 1957). Overlying the Basal Permian Sands is the Cadeby Formation. The lowermost member, which was formerly known as the Lower Permian Marls comprises a series of calcareous shales and clays generally about 15m thick, but again the thickness is variable and it may be absent in places. The upper members comprise a series of dolomitic limestones approximately 37 m thick, widely known as the Lower Magnesian Limestone formerly and now termed the Cadeby Formation (Table 1). This carbonate sequence passes up from compact reef and back-reef limestones (oolitic, pisolitic and shelly facies) into increasingly dolomitised, hard, crystalline limestones which are more massive and granular.

Table 5 Groundwater analyses in the Sheffield district from the National Well Record Archive

Ref	Aquifer	Well depth (m)	Water User	Use	Analysis date	TDS mg/l	Na mg/l	Ca mg/l	Mg mg/l	Total Hardness mg/l $CaCO_3$	Temp Hardness mg/l $CaCO_3$	Cl mg/l	SO_4 mg/l	NO_3-N mg/l	Fe mg/l	SiO_2 mg/l	pH
SK49/13	CM	91.4	Commercial	Amenity & Recreation: irrigation	1961	380	-	-	-	220	220	28	-	-	0.8	220	7.4
SK38/25	CM	89.5	Commercial	Brewery process water	1896	443	206	22	13.3	47.2	-	25.1	90	-	-	0.35	-
SK38/24 B	CM	133.7	Commercial	Brewery process water	1950	530	192	15.7	5.68	62.6	62.6	82	32.9	bdl	0.1	10	8
SK38/32	CM	142.6	Commercial	Dairy process water	1946	633	-	-	-	-	20	75	-	0.15	-	-	8
SK38/2	CM	121.9	Commercial	Amenity & Recreation: ice	1964	680	-	-	-	340	284	131	-	bdl	1.1	-	6.8
SK38/11	CM	51.1	Commercial	Brewery process water	1934	720	-	96.9	83	380	251	119	194	bdl	-	7.6	7.5
SK38/12	CM	53.6	Commercial	Industrial process water	1907	1080	-	-	-	330	-	115	-	1	-	-	-
SK49/14	CM	99.7	Commercial	Brewery process water	1930	1432	-	21.6	17.3	819	173	23.7	45.8	bdl	2.1	12	-
SK38/44	CM	85	Commercial	Amenity & Recreation: ice	1999	-	-	92.4	51.3	-	325	36.8	-	bdl	3.94	-	-
SK47/45	CM	514.8	Mining	Coal mine drainage	1951	622	142	49	31	251	251	94	78	bdl	bdl	6	8
SK47/23	CM	40.5	Mining	Coal mine drainage	1952	623	165	40	24	200	200	74	98	bdl	0.46	24	7.2
SK47/34	CM	228.8	Mining	Coal mine drainage	1953	925	194	75.7	45.1	-	375	73	313	1.1	9.3	11.5	6.65
SK48/38	CM	321.2	Mining	Coal mine drainage	1951	1762	305	142	86	710	350	287	593	bdl	bdl	42	7
SK47/20 B	CM	83.4	Mining	Coal mine drainage	-	2337	50	164	196	1220	310	163	1194	-	246	16	6.6
SK47/40	CM	-	Mining	Coal mine drainage	1952	41366	12990	1112	1341	8300	16		4335	-	8	9	6.1
SK28/12 B	MG	144.8	Public supply	Rural water supply	1934	270	-	-	-	200	143	12.9	-	0.12	-	-	-

CM Westphalian MG Namurian bdl Below detection limits TDS Total dissolved solids Note: coalmine drainage depths nominal; refer to individual record for details

Scattered outliers and down-faulted exposures of calcareous shales of the overlying Edlington Formation (formerly the Middle Permian Marls) form patches of c. 2.5 km^2 total outcrop area on the limestones.

In comparison with the underlying Carboniferous rocks, the Permian strata are relatively little disturbed, with a gentle regional dip to the east-south-east and a lower mapped fault frequency. Northwest-south-east and west-east trending faults dominate and those near Barlborough, Anston and Maltby have sufficient downthrow to dislocate and extend westwards the margin of the Permian outcrop in several places.

