

# Hydrogeology of the Peak District and its River Basin Management planning

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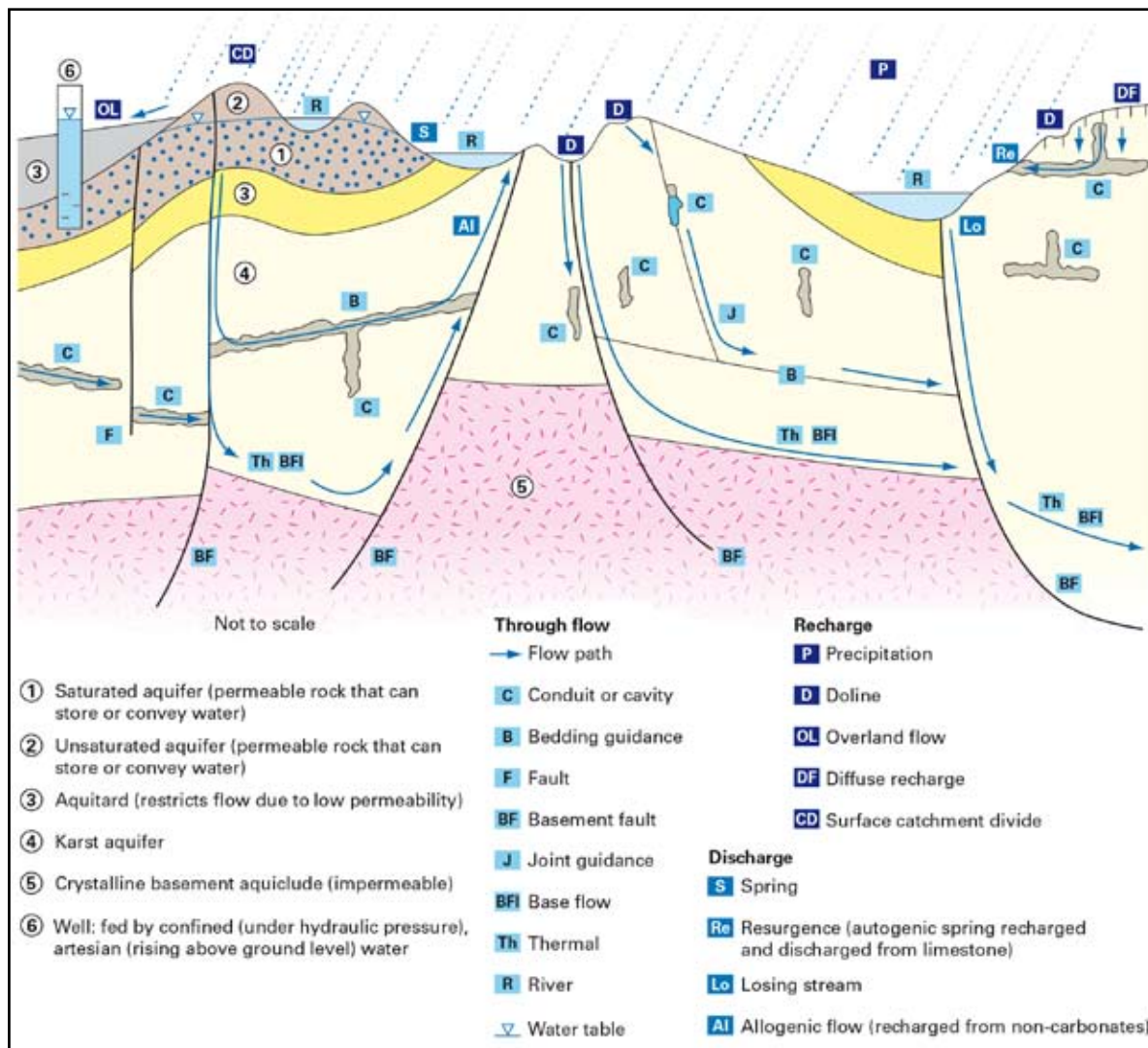
**Abstract.** The hydrogeology of the Peak District is reviewed in the context of River Basin Management planning prior to EU environmental policy being reviewed under Brexit. Relationships between bedrock aquifer outcrops and catchment boundaries are viewed in the context of safeguarding groundwater.

The Peak District encompasses a varied physiography, embracing the gritstone hills (the Dark Peak) of Saddleworth Moor, Bleaklow, Kinderscout, Stanage, Axe Edge and the Roaches (Fig. 2) and the karst landscapes of the White Peak.

