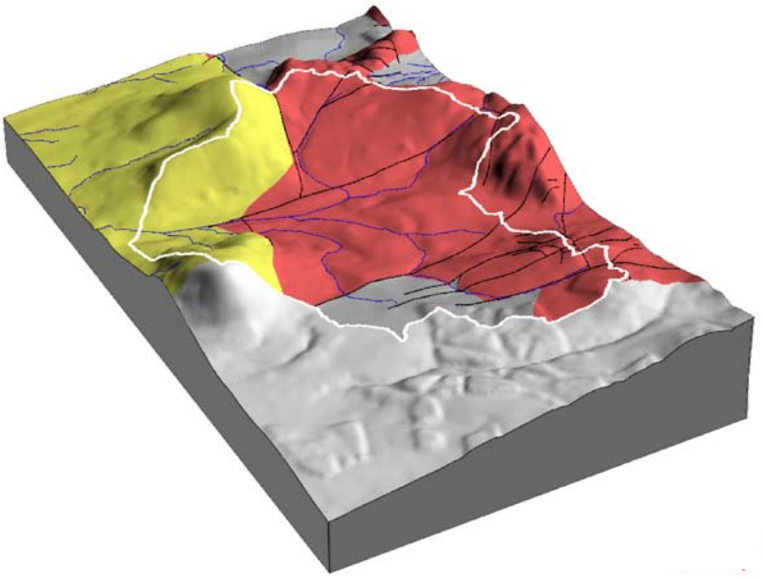
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Preliminary review of the geology and hydrogeology of the Eden DTC sub-catchments

Groundwater Science Programme

Open Report OR/10/063



BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

OPEN REPORT OR/10/063

Preliminary review of the geology and hydrogeology of the Eden DTC sub-catchments

D J Allen, A J Newell and A S Butcher

Keywords

Geology, hydrogeology, Eden Valley.

Front cover

Bedrock geology of the Dacre Beck catchment. River network data from CEH, © NERC. © Crown copyright. All rights reserved. NEXTMap Britain elevation data from Intermap Technologies.

Bibliographical reference

ALLEN D J, NEWELL A J AND BUTCHER A S. 2010. Preliminary review of the geology and hydrogeology of the Eden DTC sub-catchments. *British Geological Survey Open Report*, OR/10/063. 45pp.

Keyworth, Nottingham British Geological Survey 2010

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

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

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

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 basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

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

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

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

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

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

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Acknowledgements

The authors would like to thank Dr Ben Surridge, Lancaster University, for a number of valuable discussions and for providing the catchment boundaries used in this report.

Contents

FIGURES

TABLES

Summary

This report presents a preliminary geological and hydrogeological overview of three sub-catchments, the Pow Beck, the Morland Beck and the Dacre Beck, within the Eden Catchment in north-west England. These catchments have been selected for study by the Eden component of the Defra-funded Demonstration Test Catchment (DTC) programme. This programme involves studies in three large catchments, the Hampshire Avon, the Wensum and the Eden, in order to test the hypothesis that it is possible to reduce, cost effectively, the impact of agricultural diffuse pollution on ecological function, while maintaining food security, through the implementation of multiple on-farm measures. In each of the main catchments a number of sub-catchments are being instrumented and monitored to assess the effects of on-farm measures.

This report is based on work that was carried out as part of a BGS study, funded by NERC. The BGS study is separate from the DTC programme, but is intended to complement it. The study involves a preliminary assessment of the likely nature of groundwater flowpaths within the Eden DTC sub-catchments, and in particular aims to investigate the possibility that groundwater flow routes may occur over a range of timescales as a result of the complexity of the superficial cover in the catchments.

This report results from the first phase of the BGS study, in which currently available geological and hydrogeological data for the catchments were examined. The report is intended to provide an initial summary of available geological and hydrogeological information for the sub-catchments and to form the basis for subsequent hydrogeochemical and other field investigations.

The first part of the report provides a brief geological and hydrogeological overview of the Eden Catchment. Subsequent sections then review each of the three sub-catchments which have been chosen by the Eden DTC consortium for future monitoring and investigation. For each sub-catchment the geology is presented, followed by a review of the catchment hydrogeology, including an assessment of the relative hydrogeological importance of the different rock units.

The conclusion of this work is that the hydrogeology of all three of the sub-catchments examined is likely to be dominated by the characteristics of the superficial deposits. Major aquifers are only significantly present in one catchment, the Pow, and here they do not appear to support flow in the river. Any bedrock aquifers in the Morland are likely to be localised, and much of the Dacre is underlain by poorly-permeable material. The superficial deposits in the sub-catchments are likely to be lithologically variable, particularly in the Morland and Dacre, and perched near-surface local aquifers may be present.

On the basis of this study it is, therefore, concluded that it is quite possible that the baseflow component of the streams in all three catchments may originate from groundwaters flowing over a range of timescales. Given the likely hydrogeological dominance of the superficial deposits, a significant proportion of groundwater recharge may result in relatively rapid shallow groundwater flows to the streams. Changes to the concentrations of pollutants carried by these shallow groundwaters as a result of farm measures may potentially be detectable in the stream outflows within the lifetime of the DTC programme. The proportion of groundwater in the Pow Beck, Morland Beck and Dacre Beck is unknown; however groundwater baseflow is significant in many streams elsewhere in the Eden, and is likely to dominate summer stream flows.

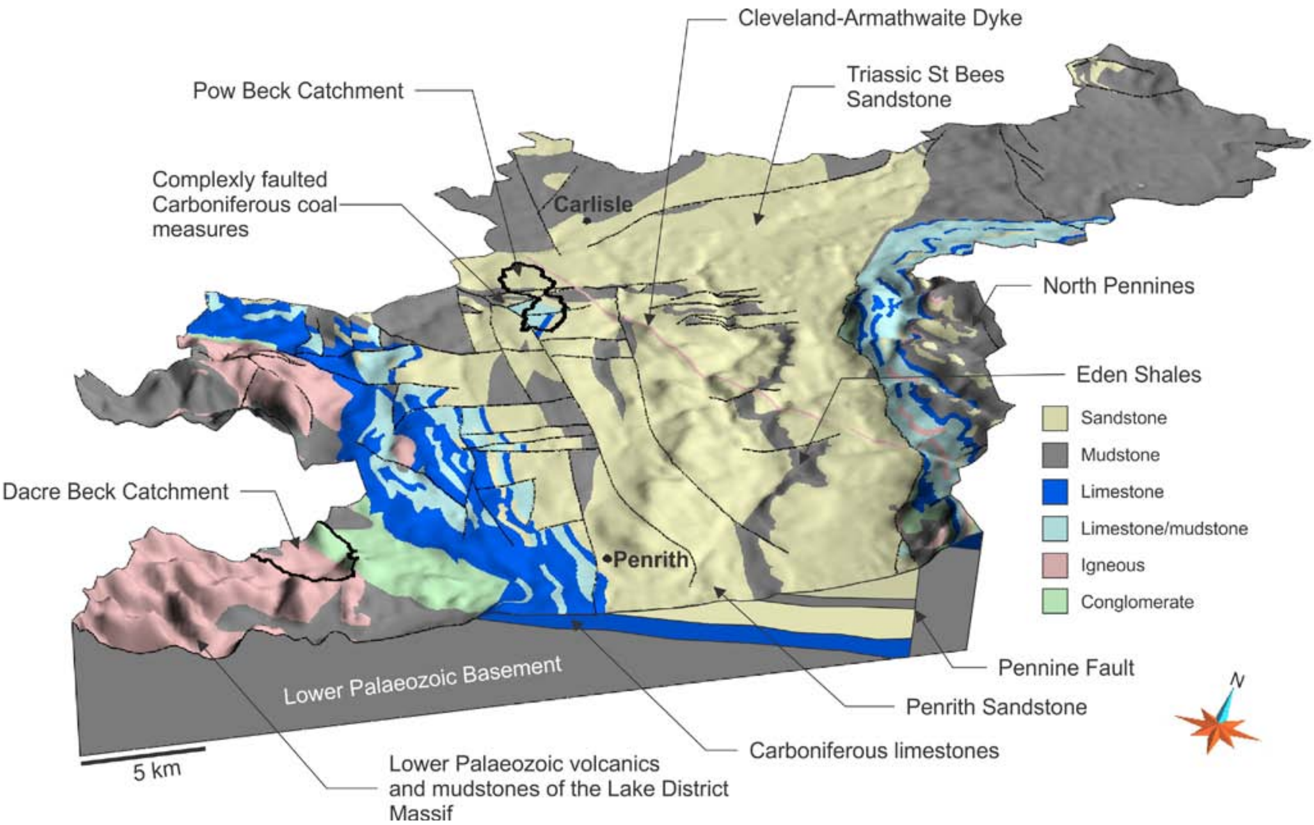
In view of the above, it is suggested that further work is carried out to investigate the nature of potential shallow rapid groundwater flow systems, and their likely importance to surface streamflows. Work to be undertaken in the next phase of the current study will help to address issues of groundwater timescale.