2.3.2 Hydrogeology

The uncemented and commonly medium-grained nature of strata in the Basal Permian Sands Formation provide aquifer potential, especially as its aeolian origin has produced well-sorted loosely coherent beds with rounded grains. Its potential, where a significant thickness is preserved, is illustrated by the single available transmissivity value of 53 m^2/d (Table 6) which represents a likely bulk hydraulic conductivity of the order of 5-10 m/d. Boreholes need to be carefully designed and constructed to avoid the problem of running sands but the main constraint on capacity is the thin and discontinuous nature of this formation.

Where present, the calcareous shales of the lower part of the Cadeby Formation are considered to act as an aquitard, separating the overlying limestones from the Basal Sands.

The Cadeby Formation limestones are nationally a significant aquifer. Transmissivity is dependent on fracturing, although there is some intergranular storage, as indicated in the porosity range of cores shown in Table 6. The highest transmissivities are reported to be associated with the fault zones; within the faulted blocks the transmissivities are generally lower but extremely variable. Borehole yields are unpredictable and dependent on the intersection of suitable fissures. Karstification is not reported, and this is due in part to the lower solubility of dolomite compared with pure limestone. Observations from pumping tests conducted further north along the strike suggest that weathering-induced fracturing and dissolution may increase the permeability within the zone of water table fluctuation (Allen et al. 1997). The limestone is unconfined, with only very sporadic and limited cover of Edlington Formation calcareous shales, and the outcrop is remarkably free of superficial deposits. The gradient of the potentiometric surface slopes approximately west-east; and in the late 1970s was about 1 in 75 declining from about 150 m to 60 m above sea level in the southern part of the district near Creswell.

Storage in the aquifer is both in the fracture system and in the matrix; the local porosity mean of 14.5% is comparable with a 107-sample larger dataset mean of 13.7% taken from Cadeby Formation samples along the strike of the outcrop between Nottingham and Sunderland (Allen et al. 1997). Based on this larger dataset, these authors report a trend of increasing porosity with hydraulic conductivity, although there is significant scatter in the data. No storage coefficient values are available for the area, and pumping test data are particularly sparse in the Sheffield district, with just a single reported value in the NAPD of 15 m^2/d. This value is low compared with other sites elsewhere in the Magnesian Limestone aquifer (Table 7) and should not be regarded as representative. The three licensed abstractions that draw from the formation echo the likely variability, with licensed daily quantities of 1.36, 6.1 and 1560 m^3/d respectively. Stephens (1929) reported yields of 91 and 1364 m^3/d respectively from limestone wells at the former collieries of Clowne Southgate (SK 491771) and Cresswell (SK 529740). The Hydrogeological Map of the Northern East Midlands (1981) covers an 80 km strike length of outcrop and the Notes suggest typical values of less than 90

m^3/d from 200 mm boreholes and c. 650 m^3/d from 400 mm diameter boreholes, although those that intersect extensive fissure systems can yield significantly more.

Table 6 NAPD* aquifer properties data for the Permian of the Sheffield district

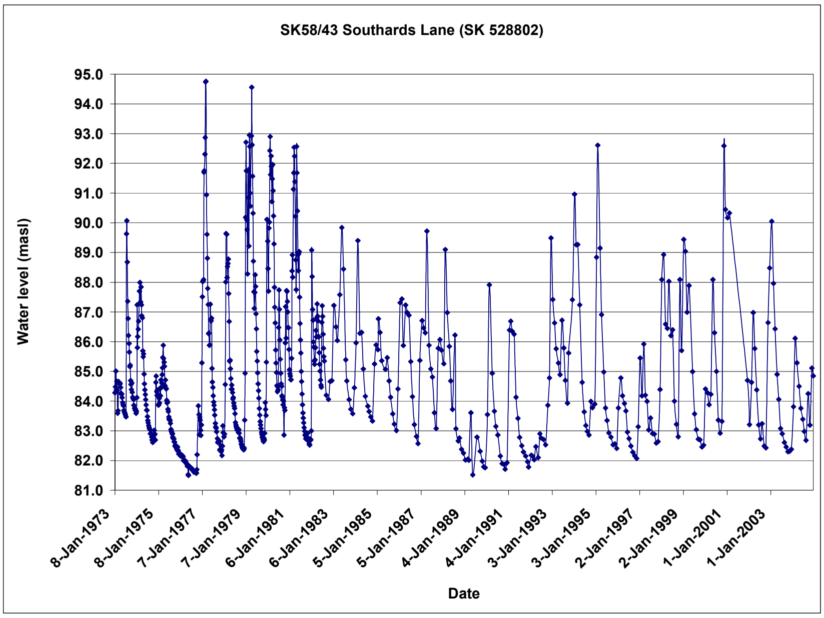
Area and statistic	Porosity %	Liq. Permeability mD	Hyd. conductivity m/d	Transmissivity m^2/d	Storage coefficient	Specific capacity $m^3/d/m$
Basal Permian Sands:						
No. of localities	-	-	-	1	-	-
Value				53	-	-
Lower Magnesian Lst:						-
No. of localities	6	4	4	1	-	-
No.of samples	12	9	9	1		
Max	23.2	205.8	0.1319	-	-	-
Min	9.4	1.0	0.0006	-	-	-
Mean/sole value	14.5	52.0	0.0482	15	-	-
Median	12.8	12.8	0.0214	-	-	-