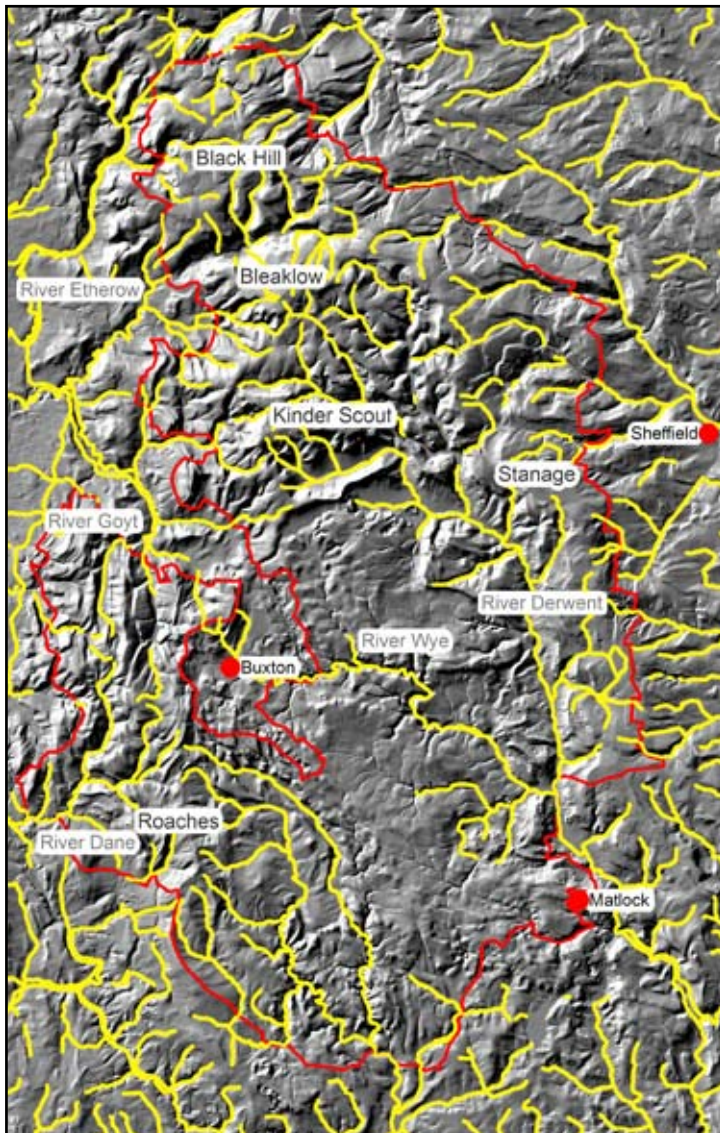
The area is largely drained by the southerly flowing upper Derwent and its tributaries the rivers Wye, Dove, Manifold and Churnet. Saddleworth Moor and parts of Bleaklow are drained by the westerly flowing River Etherow, whereas the western side of Kinderscout and the northern part of Axe Edge are drained by the southerly and westerly flowing River Goyt. Both the Goyt and the Etherow flow to the River Mersey. The southern area of Axe Edge drains to the River Dane, which is a tributary of the River Weaver.

## Bedrock geology

Geologically the Peak District is a dome, comprising a faulted series of basement half-grabens with the Peak Limestone Group forming a limestone inlier surrounded by a capping of the Bowland Shale Formation; this is overlain by the Millstone Grit Group with an on-lap of the Pennine Coal Measure Group along the eastern and western edges of the Peak District (Fig. 4). The hydrogeology of these units has been the subject of a legacy of research (Table 1). During late Carboniferous to Permian subsidence and burial, the limestone was subject to Mississippi-Valley-type mineralization due to expulsion of fluids from the sediment-filled basins adjacent to the carbonate platform. Mineralization is closely associated with the northeastern side of the



**Figure 1.** Main hydrological terminology related to the assessment of groundwater catchments (after draft by Henry Holbrook).



**Figure 2.** The Peak District and its surface drainage, with all rivers and artificial channels shown in yellow, and the Peak District National Park outlined in green (after OS data).

Derbyshire Dome and with faults that trend ENE-WSW and NNW-SSE. The richest mineral ore is developed immediately below the contact with the Namurian strata and beneath the lava horizons in the limestone, and can be traced for many kilometres along strike, but rarely extends more than about 30 m vertically (Nichol et al., 1970). The mineral deposits comprise fluorite, barite, calcite, sphalerite and galena, and occur in rakes, scrins, flats and pipes (Ford & Rieuwerts, 2000).