All the conclusions of this report are based on a desk study only, and without field investigations are very speculative, however they do provide a basis for further work, some of which will be started in the second phase of the BGS study.

1 Introduction

1.1 GEOLOGY AND GENERAL GEOLOGICAL SETTING OF THE VALE OF EDEN

The Vale of Eden lies between the Lake District and North Pennines and is a fault-bounded basin about 50 km long and 5-15 km wide that contains Permian and Triassic strata which dip gently to the north-east (Figure 1.1). The Pennine Fault and associated North Pennine escarpment form the eastern boundary of what is probably a half-graben, throwing Permo-Triassic rocks against Carboniferous or Lower Palaeozoic rocks (Chadwick et al. 1995). To the west, Permo-Triassic strata wedge out against Carboniferous limestone and overlying Coal Measures which crop in a 5-15 km wide belt around the margins of the Lake District (Figure 1.1). The Vale of Eden basin opens northwards into the NW-SE trending Solway Basin (Chadwick et al. 1995). The two basins are separated by the major Maryport-Stublick Fault Zone which downthrows to the north and crosses the Pow Beck Catchment to the south of Carlisle (Figure 1.2).



Geological features, BGS, © NERC. NEXTMap Britain elevation data from Intermap Technologies.

Figure 1.1 Perspective view showing bedrock geology (classified into rock type) of the northern part of the Vale of Eden.
Generalised NW-SE cross-section shows the structure of the Vale of Eden half graben (structure and stratigraphy of Lower Palaeozoic basement is omitted). Vertical scale is exaggerated by a factor of three.

Detailed accounts of the lithostratigraphy and structure of rocks within the Eden catchment can be found in the BGS Regional Geology of Northern England (Stone et al. 2010) and associated BGS Memoirs (e.g. Authurton and Wadge 1981; Chadwick et al. 1995). The following account seeks only to summarise the main features of the geology of the Eden Catchment.

1.1.1 Ordovician and Silurian

Ordovician and Silurian strata form the uplands of the Lake District and also occur as the Cross Fell Inlier adjacent to the Pennine Fault in the SE part of the catchment (Figure 1.2). The rocks are highly faulted and fractured and include the turbiditic sandstones and shales of the Skiddaw Group, the lavas and volcaniclastic rocks of the Borrowdale and Eycott volcanic groups and the calcareous mudstones and siliciclastics of the Windermere Supergroup.

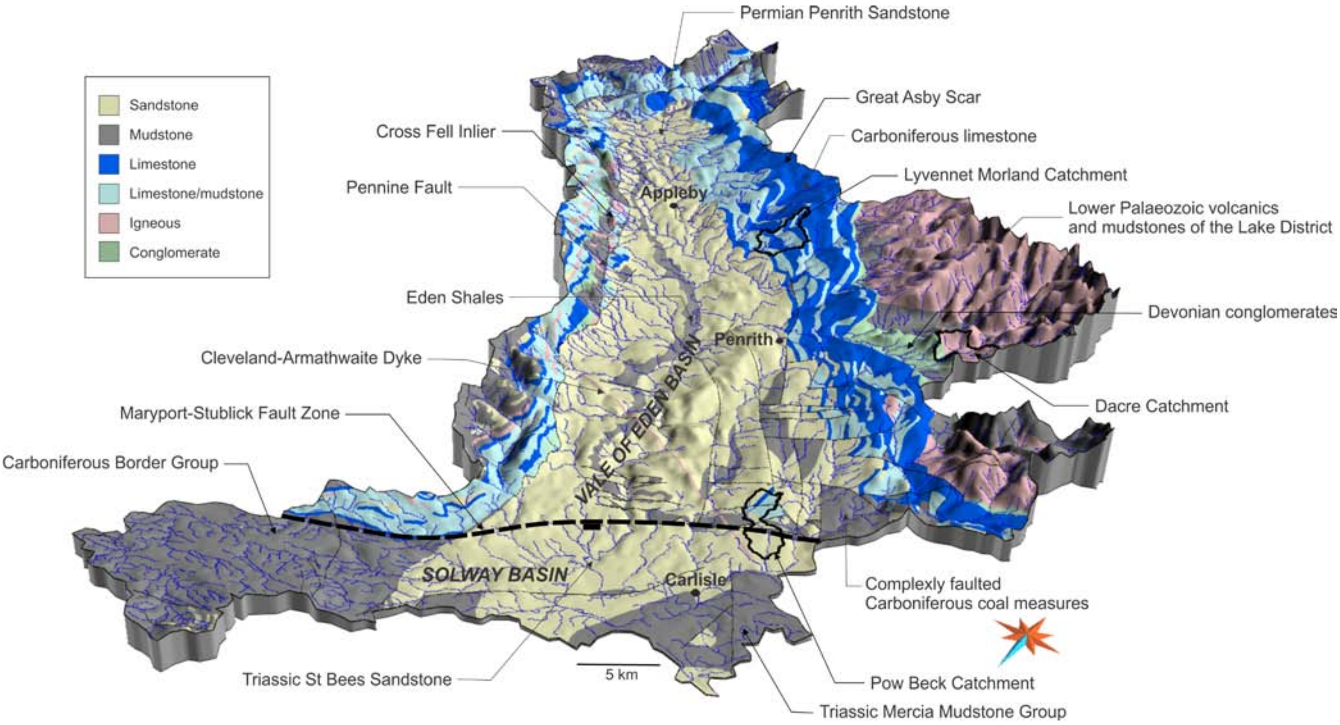


Figure 1.2 Perspective view from the NE showing the bedrock geology (classified into generalised rock type) over the full extent of the Eden Catchment.
Permian and Triassic sandstones form the central core of the catchment which is fringed by Carboniferous limestone and coal measures and extends westward into part of the Lake District volcanic massif. Approximate foreground scale shown, vertical scale is exaggerated by a factor of three.

1.1.2 Devonian

Devonian rocks are mostly represented by the Mell Fell Conglomerate Formation which forms the conical hills of Great and Little Mell Fells which partially enclose the Dacre Beck Catchment (Figure 1.2). The polygenetic, red-bed conglomerate contains clasts mostly derived from the adjacent Borrowdale Volcanic Group and the Windernere Supergroup of the Lake District. They may act as localised minor aquifers dominated by fissure flow.

1.1.3 Carboniferous

The Carboniferous is a layered succession of limestones, sandstones, mudstones and coals which fringes much of the Eden Catchment. In the Vale of Eden, thickly-bedded limestones of the Ravenstone and Great Scar Limestone groups occur at the base of the Carboniferous succession where they create the elevated, karstic watershed of Great Asby Scar in the south-west of the catchment (Fig. 1.2). These thick basal limestones pass progressively upwards into thin limestones which are cyclically interbedded with sandstones, mudstones and thin coals of the Yoredale Group. Between Penrith and the Maryport-Stublick Fault, rectilinear blocks of overlying Pennine Coal Meaures Group comprising sandstones, mudstones and thin coals are complexly faulted against rocks of the Yoredale Group. In the Solway Basin, to the north of the Maryport-Stublick Fault, Carboniferous limestones are underlain by thick siliciclastic-dominated deposits of the Border Group which occur in the extreme north-eastern part of the Eden Catchment (Figure 1.2).

Carboniferous limestones are recharged at outcrop or through permeable superficial deposits. Recharge estimates by Wadge (1966) are 420mm/y for outcrop and 95mm/y where covered. In the Vale of Eden the lower Permian, Brockram and Eden/ St Bees Shales can confine the Carboniferous rocks but this is complicated by faulting. Storage and permeability rely almost entirely on fissure size, extent and degree of interconnection. Karstic conditions can be encountered.

Upper Carboniferous minor aquifers are complex, predominantly limited confined sandstones which may be complicated where mine-workings are present.

1.1.4 Penrith Sandstone Formation

The early-Permian Penrith Sandstone Formation was deposited in a structurally-controlled, intermontane basin that was broadly coincident with the present Vale of Eden. The formation tends to thicken into depressions on the underlying, late Carboniferous to earliest Permian land surface. A ‘saddle’, separated this basin from the Solway Basin to the north and north-west. Gravity estimates indicate that the formation is locally about 900 m thick in the centre of the basin (Bott 1974). The sandstone is largely aeolian in origin. Towards the margins of the basin these pass laterally into water-lain, alluvial fan sandstones with lenses of breccia (Macchi 1991; Holliday 1993). Breccia (known locally as brockram) becomes more dominant southwards.

The Penrith Sandstone is red-brown to brick red in colour, consisting of well-rounded and well-sorted, medium to coarse grains. Less well-sorted, fine to coarse-grained sandstone beds with thin mudstone intercalations are common at some levels and indicate episodes of fluvial deposition; these occur mainly near the top of the sequence and at the margins of the basins. Brockram lenses, present within the sandstone towards the basin margin, consist largely of angular fragments of dolomitised limestone in a strongly cemented calcareous sandstone matrix.