* National Aquifer Properties Database

Table 7 Transmissivity statistics for wells located along the Magnesian Limestone between Nottingham and Sunderland (from Allen et al., 1997)

Transmissivity (m^2/d)			
No. of localities	80	Geometric mean/	255
No.of pumping tests	105	Median	229
Max	4300	Interquartile range	131-763
Min	6		

Water level fluctuations can be similarly variable. The average annual fluctuation for the 31-year period 1973-2004 in two long-term hydrographs shown in Fig. 7 is 2.14 m and 6.71 m. These locations are Environment Agency observation wells 4 km apart, remote from local pumping influences and stratigraphically at approximately similar levels.



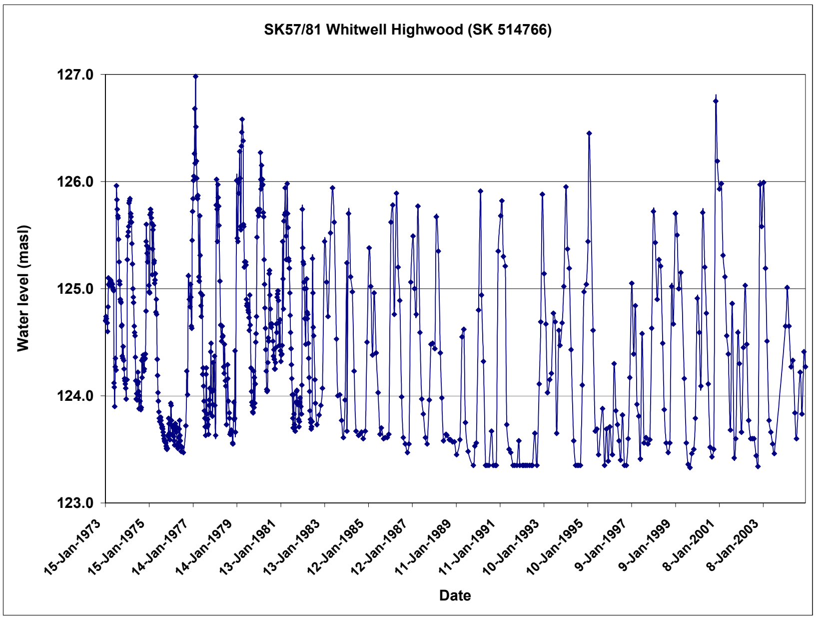


Figure 7 Water level hydrographs for Southards Lane and Whitwell Highwood wells in the Lower Magnesian Limestone (with acknowledgements to the Environment Agency)

Groundwater from the Cadeby Formation is normally of good natural chemical quality, but may be quite hard, with total hardness (as $CaCO_3$) between 200 and 350 mg/l. The chloride ion concentration rarely exceeds 40 mg/l, sulphate concentrations should be less than 50 mg/l and levels of iron and manganese are generally low. The aquifer is prone to microbiological pollution as joints can allow rapid penetration of potentially contaminated surface water.