Groundwater contours constructed from water level data from boreholes, mineshafts, caves, springs and soughs (Downing et al, 1970), indicate an easterly hydraulic gradient from about 300 m OD in the northwestern part of the limestone outcrop near Buxton, reducing to below 120 m OD to the southeast. The groundwater units of the Peak District cross the surface water catchment divides. Empirical evidence (Simms, 2004) suggests that the climatic conditions prevailing in Britain during the Tertiary should have resulted in greater differential in the relief of the limestones and the siliciclastic rocks, due to

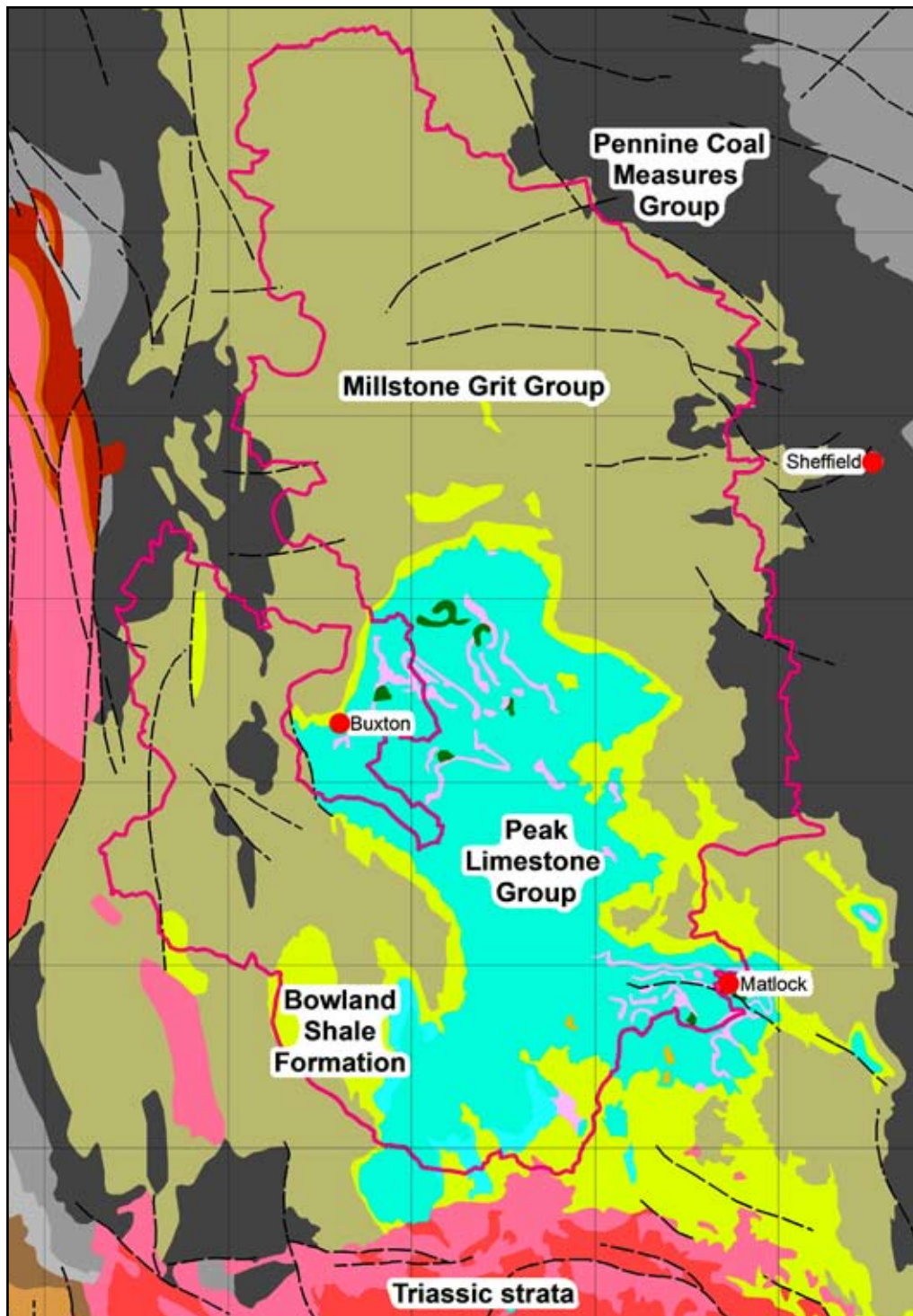
more continuous dissolution and surface lowering of the Peak District limestones. The siliciclastic Millstone Grit forms a horseshoe of ridges surrounding the limestone in the upper catchment of the Peak District tributaries of the River Derwent, albeit the topographical difference is not as great as might have been anticipated. In this respect, the River Derwent is typical of other major English rivers, such as the Thames (Bloomfield et al., 2011) and Severn, with more resistant rocks dominating in the upper catchment interfluvies and weaker, less permeable sediments in the downstream reaches. This distribution of sediments, in conjunction with strong bedding guidance of groundwater flow, is reflected in differences between the boundaries of the ground and surface water catchments, such that the hydro-lithological boundaries are independent of surface water boundaries. Thirteen groundwater systems largely focused on river or dry valley systems are identified within the White Peak (Beck & Gill, 1991; Downing et al., 1970; Edmunds, 1971).