In the northern part of the basin, parts of the top 100 m or so of the Penrith Sandstone Formation have been secondarily cemented by silica, producing quartz overgrowths with well-developed crystal faces. In places these overgrowths fill up to 70% of pore space. The extent of silicification is reflected in the local geomorphology on the formation outcrop: where the silica cement is sparse the outcrop has low relief and is commonly drift covered, but where the cement is abundant the relief is strong with prominent scarps and dip slopes. These siliceous sandstones are very indurated and poorly permeable, and have been used locally as a building stone. They typically occur in layers up to 10 m thick, separated by less well-cemented sandstone. Beneath this silicified zone, the Penrith Sandstone Formation is only moderately cemented and in parts completely uncemented (Ingram 1978), forming some of the most permeable strata of the Permo-Triassic sandstones of the Vale of Eden.

1.1.5 Eden Shale Formation

The formation is broadly equivalent to the St Bees Shale Formation of West Cumbria and the Solway Basin. It consists mainly of mudstone and siltstone; sandstone, breccia and conglomerate intercalations are subordinate, though they increase in abundance towards the south of the basin. Gypsum and anhydrite are present as beds, scattered nodules, cements and gypsum veins. These evaporites have been dissolved in places and are likely to be responsible for high groundwater salinities in the sandstone aquifers above and below.

1.1.6 St Bees Sandstone Formation

This formation conformably overlies the Eden Shale Formation and is very similar in depositional environment and lithology to its equivalent in the Solway Basin. The outcrop of the St Bees Sandstone is five kilometres wide and occupies the axial part of the Vale of Eden syncline. It consists mainly of very fine to fine-grained, indurated sandstone. Mudstone beds are generally subordinate, though increase in abundance towards the boundary with the underlying Eden Shale Formation.

1.1.7 Mercia Mudstone

The Mercia Mudstone Group is largely restricted to the Solway Basin north-west of Carlisle. All strata are assigned to the Stanwix Shales Formation, typically comprising grey-green mudstones with minor sands and halite.

1.1.8 Cleveland-Armathwaite Dyke

The Cleveland-Armathwaite Dyke is a major Tertiary vertical igneous intrusion which cuts SE across the Vale of Eden from Dalston, near Carlisle toward Renwick [NY 60 43] (Figure 1.2). The dyke is up to 30 m wide and has a significant influence on catchment topography, forming a chain of low linear hills, and a natural weir on the River Eden near Armathwaite [NY 50 45]. The dyke is likely to have an impact on groundwater movement.

1.1.9 Superficial Deposits

In the Eden Catchment more than 75% of the bedrock geology is covered by Quaternary Superficial Deposits (Figure 1.3). Only upland areas such as the Lake District and the escarpment of the Northern Pennines have extensive areas of exposed bedrock.

The stratigraphy of the Quaternary deposits is complex. Interdigitations of sand, gravel, silt and clay may each develop their own piezometric level, resulting in complex perched water tables above the bedrock formations.

Glacial Till as low-relief sheets or moulded into hummocky drumlin fields dominates the Quaternary cover. Along the River Eden extensive glacial outwash deposits of sand and gravel are recorded, above the level of the Holocene terraces and alluvium. Large peat-filled basins are also present in upland areas around the fringes of the catchment (Figure 1.3).

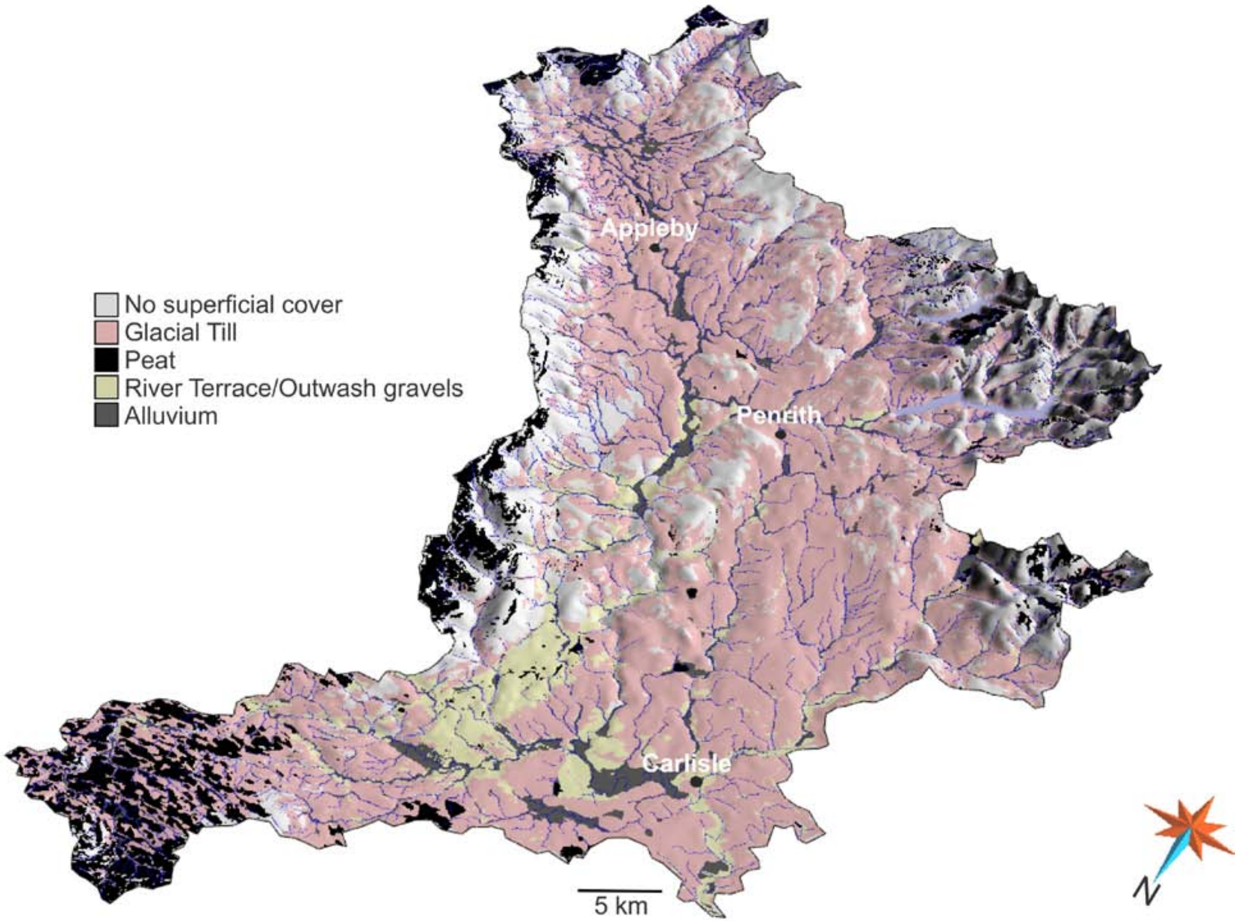


Figure 1.3 Perspective view looking south-east showing the extensive superficial cover of the Eden Catchment. Approximate foreground scale shown. Vertical scale is exaggerated by a factor of three.

CHARACTERISTICS OF MAIN SUPERFICIAL DEPOSITS

Till

The most extensive deposit in the catchment, borehole logs and sections reveal that Glacial Till is typically a red-brown, stiff, silty sandy clay to a friable clayey sand with pockets and lenses of medium and fine sand and gravel and cobble grade clasts, typically of limestone, Permo-Triassic sandstone and volcanic dolerite. Sand bodies within the Till may exceed 5-6m in thickness, and laminated clays and silts may also be present within the Till, perhaps indicating a complex history of Till emplacement within the Eden valley. In the upper Eden valley, much of the Till is formed into high mounds with a preferred long axis and is often described as 'drumlinoid'.

Glacio-fluvial Outwash

These deposits are characterised by stratified, well-sorted sand and gravel deposits that post-date the Glacial Till deposition. Their greatest extent in the Eden valley occurs north of Penrith, where a variety of typically glacio-fluvial landforms can be recognised including long, linear, ridge-forming eskers, valley marginal hummocky-surfaced kame terraces and glacio-fluvial sheet deposits which the river Eden has subsequently dissected. Thicknesses are highly variable, and can reach 40m, although 10-20m is more typical.

River Terrace Deposits

These post-date the glacio-fluvial and glacio-lacustrine deposits and are associated with the modern rivers and streams. The terraces consist mainly of sand and gravel, and a single terrace surface ranges in height between 5-9 m above present river levels. This variation may reflect the importance of locally fluctuating base levels associated with breaching of morainic dams, rather than regional base-level variation.

Alluvium

Associated with all the major streams and rivers, these deposits for the most part are composed of fine sand and gravel south of Penrith, and brown sandy loam north of Penrith, where the alluvial tract in the Eden valley becomes almost 1km wide. Organic silt and peat may be present in abandoned channels.