2.4 QUATERNARY AND RECENT

2.4.1 Quaternary deposits

Quaternary deposits are not recorded as of wide lateral extent or thickness in the Sheffield district. The principal superficial deposits are the alluvial tracts, which are generally less than 0.75 km wide, that floor the valleys of the Rivers Don and Rother. The alluvium comprises a few metres of silts and clays overlying a lower, more gravelly part. Thinner and narrower ribbons of alluvium are associated with the River Sheaf, and the Barlow and Pools Brooks. No current licensed abstractions draw from the alluvium, but a single record in the NWRA with a yield of 870 m^3/d from a borehole only 9.1 m deep with a specific capacity of 249 m^3/d/m shows that in places the alluvium could be productive. Even so, while a number of well logs in the Sheffield city area record its presence, there is little evidence to suggest that these deposits have been tapped for water supply in their own right.

The small peat tracts of Totley Moss, Burbage and Big Moor are likely to provide a storage medium for the Westphalian and Namurian sandstones that they overlie. The main patches of older glacial deposits are located around Kiveton (stony clay tills) and Beighton (fluvioglacial sands and gravels, much quarried) but their limited extent and thickness renders them of negligible hydrogeological significance.

2.5 GROUNDWATER RESOURCE ISSUES

2.5.1 Water supply

LICENSED GROUNDWATER ABSTRACTION

Public water supply for Sheffield and Rotherham has historically been drawn from surface water sources, latterly impounding reservoirs located in the Derwent Valley and on the moors overlooking the city. Flow from the Derwent Valley reservoirs through the Rivelin water-tunnel beneath Hallam Moors is reported to be enhanced by percolation from the Millstone Grit (Eden et al., 1957) but otherwise the groundwater contribution to public supplies by the Carboniferous rocks is currently insignificant.

Groundwater abstraction and water use data are shown in Table 8; these are compiled from information supplied by the EA Midlands and Northeast regions.

Coal Measures outcrops extend across more than 70% of the district, so it is not surprising to find that this Group is the most important of the three aquifer systems in terms of licence numbers and total abstraction. However, 1.7 million m^3/a from an area of perhaps 400 km^2 is not particularly large in terms of total quantity. 60% of all licensed supplies are used for manufacturing process water, over 90% of which comes from the Coal Measures. An allied use is for industrial cooling water from a handful of boreholes which draw on both the Coal Measures and the Millstone Grit, and together these two uses account for more than 80% of demand.

Table 8 Licensed water use in the Sheffield district

Use	Sub-category	Upper Carboniferous (Silesian)		Lower Permian	Quaternary	Totals
		Namurian	Westphalian	Lower Magnesian Limestone	Various superficial deposits	
Domestic supplies and bottled water		5,156 *(3)*	7,381 *(3)*	2,239 *(1)*		14,776 *(7)*
Agriculture	General	19,990 *(9)*	37,108 *(11)*	48,498 *(2)*		105,596 *(22)*
	Irrigation	4,546 *(1)*	66,019 *(12)*	-		70,565 *(13)*
Industrial	Process	10,789 *(3)*	1,237,008 *(11)*	-	108,760 *(5)*	1,356,557 *(19)*
	Cooling	363,688 *(1)*	117,329 *(2)*	-		481,017 *(3)*
	Mineral Washing	-	220,000 *(1)*	-		220,000 *(1)*
Unspecified			14,935 *(3)*			14,935 *(3)*
	Totals	404,169 *(17)*	1,699,780 *(43)*	50,737 *(3)*	108,760 *(5)*	2,263,446 *(68)*

Key: 5,156 *(3)* Licensed annual abstraction in m^3/a *(Number of licences)*

SMALL PRIVATE SUPPLIES

Small licence-exempt water supplies (<20 m^3/d and for abstractor's domestic purposes only) are not represented in Table 8 and are not well-documented. 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 LAs that include parts of the Sheffield district (Table 9). It should be noted that these statistics will subsume a number of Category 2 licences that figure in Table 8 (see note in Table 9). Nevertheless, small sub-licence users of groundwater form by far the largest category in this survey.

Table 9 Private water supplies supplies and populations served in 5 local authority areas in the Sheffield district. (adapted from DoE survey data Anon. 1994).

Local authority	Popn served (1+2*)	No. of supplies (1+2*)	Approx volume (1+2*) m^3/a	Approx. % of LA in Sheet 100
Sheffield	478	176	34,894	>50%
Chesterfield	6	3	438	40%
North East Derbyshire	620	213	45,260	25-30%
Bolsover	54	7	3,942	>20%
Derbyshire Dales	1414	262	103,222	<10%
Totals:	2572	661	187,756	

Note: statistics in columns 2-4 are for whole LA area.
* Categories 1 & 2 under Private Water Supplies Regulations 1991: Category 1 supplies are those only used for drinking, washing and cooking by people who live in the properties supplied. Category 2 supplies are those used to make food or drink that will be sold or used in properties providing accommodation on a commercial basis .