**Figure 3.** Wiers on the River Lathkill.

### Structural influences on hydrogeology

Comparison of the findings of the Woo Dale Borehole (Cope, 1973) and the Eyam Borehole (Dunham, 1973; Strank, 1985) has led to the interpretation that the structural setting of the Peak District comprises a series of half grabens in the basement (Grayson & Oldham, 1987; Smith & Smith, 1989; Gawthorpe et al., 1989). The limited available data indicate that the basement elevation varies by up to 1500 m, which is considerably greater than that of the surface topography. Support for this comes from geophysical studies, including gravity and seismic data (Cornwell & Walker, 1989; Lee, 1986; Maroof, 1976; Maguire, 1987; Smith & Smith, 1989; Pharaoh et al., 2011). The half grabens formed a structural high, against which a southeasterly dipping carbonate ramp formed. Syn-depositional movement of the faults is evident (Aitkenhead et al., 2002). For example, the intra-shelf Ashford Basin developed at the beginning of the Brigantian due to reactivation of the Bakewell Fault. Subsequently, faults facilitated the development of deep basins (or gulfs >500 m deep) as tensional tectonics developed. Consequently, a large



**Figure 4.** Bedrock geology of the southern Pennines, with the Peak District National Park is outlined in pink (after British Geological Survey).

thickness of the Millstone Grit is preserved around the carbonate platform. The faults associated with this tectonic regime were mainly aligned NW-SE and are represented by the Bakewell and Cronkston-Bonsall faults. Later faulting was along a more northerly alignment, and is better represented in the younger rocks. Subsequent inversion and mineralization, associated with over-pressurization and hydraulic fracturing of the carbonate platform, gave rise to ENE-WSW-trending mineral veins that are particularly evident in the Monsal Dale and Eyam Limestones. Further folding and fault reactivation occurred in the compressional Variscan tectonics.

There is evidence of strong structural guidance of the hydrogeology. A number of faults, which have been enduringly active, are suspected to form significant hydrogeological boundaries, for example the ingress of thermal water on Townhead vein in Magpie Sough. Spring lines are commonly associated with the faulted juxtaposition of sandstones and mudstones. In the Castleton, Bradwell and Stoney Middleton catchments the role of mineral veins in groundwater drainage has been clearly demonstrated by various dye tracing tests. Evidence for the focusing of groundwater on synclinal structures is typified in the close association of the Lathkill Cave system with its synclinal setting in the