Age	**Group**	**Formation**	**Thickness (m)**	**Aquifer Unit**	**Comments**
Lias					Mudstone with minor limestone and sandstone
Triassic	Penarth	Lilstock / Westbury		Minor aquifer/ Aquitard	Shallow marine mudstones - poor local aquifer
	Mercia Mudstone	Stanwix Shale	<400-	Aquitard	Mudstone with minor sands not exploited for groundwater. Present to the north of Carlisle.
	Sherwood Sandstone	Kirklinton Sandstone St Bees Sandstone	10-100 <500	Aquifer Aquifer	Productive highly yielding aquifer Fine-grained, well-cemented fluvial sandstone. Productive well-exploited aquifer
Permian	Cumbrian Coast- Appleby	Eden Shale Penrith Sandstone and Brockram	<180 <900	Aquitard Aquifer	Mudstones and evaporites. Gypsum/anhydrite present which may affect water quality at edge of adjacent aquifers Mostly highly permeable aeolian sandstone, but with local cemented zones. Productive highly yielding aquifer
Carbon-iferous	Pennine Coal Measures			Minor aquifer	Carboniferous: The northern part of the catchment includes the Inverclyde and Border Groups of the Solway Basin
	Yoredale	Stainmore Formation Alston Formation		Minor aquifers	The Carboniferous includes potentially high yielding aquifers of local significance often largely controlled by degree of fissuring/faulting
	Great Scar Limestone Ravenstonedale			Minor aquifer	
Devonian	Upper ORS			Minor aquifer	Potential local minor aquifer

Table 1.1 Bedrock Stratigraphy of the Vale of Eden and Carlisle Basin north-west England (after Stone *et al.* [2010])

1.2 HYDROGEOLOGY

The main aquifer formations in the region are the St Bees Sandstone of the Sherwood Sandstone Group (early to mid-Triassic age), and the Penrith Sandstone Formation (early Permian age). The aquitards within the sequence are formed by the Eden Shale Formation and the Brockram Formation. The Eden Shale Formation separates the Penrith Sandstone Formation and St Bees Sandstone aquifers in the Vale of Eden. The Brockram interdigitates with the Penrith Sandstone Formation in the southern part of the Vale of Eden.

The groundwater in the Permo-Triassic sandstones is widely used for industry, public supply and small farms.

The Penrith Sandstone Formation is an important aquifer from which large quantities of groundwater for public supply are obtained from a number of boreholes located in the northern part of the outcrop. The formation is confined by the Eden Shale Formation to the east of the River Eden and by drift cover over much of the area to the west. Boreholes that intersect the silicified part of the formation tend to have very low yields. The friable nature of other layers of the formation may cause borehole construction problems.

The St Bees Sandstone Formation is an important lower part of the regional Sherwood Sandstone aquifer; however with depth its matrix permeability decreases and fractures are less transmissive. In consequence the effective aquifer thickness is confined to the top few hundred metres.

The Carboniferous Limestone and Millstone Grit surround and to a large extent underlie the Eden Valley. Both contain productive aquifer horizons. They are significant hydrogeologically as they provide a baseflow to streams in sub-catchments of the River Eden and its tributaries and issue as springs along the western margin of the Eden Valley. The potential amount of groundwater transported to overlying Permo-Triassic aquifers has not been investigated but will be dependent on the nature of these rocks at the contacts.

Faults are present in the Vale of Eden. The two main sets trend west-north-west and north-north-east and are extensional normal faults (Knott 1994). These faults are likely to have a low permeability across their shear zones, though they may transmit water rapidly, parallel to any associated fracturing. Fault zones are generally thicker, (i.e. a thicker sheared zone), where there has been significant fault displacement and may be more impermeable to flow perpendicular to them, than those with a small displacement. However boreholes in the St Bees Sandstone Formation which intersect fault zones have higher yields, suggesting that generally the fracturing increases the transmissivity of the sandstones. Fault zones may be detected in the Vale of Eden where there is no drift cover, but the more general superficial cover in the Carlisle Basin obscures faults within the sandstone.

1.2.1 Piezometry and groundwater flow

The groundwater regime in the Vale of Eden is dominated by the river Eden which gains over most of its length, (in the region broadly between Langwathby [NY 57 33] and Temple Sowerby [NY 61 27] the river is mainly underlain by the Eden Shale Formation and is not in contact with the main aquifer).

The water table is close to the surface near the River Eden but lies at around 50 m below ground level in the north of the basin and may be as much as 100 m deep below high ground

In the Penrith area hydraulic gradients are gentle and predictable, generally towards the rivers Eamont and Eden (Ingram 1978). Water may be encountered at depths of over 100 m when drilling at high elevations. Steeper hydraulic gradients in the northern part of the Penrith Sandstone Formation outcrop may reflect the lower permeability of the sandstone in this area. Areas with water levels above silicified bands may act as a number of aquifers with perched water tables (Ingram 1978). The Permo-Triassic sandstones exhibit interbedding, often at a variety of scales. This may give rise to directional permeability depending on the bedding, inclination and the cross-bedding of the sandstone.

Laterally groundwater may be transferred from the Carboniferous Limestone where the Penrith Sandstone Formation lies directly on the limestone to the south of Penrith. Along the Pennine Fault there are many springs, indicating that much of the lateral inflow to the basin is from surface flow rather than between aquifers across the fault zone.

The Cleveland-Armathwaite Dyke (Section 1.1.8) is an important linear geological feature which is likely to impede lateral groundwater flow; however its hydraulic significance is unknown.

1.2.2 Water balance

Recharge assessment is complex as the permeability of the superficial deposits is variable.

So far the water balance in the Eden Valley has only been considered in general terms by Ingram (1978) and Monkhouse & Reeves (1977). The approaches were based on effective rainfall, recharge, abstraction and surface water discharge calculations. Ingram separated the Penrith and St Bees Sandstones as they are separated by a thick aquiclude (the Eden Shales). Recharge was apportioned on the basis of a 70% and 30% split which resulted in estimates of 315 mm/y for the drift-free aquifer and 90 mm/y for drift covered aquifer.

Work by Vines (1984) has suggested that these figures should be revised and a figure of 50 mm/y recharge to a drift covered aquifer now considered as more appropriate (Ingram, J. A. personal communication).

The potential for enhanced recharge through 'drift windows' has also been studied by Butcher et al. (2006).

The Met Office rainfall and evaporation calculation system (MORECS) is based on a 40 km by 40 km grid. Most of the Eden Valley is contained within MORECS grid square 78 with the southern part from Appleby southwards contained in MORECS grid square 84. (The Met Office Surface Exchange System (MOSES**)** provides an improved process description of the soil-water balance).

The average rainfall for a combination of squares 78 and 84 is 1738mm/y. For Square 78 this is 1148mm/y. The Potential and Actual Evapotranspiration rates are very similar at approximately 480 mm/y. Because the Eden Valley is relatively narrow, and is bounded by the highlands of the Lake District and Alston Block, there is a danger that the rainfall averages provided by the MORECS system will be skewed towards a greater rainfall found in these higher terrains. Rainfall in the centre of the Eden Valley is more typically 850-900mm/y.

Low flow condition measurements on rivers help to ascertain the accuracy of the water balance estimates. In these conditions the total surface flows can be dominated by the baseflow component derived from groundwater. For the River Eden, the baseflow index - a measure of the proportion of the river runoff derived from stored sources (groundwater) - increases from 0.26 near source at Kirby Stephen [NY 77 08] to 0.5 at Carlisle. The baseflow index in the lower reaches of the River Caldew is 0.49 and similarly in the River Petteril it is 0.47 (both rivers join the River Eden at Carlisle). These indicate that there is a significant stored component in the 'greater' Eden catchment.

1.3 SUMMARY OF THE HYDROGEOLOGY OF THE EDEN VALLEY

- The Penrith and St Bees Sandstones are the major aquifers in the Eden Valley. These aquifers are characterised by moderate-high permeability and porosity. Groundwater flow is both intergranular and fracture; regional flow appears to be dominated by intergranular flow whilst flow into boreholes is predominantly contributed by fractures.

- Large areas of the sandstone aquifers (c 75%) are covered by superficial deposits of variable lithology (from clay to gravel size) and thickness (up to 30m). These have a significant impact on recharge and its distribution; where deposits are permeable or absent rates of infiltration, considerably in excess of 350 mmy^{-1}, is possible whilst beneath till deposits the infiltration rate may be 50 mmy^{-1} or less.
- Principal aquifer types are:
    - Unconfined sandstone with no, or little, drift cover.
    - Unconfined sandstone with thick drift cover (≥5 m) and an unsaturated zone within the sandstone.
    - Confined sandstone, groundwater level fluctuates within drift.
    - Limestone exhibiting significant fracture flow.
- The stratigraphy of Superficial Deposits is complex. Interdigitations of sand, gravel, silt and clay each develop their own piezometric level, resulting in complex perched water tables above the bedrock formations.
- Groundwater nitrate concentrations are normally significantly lower in the confined aquifers.
- River flow in the Eden Valley is derived from several sources:
    - Surface water from adjacent upland areas outside the Vale of Eden, including runoff and flow from the Carboniferous Limestone and sandstones.
    - Direct runoff within the Vale of Eden.
    - Base flow contribution from the Permo-Triassic sandstones and other aquifers.