The figures, which are for the early 1990s, suggest that in the Sheffield district at least a hundred properties depended on groundwater for supply.

2.5.2 Urban groundwater issues

Human activity has profoundly influenced the hydrogeology of the Sheffield district in several ways. Not only is there a mining legacy but also the Sheffield-Rotherham conurbation overlies much of the northern half of the district, lying either directly upon the Coal Measures outcrop or upon the intervening thin alluvium of the Rivers Don and Rother and their tributaries. Some suburbs on the higher ground west of Sheffield also straddle the fault-dislocated western margin of the Westphalian to extend onto the uppermost members of the Namurian sequence. Both cities have had a long industrial tradition centred on steel and iron-working and while economic diversification has been extensive since the late 1960s, there is inevitably an industrial legacy of contaminated land which can pose a groundwater resource hazard. As Sheffield has continued to grow, suburbs and dormitory towns extend southwards and eastwards over former mining areas towards the M1, further reducing the extent of agricultural land-use. As a result, much of the recharge to the Coal Measures in the northern two-thirds of the quadrangle takes place in an urban and suburban environment.

In such settings, the relative rural simplicity of direct recharge from rainfall via the soil zone and from rivers by bed leakage is replaced not only by additional sources of recharge but also by more complex pathways as different urban services and development requirements interact (Fig.8).

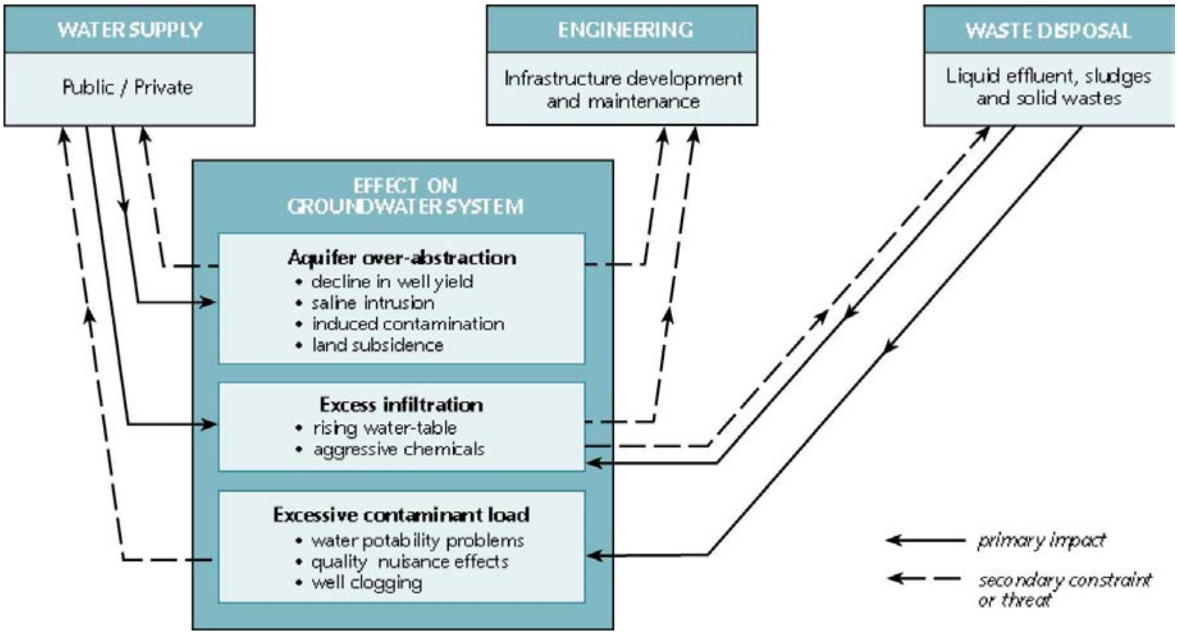


Figure 8 Facets of degradation of groundwater system underlying a city as potentially conflicting urban services interact (from Morris et al, 2003)

Losses by leakage from the large volumes of water circulating within the pipe infrastructure (pressurised mains, foul sewers, combined sewers, pluvial drains), together with percolation from roof runoff/paved area soakaways, provide sources of near-surface recharge additional to those available in rural catchments. At the same time impermeabilisation of the land surface by buildings and paved areas changes the scope for local precipitation to enter the aquifer. The resultant intricate mosaic of at-surface and near-surface recharge sources complicates both the quantification of net recharge to the aquifer and the prediction of the effect such recharge may have on groundwater quality (Eiswirth and Hötzl 1994, Howard 2001).