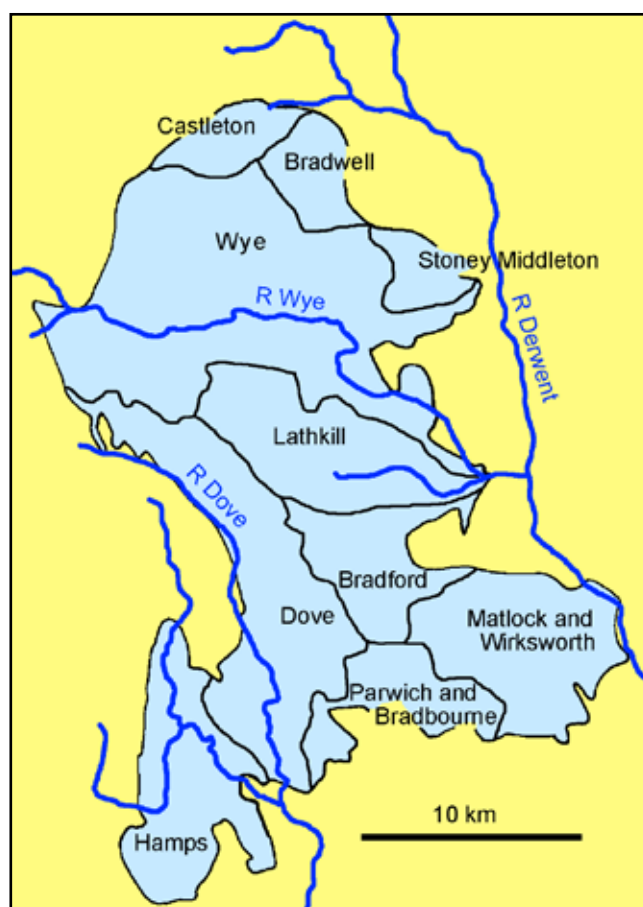
Strata	Hydrogeological characteristics	References
Pennine Coal Measures Group	Cyclic sequences of coal, seat earth, ganister or fireclay, sandstone or siltstone, shale and mudstone. Cycles are not always fully developed. The principal water bearing members are the sandstones, with well-developed jointing that dominates the beds' hydrogeology. Yields reach 960 m <sup>3</sup> /d at outcrop. Most yields range between about 50 and 650 m <sup>3</sup> /d. Specific capacity values range from 1.5 to 56 m <sup>3</sup> /d/m. The water is commonly hard with calcium carbonate, giving way to sulphate waters with depth. Chloride concentrations are typically low.	Downing et al, 1970 Jones et al, 2000 Cheney, 2007
Millstone Grit Group	Six major grits: Rough Rock, Middle Grit, Kinderscout Grit, Middleton Grit, Silsden Moor and Skipton Moor grits. Sandstones, shales and mudstones with thin coals; up to 900m thick in which fissure flow can be important. Coarsening upward cycles result in multi-layered aquifers that are variably cemented. Porosities range from 6 to 23% . Flow in the Millstone Grit aquifers tends to decrease with depth due to better preservation of cements. Fracture systems guide water flow at depth. Average yields range from 432 to 864 m <sup>3</sup> /d, but up to 4320 m <sup>3</sup> /d has been obtained. Numerous springs occur at the boundaries between the sandstone and the shales or mudstones. Water quality is described as salt, but of good quality. Iron concentrations locally exceed 0.5 mg/l, which may impart a taste. Annual groundwater level fluctuations (< 5m) are lower than in the Peak Limestone Group.	Downing et al, 1970 Jones et al, 2000 Cheney, 2007
Bowland Shale Formation	Shale with very fine-grained clay particles in thin laminae and interspersed with organic matter, were compacted at depth, when pore water was expelled. With low permeability, the shales form barriers (aquicludes or aquitards) to fluid migration.	Andrews, 2013
Peak Limestone Group	Fissured, karstic limestones with transmissivity values ranging from 0.1 to 770 m <sup>2</sup> /d with a geometric mean of 10 m <sup>2</sup> /d. The largest natural springs in the region have discharges up to 9000 m <sup>3</sup> /d. Provides a significant component of the river base flow. Large seasonal water level fluctuations (10s of metres), particularly beneath the plateau. Formational differences cause the hydrogeological properties to vary, with some formations dominated by bedding related fractures and others by joint-related fractures. These differences are also reflected in the water chemistry. Groundwaters are largely a calcium/magnesium bicarbonate type. Thermal springs on the eastern and western side of the inlier tend to be more mineralised, and can have a higher fluoride content.	Abesser, 2006 Allen et al, 1997 Bamber, 1951 Banks et al, 2009 Bertenshaw, 1981 Cheney, 2007 Downing et al, 1970 Edmunds, 1971 Gunn et al, 2006

**Table 1.** Hydrogeological properties of the main rock units within the Peak District.

Lathkill subcatchment. Within the Wye sub-catchment (Fig. 5) there is extensive structural guidance of the cave and conduit morphology and of the distribution of groundwater resurgences and their recharge sites, including dolines, though there are contrasts in detail between the limestone units (Banks et al., 2009). However, despite the strong structural guidance, dye tracing has shown that spring catchments in the limestone cannot be solely defined based on structure.