1.4 LOCATION OF THE EDEN SUB-CATCHMENTS

The three catchments chosen for further investigation by the Eden DTC project are the Pow Beck, which lies to the south of Carlisle, the Morland Beck, to the west of Appleby, and the Dacre at Nabend, to the west of Penrith. The locations of these sub-catchments are shown in Figure 1.4.

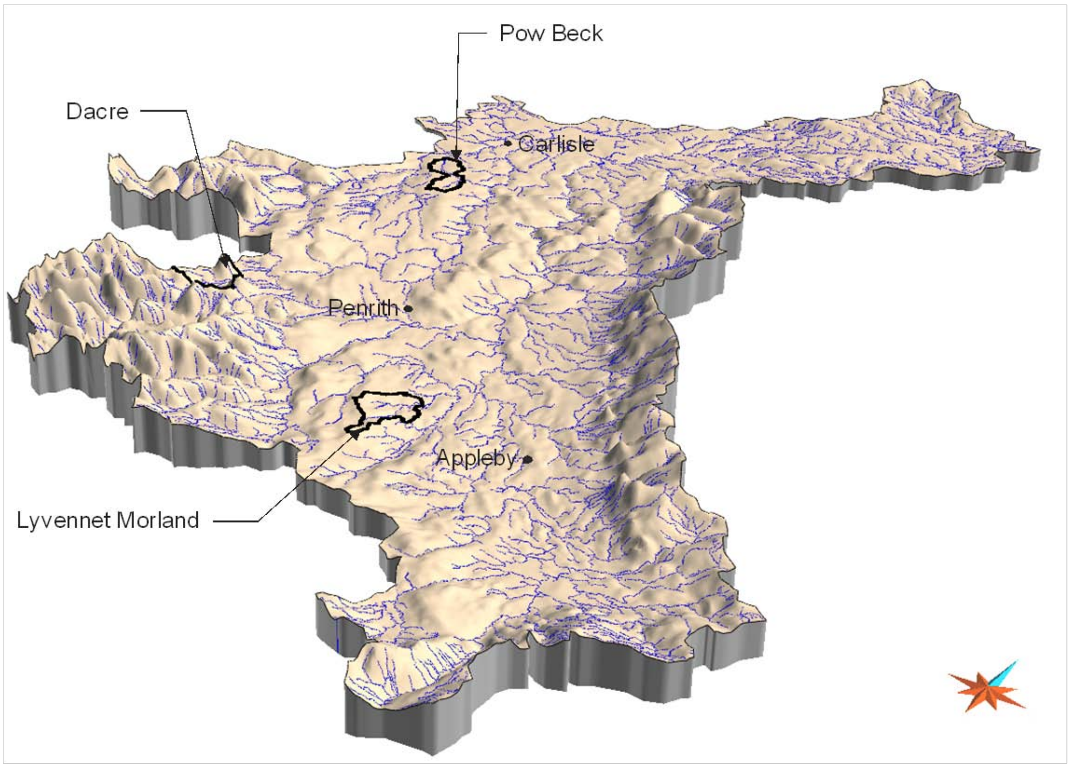


Figure 1.4 Perspective view looking NE across the Eden Catchment showing the location of the Eden DTC sub-catchments. Blue spine on orientation symbol indicates direction of North.

2 Pow Catchment

2.1 CATCHMENT SETTING

The Pow catchment in the Eden Valley is situated to the south of Carlisle. The catchment lies between the valleys of the River Caldew (to which the Pow Beck is a tributary) to the west and the River Petteril to the east. Both the Caldew and the Petteril are more deeply incised than the Pow Beck, whose valley has relatively low relief and is generally at a significantly higher altitude than the larger adjacent rivers (Figure 2.1).

Figure 2.1 The Pow catchment showing the 'interfluve' position with the River Cardew to the west and the River Petteril to the east. Long axis of block diagram is 8km across. Blue spine on orientation symbol indicates direction of North.

2.2 DRAINAGE

The Pow Beck rises from two sources near to Monkcastle, a spring located at GR NY 4199 4553 and issues located at GR NY 4281 4607 and flows initially northwards before turning west near Foulbridge and then north-west at Sprunston to join the Caldew near Dalston.

2.3 GEOLOGY

The geology of the Pow catchment is complex, consisting of sandstone, limestone and mudstone bedrock units, and with extensive faulting (Figure 2.2). The stream rises on the Stainmore Formation (Millstone Grit Group), then passes for a short distance over the Alston Formation (Carboniferous Limestone Supergroup) before flowing over the Penrith Sandstone Formation. It then passes over the St Bees Sandstone Formation (Sherwood Sandstone Group) with a short reach over Eden Shales Formation (Cumbrian Coast Group) before flowing over the St Bees Sandstone Formation again to reach its confluence with the Caldew. The stream crosses several faults in its upper reaches (upstream of Sprunston).

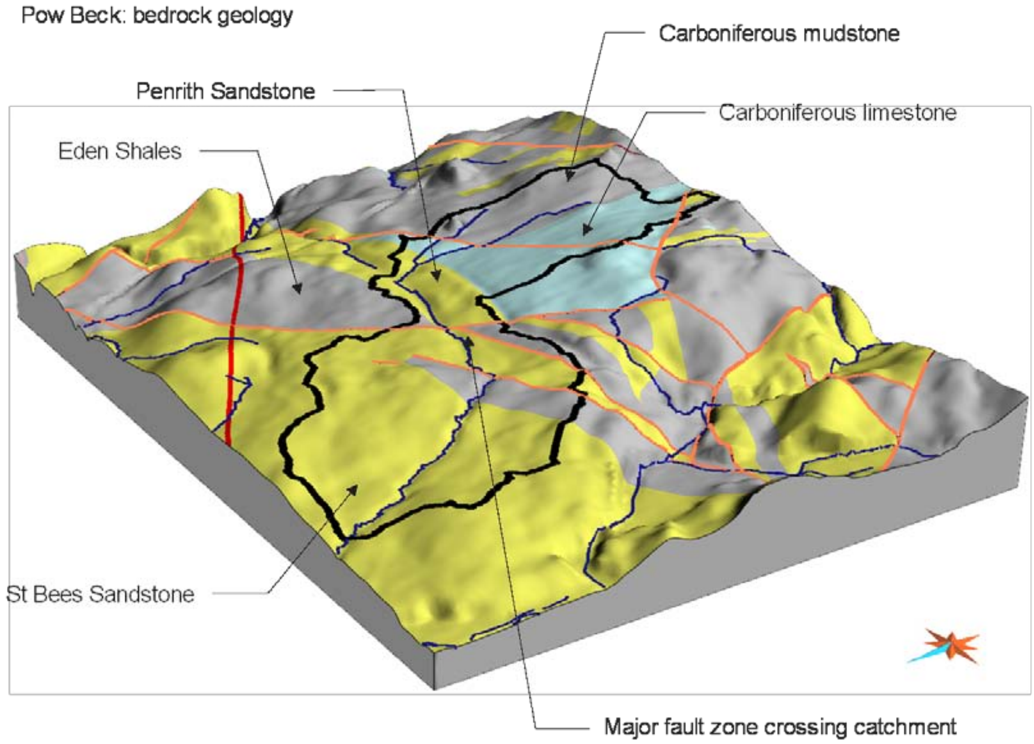
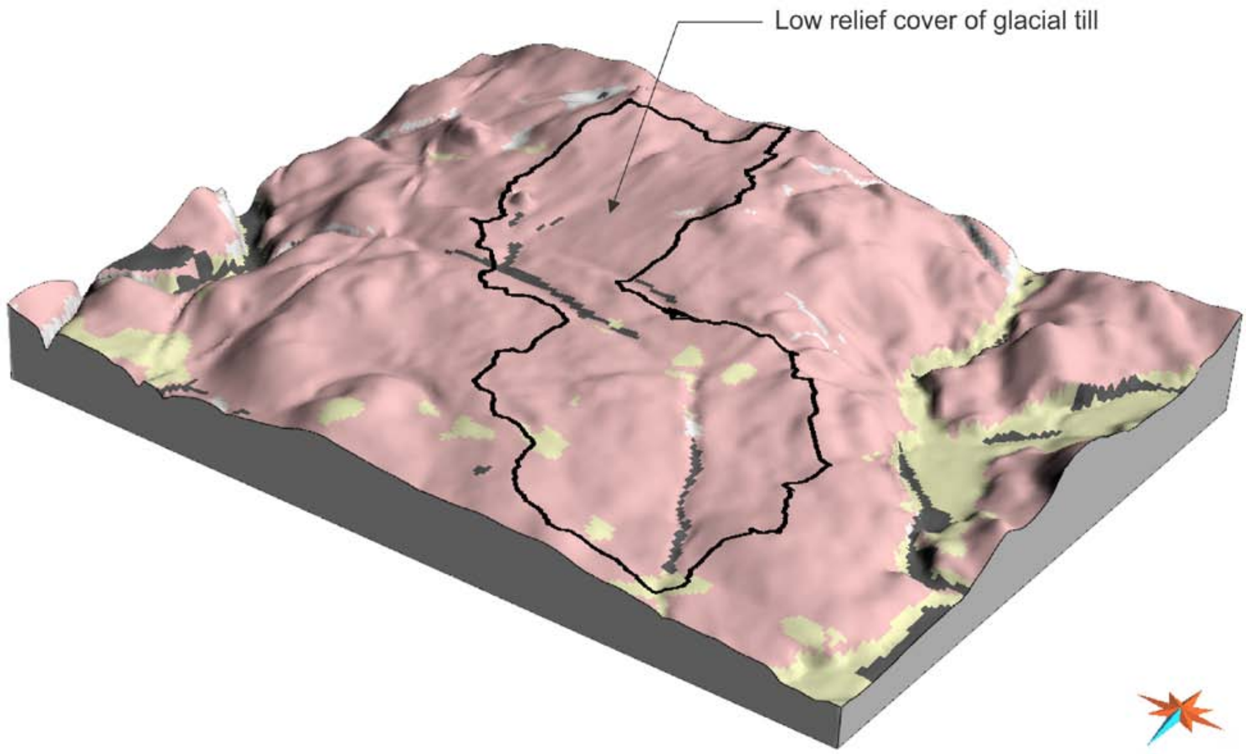