There is accumulating evidence to show that recharge in urbanised areas is typically increased over the pre-urban condition (Foster et al. 1993; Lerner et al. 1990, Krothe et al. 2002). Perhaps the main contributor of additional recharge is the pipe infrastructure and it is not difficult to envisage why this should be. For example, with a combined population of 760,000 in 2001 (Office of National Statistics 2005), and a typical domestic design supply of 250 litres/person/day, approximately 70 million cubic metres (Mm^3) of water circulates annually in the water mains of Sheffield and Rotherham. As UK mains leakage rates in older cities in the UK are rarely less than 14-15% and may be significantly more, as a rough estimate about 10 Mm^3 may be lost to the subsurface annually. This extra recharge over that from local rainfall is drawn mainly from reservoirs located outside the city. It is further added to downstream by sewer leakage, which can be significant, especially in older systems; leakage rates of 3-14% of total effluent volume have been estimated for Nottingham (Yang et al, 1999). Typical indicators of urban recharge are increased concentrations in groundwater of chloride, nitrate, sulphate, and in some cases boron, while deep penetration of faecal contamination indicators (e.g. faecal streptococci and sulphite-reducing clostridia) has also been noted in studies of the sandstones underlying Birmingham, Nottingham and Doncaster (Barrett et al 1999, Powell et al 2003, Cronin et al 2005).

Such pipe networks can be very extensive. In a recent urban recharge study of Doncaster (Morris et al. 2005), GIS analysis of a 6.3 km^2 suburban area with 8300 properties showed that the district was served by a 220 km infrastructure of sewers, pluvial drains and mains water distribution systems. So the 218,000 households in Sheffield alone could be underlain by over 5000 km of water pipe infrastructure.

Cities like Sheffield that develop over an aquifer system commonly undergo an evolution in their water infrastructure like that shown in Fig. 9.

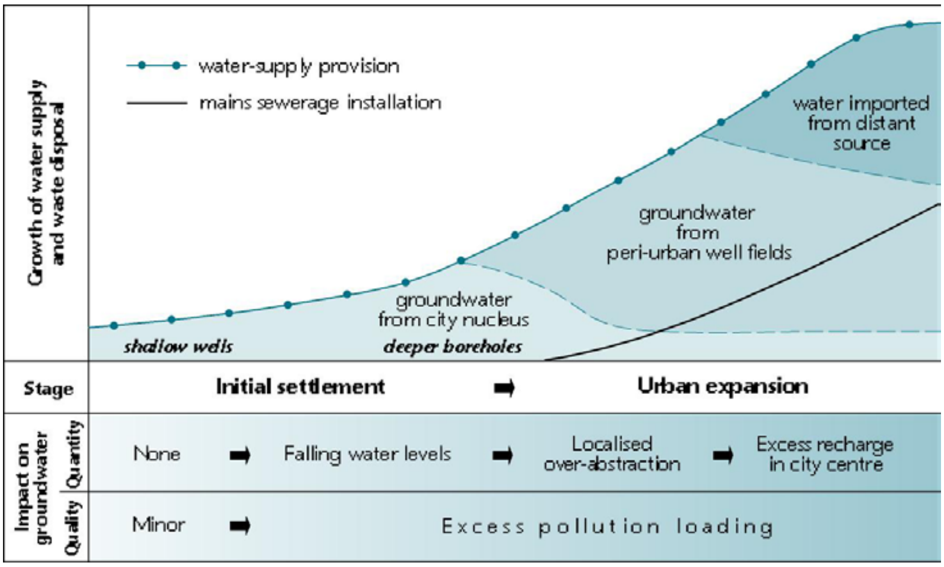


Figure 9 Typical stages in the evolution of a water infrastructure in a city overlying a productive aquifer (from Morris et al. 2003)

Sheffield's development differs slightly from that shown in the diagram because expanding demand has been met by reservoir supplies from the adjacent Peak District rather than from periurban wellfields and because there are productivity and natural water quality constraints on water from the Coal Measures. Nevertheless, the city did originally tap groundwater in the city centre before supplies from outside the city led to their abandonment and removed a factor that would keep water levels depressed regionally. Additional sources of recharge enter into a complex urban water budget whose balance depends on the stage of evolution reached.