The distribution of thermal springs around the perimeter of the limestone inlier provides further evidence of structural influence on groundwater (Stephens, 1929; Gunn et al., 2006; Brassington, 2007). Most of the thermal springs are associated with anticlines and fault zones, though later sedimentation masks the fault influence at some sites (Fig. 7). Further evidence of structural guidance of karstic flow comes from a 'pressure ridge' associated with an area of less saline water at the easterly limit of the Millstone Grit (Downing et al., 1987) in pressure data from drill-stem tests within those rocks. The rise of the groundwater from the Carboniferous Limestone coincides with an area of anomalous heat flow in the area of a faulted, north-south-trending, anticline at Eakring. This provides evidence of limestone groundwater underflow beneath the River Derwent.

**Figure 5.** The ten groundwater sub-basins of the Peak District that fall within the White Peak (after Beck and Gill, 1991).



## Superficial domains and hydrogeology

No assessment of the hydrogeology is complete without consideration of the superficial deposits, which are potentially influential in terms of focusing recharge, providing aquifer protection and contributing to catchment base flow. The hydrogeology of superficial deposits can be conceptualised in terms of domains for assessing potential recharge or aquifer vulnerability (McMillan et al., 2000). However, superficial deposits are relatively sparse in the Peak District. Tills and glaciofluvial sand and gravel are mainly in areas underlain by cohesive strata (Bowland Shale Formation and the Pennine Coal Measures Group), and, reflecting this, they are thickest northwest of the Peak District. Alluvium, and river terraces are focused on the valley floors and lower valley sides, whereas head and scree are associated with steeper slopes. In contrast, the limestone is largely devoid of Quaternary surface deposits, largely due to their loss into the fissured and cavernous karst. The Millstone Grit Group is also largely devoid of superficial deposits, except where upland peats cap the higher ground, which suggests that the distribution of till is more closely linked to the ice sheet hydrology. Vulnerability of groundwater to contaminants (either diffuse nutrients or point sources) is greater within the principal aquifers where there is no protection by superficial deposits.

## Anthropogenic impacts

Exploitation of the lead-zinc mineralization occurred in multiple phases, probably starting during the Roman period and locally continuing until the 1900s; the phasing was influenced by the price of lead and by technological improvements in dewatering the mine workings. By the 1600s most of the lead had been worked down to the local water table, and dewatering became necessary. Initially this was achieved using rag and chain pumps, and by directing underground water into natural cavities. Sough driving from the valleys, to de-water mine workings through adits

(Fig. 8), appears to date back to the 1640s (Rieuwerts, 1980). This has impacted on both groundwater levels and groundwater chemistry. More specifically, the lowering of groundwater levels by driving soughs to drain lead-zinc-fluorite-baryte mines has contributed to steepening of an easterly hydraulic gradient across the Peak District. In areas of coal mining, collapse subsequent to mineral exploitation has resulted in the dislocation of overlying strata resulting in zones of higher transmissivity throughout the sequence, which may be several hundred metres thick.

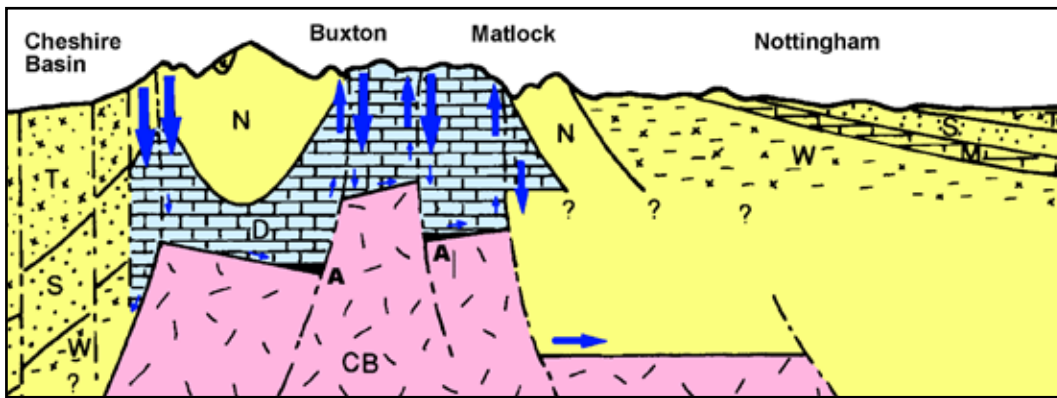
A detailed assessment of the flow hydrograph for the Meerbrook Sough (maximum discharge of 85,000 m<sup>3</sup>/d; Allen et al., 1997) was carried out to determine the large-scale hydraulic behaviour of the artificially drained aquifer (Shepley, 2007). Available hydrogeological and hydrological data was utilized to construct a conceptual model that was in turn used to carry out numerical modelling. Analysis indicated that, at a large scale, the limestone aquifer behaves 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.