Figure 2.2 Solid Geology of the Pow Catchment. The northern (lower elevation) part of the catchment is underlain by St Bees Sandstone.
South of the the major Maryport-Stublick Fault, which crosses the centre of the catchment, the geology is dominated by Carboniferous mudstones, sandstones and limestones. Faults are shown as orange lines while the thick red line crossing the NE part of the block is the Cleveland-Armathwaite Dyke. Long axis of block diagram is 8km across. Blue spine on orientation symbol indicates direction of North.

Virtually the whole catchment is covered in glacial till (Figure 2.3), with a few patches of glaciofluvial deposits with thicknesses in boreholes ranging from 2m to around 25 m. The river channel is underlain by alluvium over much of its length, with river terrace deposits present in the lowest reaches.

The Pow catchment lies on 1:50 000 scale geological maps 17 (Carlisle), 18 (Brampton), 23 (Cockermouth) and 24 (Penrith).



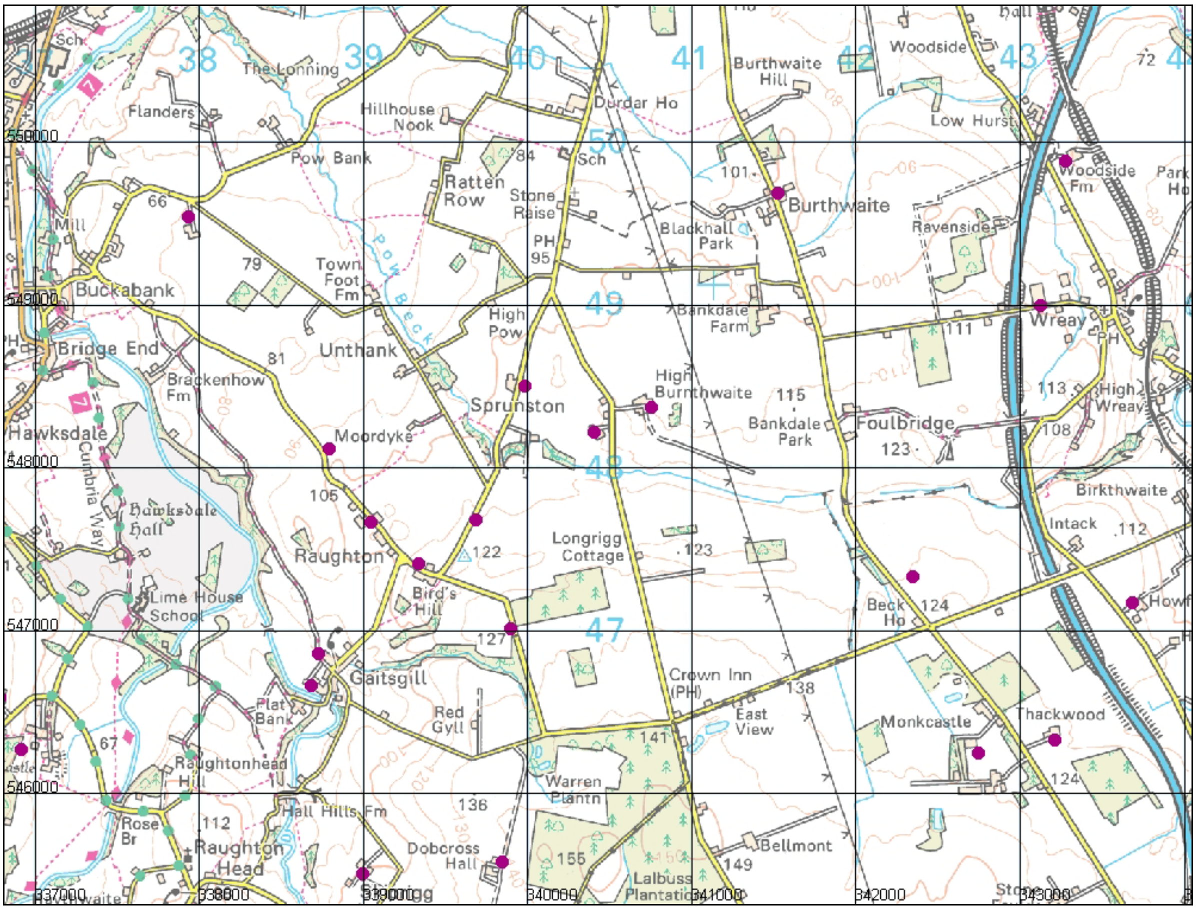
Geological features, BGS, © NERC. NEXTMap Britain elevation data from Intermap Technologies.

Figure 2.3 Superficial geology of the Pow Catchment showing the extensive cover of glacial till (pink) with minor patches of terrace gravels (yellow) and alluvium (grey) in the valley floor. Long axis of block diagram is 8km across. Blue spine on orientation symbol indicates direction of North.

2.4 HYDROGEOLOGY

2.4.1 Boreholes

A number of water boreholes (12) are present within or on the borders of the catchment. These are all water boreholes and are shown in Figure 2.4 and Table 2.1.



Borehole locations, BGS © NERC. Based on OS topography © Crown Copyright.

Figure 2.4 Water boreholes (purple dots) in and around the Pow catchment (grid lines at 1 km intervals).

Table 2.1 Location data for boreholes in and adjacent to the Pow catchment

Borehole Name	BGS No.	BGS Hydro No.	Easting	Northing	Altitude (m AOD)*
Buckabank Farm, Dalston	NY34NE21	NY34/25	337940	549540	71
Dalston D2	NY34NE9	NY34/5B	338800	548120	105
Raughton Farm	NY34NE24	NY34/30	339050	547670	105
Birds Hill Farm	NY34NE26	NY34/33	339340	547410	112
Dalston D3	NY34NE10	NY34/5C	339900	547010	124
Dalston D1	NY34NE11	NY34/5A	339690	547680	111
Dalston D4	NY34NE16	NY34/5D	339990	548500	105
Crownstone Farm, Durdar	NY44NW107	NY44/50	340410	548220	110
High Burnthwaite	NY44NW102	NY44/39	340760	548370	110
Beck House, Southwaite	NY44NW105	NY44/42	342350	547330	121
Monkcastle Farm	NY44NW104	NY44/25	342750	546250	126
Thackwood Farm	NY44NW97	NY44/28	343220	546330	121

*Altitude estimated from 1:25000 OS map

Preliminary geological information from the borehole logs is presented in Table 2.2, Of particular significance is the thickness of superficial deposits penetrated and the nature of the aquifer; these can be seen to range from virtually zero to 25 m or more across the catchment.

Table 2.2 Summary of geological information from boreholes (based on borehole log interpretation and location of boreholes relative to mapped geology.