It is against this background that a number of older UK cities overlying productive aquifers have reported groundwater rebound; London, Birmingham, and limited areas of Liverpool and Nottingham all report problems of rising water levels (Morris et al. 2003). The number of factors involved makes it impossible to predict whether urban groundwater flooding will become an issue, but the topography of Sheffield makes it likely that if the combined effects of extra urban recharge and cessation of minewater pumping do cause rebound problems, they are likely to be very localised.

References

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, 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

BARRETT MH, HISCOCK KM, PEDLEY S, LERNER DN, TELLAM JH, FRENCH MJ. 1999. Marker species for identifying urban groundwater recharge sources: a review and case study in Nottingham, UK Water Research, Vol. 33, No. 14, 3083–3097

CRONIN AA, RUEEDI J, MORRIS B L. 2005. The effectiveness of selected microbial and chemical indicators to detect sewer elakage impacts on urban groundwater quality. Procs of 10th Int'l Conference on Urban Drainage, Copenhagen, Denmark 21-26 Aug 2005

DUMPLETON, S, AND GLOVER, B W. 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

EDEN, R A, STEVENSON, I P , EDWARDS W. 1957. Geology of the country around Sheffield. Geological Survey of England and Wales. HMSO, London

EISWIRTH M, HÖTZL H. 1994. Groundwater contamination by leaky sewer systems. In Water Down Under, National conference of Institution of Engineeers, Adelaide, Australia 111–114 pp, Nov.1994

FOSTER S S D, MORRIS B L, LAWRENCE A R.1993. Effects of urbanisation on groundwater recharge. In Procs of ICE International Conference on Groundwater Problems in Urban Areas, London, June 1993. Thomas Telford, London

HOWARD KWF.2001. Urban groundwater issues- an introduction. In: Current problems of hydrogeology in urban areas, urban agglomerates and industrial centres, Proceedings of NATO Advanced Science Workshop, Baku Azerbaijan, June 2001 NATO Science Series IV, Vol. 8, Kluwer Dordrecht

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.

KROTHE JN, GARCIA-FRESCA B, SHARP JM JR. 2002. Effects of urbanisation on groundwater systems. # 45 in Procs XXXII IAH and VI ALHSUD Congress on groundwater and human development. 21–25 October 2002. (Mar del Plata, Argentina: Univ National de Mar del Plata.)

LERNER DN, ISSAR SI., SIMMERS I. 1990. Recharge due to Urbanisation, from 'Groundwater Recharge, A guide to understandingand estimating natural recharge'. International Contributions to Hydrogeology Vol 8, IAH Publications Verlag Heinz Heise, Hannover

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

MORRIS, B L, NEUMANN I, CUNNINGHAM J E, HARGREAVES R L , RUEEDI J, CRONIN A A. 2005. Groundwater surcharging of sewers: example from Doncaster, England of a technique for identifying its extent. 10th International Conference on Urban Drainage, Copenhagen Denmark, 21-26 August 2005

MORRIS BL, LAWRENCE ARL, CHILTON PJ, ADAMS B, CALOW RC, KLINCK BA. 2003. Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for

Management. Early Warning and Assessment Report Series RS.03–3. United Nations Environment Programme, Nairobi, Kenya

OFFICE OF NAT STATISTICS. 2005 http://www.statistics.gov.uk/census2001/pyramids/pages/00cg.asp

POWELL, K.L., TAYLOR, R.G., CRONIN, A.A., BARRETT, M.H., PEDLEY, S., SELLWOOD, J., TROWSDALE, S., LERNER, D.N. 2003. Microbial contamination of two urban sandstone aquifers in the UK, *Water Research*, Vol. 37, No. 2, p339-352.

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

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

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

YANG, Y., D. N. LERNER, M. H. BARRETT, AND J. H. TELLAM. 1999. Quantification of groundwater recharge in the city of Nottingham, UK. Environmental Geology 38:183-198

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