## River Basin Management Planning

In 1998, EU Directive 2000/60/EC set out to establish a community framework for the protection of surface and underground waters across the European Union. The aim was to formulate a common approach with common objectives, principles and basic measures designed to prevent any further deterioration of the water system, and to protect and enhance the quality and



*Figure 6. The River Dove flowing through the section of Dovedale that is deeply entrenched into the Peak Limestone, with gorse-covered screes along its flanks.*



**Figure 7.** Model of the regional hydrogeology.  
*D = Peak Limestone;*  
*T = Triassic mudstones;*  
*S = Sherwood Sandstone;*  
*M = Magnesian Limestone;*  
*W = Westphalian;*  
*N = Namurian;*  
*CB = Caledonian basement;*  
*A = possible locations of inter-block anhydrite.*  
*Arrows = groundwater flow.*  
*Vertical exaggeration = x20.*

quantity of aquatic eco-systems and water-dependent terrestrial systems. The underpinning values are that good-quality water is essential for wildlife, agriculture and industry to thrive. The common approach was intended to ensure sustainability of water use into the next century, by requiring that all water reaches good status, in terms of quantity and chemical and ecological quality. By introducing the “polluter pays” principle, provision was made for facilitating the objectives of the directive.

For each river basin, member states were required to coordinate their actions, integrate all the existing water policy measures, and report the results in river basin management plans developed with full public participation. In parallel with this, the European Commission developed a list of priority substances, including many pesticides, to be targeted with the aim of improving water quality. Conceptually this aligned very well with the Environmental Protection Act, 1990 and the Integrated Pollution Prevention and Control Directive (Council Directive 96/61/EC). The framework allowed for integration with the Government framework for 25-year environmental planning. In response to this and under the guidance of the European Environment Agency, River Basin Catchment Management plans (RBCMPs) were prepared for the eleven river basin districts in England and Wales. The RBCMPs cover entire river systems, including rivers, lakes, groundwater, estuarine and coastal water bodies. Following public consultation, they were first published in 2009 and updated in 2015. The updated RBCMPs set out how waters will improve over the next six years from around £3 billion investment. Whereas the Environment Agency (EA) manage the seven River Basin Districts (RBDs) in England; Natural Resources Wales (NRW) manage the Western Wales RBD; NRW and the EA jointly manage the Dee and Severn RBDs and the Scottish Environment Protection Agency (SEPA) and the EA jointly manage the Solway Tweed RBD. The Peak District spans the North West and Humber River Basins.

River Basin Management planning was considered a novel approach because it required an integration of hydrogeology and hydrology within the catchment context. How different was this? Prior to the Water Framework Directive, groundwater and surface waters

Management - unit	Area/unit	G.U. index	Aquifer classification
Coal Measures	Alfreton	D.2.1	Secondary A
Millstone Grit	Belper	D.2.2	Secondary A
	Hathersage	D.2.3	
	Barbrook	D.2.4	
Bowland Shale			Unproductive
Carboniferous Limestone	Hollinsclough	D. 3.2	Principal
	Alstonefield	D.3.3	
	Matlock	D.3.4	
	Buxton	D.3.5	

**Table 2.** Classification and hydrogeological characterisation of the principal strata of the Midlands Region within the Peak District Derwent-Trent catchment. Secondary aquifers comprise permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers; these were formerly classified as minor aquifers. G.U. = groundwater unit.

were considered separately and were managed in a regional context. The regional context was focused on larger areas but subdivided into smaller areas or sub-catchments. For example, in the Environment Agency Midlands Region Review of Groundwater Abstractions subdivisions were made based on geological units (Table 2), but were interpreted in the catchment context in order to facilitate water resource calculations (Downing et al., 1970), while surface water divides guided the administrative divisions. This situation was probably more complex, but developed as a framework of manageable units.

### Implications for the Peak District

A number of linked philosophical points come out of the summary of the hydrogeology of the Peak District.