Borehole Name	BGS Number	Depth(m)	Superficial deposits thickness (m)	Aquifer penetrated
Buckabank Farm, Dalston	NY34NE21	80	19.5	St Bees Sst
Dalston D2	NY34NE9	121.9	1.5	St Bees Sst/Eden Shales/ Carboniferous
Raughton Farm	NY34NE24	72	25	Eden Shales/Sherwood Sandstone?
Birds Hill Farm	NY34NE26	60	25.5	Eden Shales/St Bees Sst?
Dalston D3	NY34NE10	38.4	6.7	Penrith Sandstone/Carboniferous
Dalston D1	NY34NE11	42.06	3.05	St Bees Sandstone
Dalston D4	NY34NE16	59.4	18.2	Eden Shales/Carboniferous
Crownstone Farm, Durdar	NY44NW107	60	25 or 33	St Bees Sst?
High Burnthwaite	NY44NW102	50	15.1	?
Beck House, Southwaite	NY44NW105	101	9.5	Alston Fm?
Monkcastle Farm	NY44NW104	48	24	Millstone Grit?
Thackwood Farm	NY44NW97	45	3.2	Millstone Grit?

Of the borehole records identified, most (8) have some hydrogeological information and many have some pumping test information. Table 2.3 shows a summary of the information concerning water strikes and water levels and indicates where pumping test data are available.

Table 2.3 Summary of hydrogeological data available from boreholes in the Pow catchment.

Borehole Name	BGS No.	Depth (m)	Water strikes (m bd)	RWL (m bd)	RWL Elevation (m AOD)	RWL date	Pump test Info?
Buckabank Farm, Dalston	NY34NE21	80	47, 68(main)	29.05	41.95	13/06/2003	Yes
Dalston D2	NY34NE9	121.9					No
Raughton Farm	NY34NE24	72	27	25.1	80.4	14/02/2004	Yes
Birds Hill Farm	NY34NE26	60	42	30.06	81.94	13/10/2006	No
Dalston D3	NY34NE10	38.4					No
Dalston D1	NY34NE11	42.06					No
Dalston D4	NY34NE16	59.4					
Crownstone Farm, Durdar	NY44NW107	60		20.4	89.6	04/02/2004	Yes
High Burnthwaite	NY44NW102	50	32, 38	21.04	88.96	08/09/2000	Yes
Beck House, Southwaite	NY44NW105	101	84, 95.5	14.45	106.55	30/11/2001	Yes
Monkcastle Farm	NY44NW104	48	6, 28	10.2	115.8	07/01/1995	Yes
Thackwood Farm	NY44NW97	45	18.6, 40.25	8.4	112.6	08/03/1995	Yes

An important observation is that the rest water level in the boreholes is apparently at a lower elevation than that of the nearest stream reach (Figure 2.5 – elevations are approximate as they are estimated from 1:25 000 OS maps. This means that the stream does not gain water from the underlying main aquifers such as the St Bees Sandstone at any point along its length, and will have a tendency to lose water to the bedrock aquifers. It should be noted that this conclusion is not definitive because there are no boreholes immediately adjacent to the stream; however where reasonable interpolation between boreholes can be made (e.g. between for example High Burnthwaite and Birds Hill Farm) the assumed groundwater level at the river is at least 10 m lower than the elevation of the river bed, and elsewhere borehole water levels are uniformly lower than the nearby river bed.

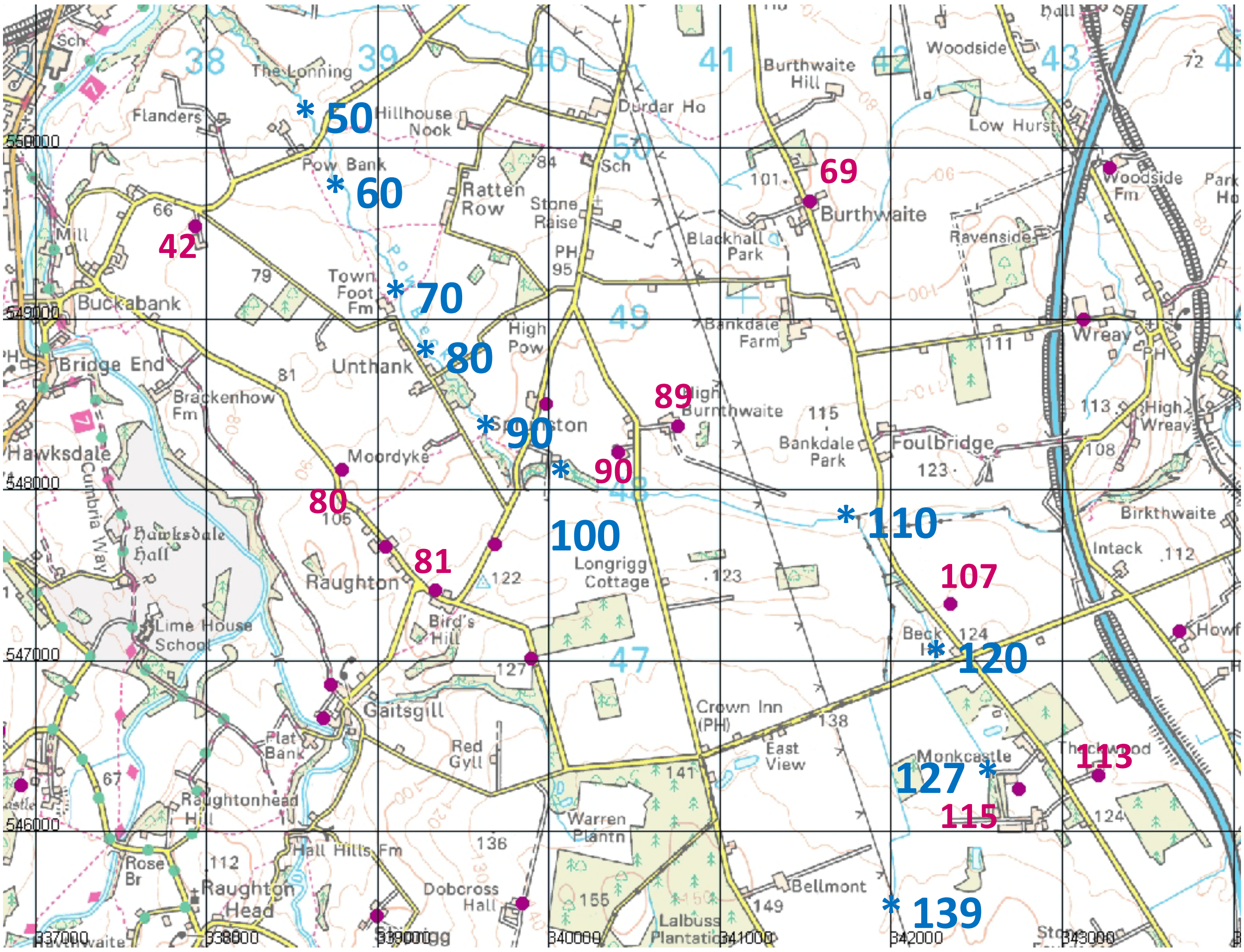
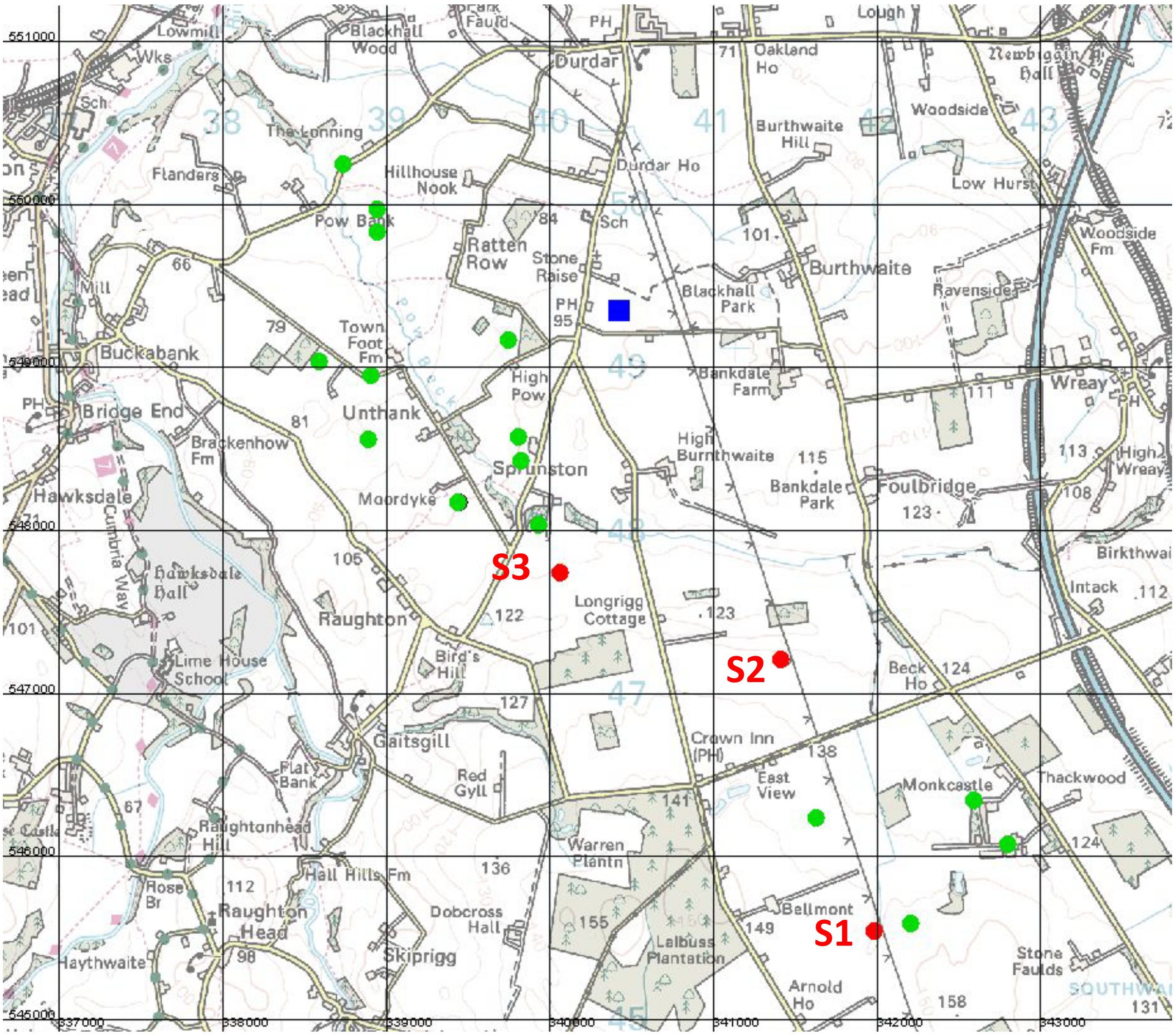