Whereas the River Basin Management planning framework has focused on the regional catchment scale, much of the analysis and presentation of data has been focused on sub-catchments and local groundwater flow. However, groundwater basins can be considered as functioning within local, intermediate and regional boundaries, each respectively extending to increasing depth (Tóth, 1963). The larger the topographic relief the greater the significance of the local system, while



**Figure 8.** Monitoring the discharge from Magpie Sough.

at the regional flow scale bedrock guidance becomes increasingly significant. This reflects in the structural approach to the deep karst flow (Fig. 7) and questions whether there is a requirement to ensure that the regional-scale hydrogeological context does not get overlooked through the RBCM reporting approach. Further to this, consideration of basement topography is significant to the understanding of regional flow systems.

The Peak Limestone Group is important both as a potable resource and base flow contributor to the river systems. For example the base discharge to the River Wye at Ashford was calculated as  $0.0086 \text{ m}^3/\text{s}/\text{km}^2$ , and  $0.0034 \text{ m}^3/\text{s}/\text{km}^2$  was calculated for the River Lathkill at the Environment Agency monitoring point [SK198661]. Karst catchments are particularly susceptible to contamination (Zwahlen et al., 2003) and function differently from more porous, uniform strata. Unless the base flow for the system can be defined, they cannot be modelled as porous media. Instead, there is a reliance on water tracing and water balance approaches requiring catchment-focused consideration of recharge, through-flow, storage and discharge. Both of these approaches become less tangible with karst systems that have long flow paths. With respect to the Peak District, whereas the Millstone Grit Group can be better modelled as a porous media, improved understanding of the hydrogeological connectivity between the Peak Limestone Group and the Millstone Grit Group requires that the water balance approach be extended, in conjunction with the interpretation of pumping tests as and when they become available.

Safeguarding is an important component of the RBCMPs, which set out how organisations and communities can work together to improve the water environment using catchment-based approaches. They embrace new environmental standards and revised water-body classifications, with a focus on ecosystem services and environmental change (climate and anthropogenic) being recognised. RBCMPs form a platform for groundwater accounting with beneficiaries being identified to pay for ecosystem services, and

allow local communities to find more cost-effective ways to take action to further improve our water environment. Such an approach promotes catchment-scale engagement with farmers, such as Catchment Sensitive Farming, to make significant reductions in some pollutants through farmers' engagement in workshops, capital grants and one-to-one advice. These schemes also assist with improved targeting of supplementary measures and facilitate better practice in soil and nutrient management. In the context of the Peak District, it is particularly important to consider groundwater safeguarding in catchment boundary areas, particularly where groundwater units are exposed at the upstream margins of catchment boundaries.

The River Basin Management approach is iterative and progressive, providing a platform for future standardisation and improvements in water quality, and the National Environment Programme requires conceptual understanding and baseline data for all groundwater resources. The approach builds on underpinning research and is valuable in delivering high-quality and national-scale reporting, and to achieve this, identifying future research directions. The overview of the Peak District hydrogeology indicates that in the context of the Peak District this should include three components:

1. Ensuring that the catchment focus of River Basin Catchment Management planning does not ignore the significance of groundwater recharge of more resistant aquifers at the catchment boundaries. Such an approach emphasises the importance of bedrock influences on the functioning of catchments (Bloomfield et al., 2011; Devito et al., 2005). More specifically, permeable bedrock strongly influences regional flow systems and suppresses the importance of topography in controlling surface flow, whereas impermeable bedrock tends to produce more local flow systems where topographic features exert more influence on surface flows.
2. Developing the conceptual understanding and management of the bedrock geology that extends across the North West and Humber River Basin Management boundaries. More specifically, in the context of the Buxton area, further understanding of the local and regional structural influences on groundwater flow is critical. This would be of particular value for further defining the source protection zone for the Buxton thermal source. A focus on the structural context and basement geology may also assist in the interpretation of deep groundwater flow, notably where deep karst differ from those occurring at the surface. More specifically the context (Fig. 7) highlights the presence of intra-graben salts that may be involved, through the common ion effect, in the dissolution of dolomitised limestone.
3. A more detailed national focus on the distribution of aquifer head, as well as resource volumes. There are new technologies that could facilitate this, for example improved sensor ability and the use of satellite data such as InSAR (Novellino et al., 2017) to assess the impact

of changes in the head distribution due to climate or environmental change; these changes include post-mine-dewatering rebound. This has implications for predictive understanding of potential water quality changes.

It is the view of this author that cross-catchment groundwater studies are particularly important in establishing approaches to resilience in the context of climate and environmental change.

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