Figure 2.5 Borehole rest water levels (red figures, metres AOD) and stream levels (blue figures, metres AOD) in the Pow catchment. Grid lines are at 1 km intervals.

If the stream does not gain groundwater water from the underlying bedrock aquifers then it follows that its discharge is obtained either entirely from surface runoff, or from a combination of surface flow and discharge from the superficial deposits. The significance of the latter may be examined by considering indications of springflow.

2.4.2 Springs and Issues

Three springs feeding the Pow Beck are marked on OS 1:10000 scale maps. The locations are given in Table 2.4 and are shown in Figure 2.6.



Based on OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010.

Figure 2.6 Location of Springs (red) and Issues (green) supporting the Pow Beck; lake feeding the river is also shown (blue). Grid lines are at 1 km intervals.

PS1 is the source for the western tributary of the Pow, PS2 is a spring near Great High Plantation which lies c. 600m from the river and drains to it via a series of ditches (total drainage distance c. 750 m); PS3 is a spring south of Sprunston which lies at a distance of c. 330 m from the river and drains to it via ditches (drainage distance c. 550 m).

In addition 15 'issues' which drain into or towards the Pow Beck are marked on the 1:10 000 scale OS map and are shown on the figure. The nature of the issues is unclear e.g. whether they are intermittent, whether they obtain their water from mole drains for example, or from surface depressions, or are natural springs.

Flow is also obtained from a lake at White Quay, near to Stone Raise.

Table 2.4 Locations of Springs and Issues in the Pow catchment

ID	Type	Easting	Northing	Comment
PS1	spring	341987	545533	Source of Pow
PS2	spring	341418	547202	
PS3	spring	340061	547741	
PI1	issue	342219	545587	Feeds into pit
PI2	issue	342804	546071	2nd Source of Pow
PI3	issue	342599	546340	
PI4	issue	341627	546232	
PI5	issue	339930	548030	
PI6	issue	339822	548421	
PI7	issue	339810	548569	
PI8	issue	339443	548168	
PI9	issue	339750	549164	Feeds to sink
PI10	issue	338897	548556	
PI11	issue	338598	549036	
PI12	issue	338909	548950	
PI13	issue	338951	549817	
PI14	issue	338945	549961	
PI15	issue	338741	550247	
Lake	lake outflow	340422	549340	

At the time of writing no information is available concerning the nature or flow patterns of the springs, of the issues, or of the river itself, and, therefore, further speculation on the nature of these systems and their interaction is premature.

2.4.3 Geochemical data

A little stream water and streambed sediment chemistry data is available from the BGS GBASE study.

2.5 CONCLUSION

On present evidence the hydrogeology of Pow catchment may be summarised as follows.

1. The catchment lies in an elevated position with respect to larger, adjacent catchments.
2. The Pow is underlain by a number of bedrock aquifers; however groundwaters within these units drain to outlets at lower elevations which lie outside the Pow catchment and do not contribute to the Pow Beck itself. In fact the Pow Beck will tend to drain to the underlying bedrock aquifers where it is in hydraulic continuity with them.
3. The Pow catchment is covered by extensive superficial deposits; these appear to comprise mainly clays but also include arenaceous materials which could form local minor aquifers. The thickness of the superficial deposits is variable but can be significant.
4. The presence of springs indicates that groundwater discharges from the superficial deposits and contributes to the river; however the significance of the springs is at present unknown. In addition, numerous features denoted as ‘issues’ are seen which may suggest an enhanced groundwater role in the catchment (on the other hand they may simply be surface drains).

Therefore, the flow of the Pow Beck probably derives from a combination of rapid surface runoff and delayed flow from precipitation recharge which is routed to local discharge points.

This delayed discharge may have a range of timescales, with perhaps relatively rapid flow from small scale field drains (if present), and slower groundwater movement through shallow aquifers in the superficial deposits, which also may discharge to field drains, or to springs. Any recharge into the catchment which passes through the superficial deposits and reaches the deeper bedrock aquifers appears to leave the catchment and does not contribute to the flow of the Pow Beck.

3 Morland Catchment

3.1 CATCHMENT SETTING

The Morland Beck catchment lies to the west of Appleby. It is drained by a number of small streams which broadly flow northwards, coalescing to form the Newby Beck to the south of Newby, which then becomes the Morland Beck, draining into the River Lyvennet to the north-east of Morland (Figure 3.1).

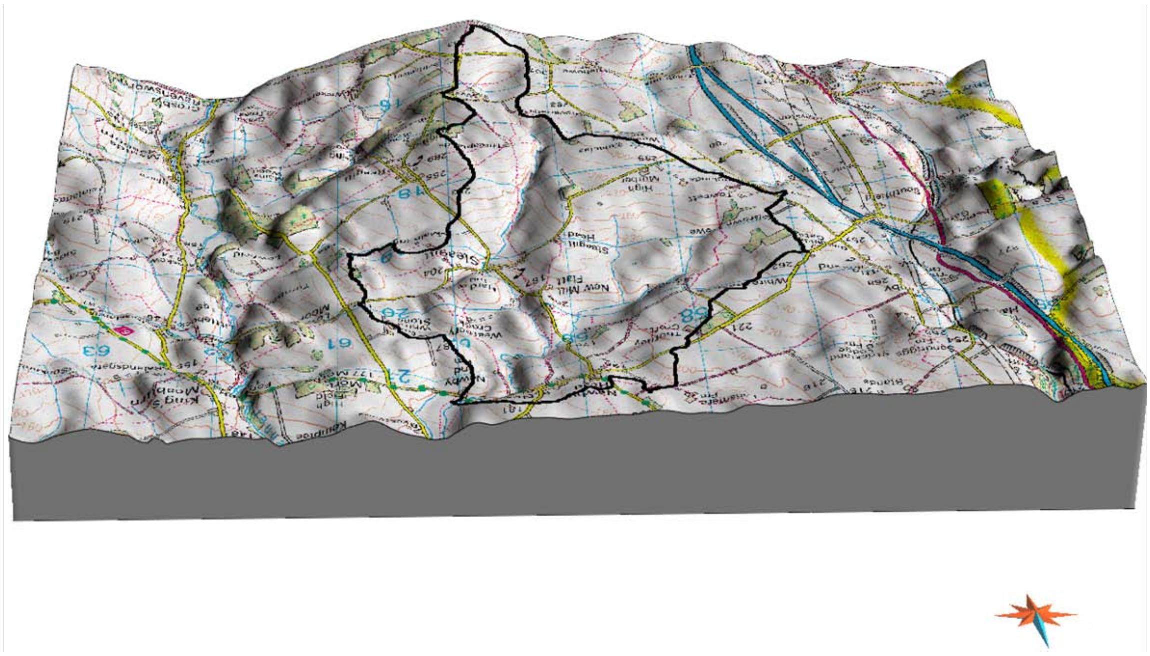


Figure 3.1 The Morland Catchment viewed from the north. Long axis of block diagram is 9.5 km across. Blue spine on orientation symbol indicates direction of North.

3.2 GEOLOGY

The bedrock geology of the Morland catchment is predominantly Carboniferous Yoredale Group which comprises cyclically interbedded limestone, mudstone and sandstone (Figure 3.2). Bedding dips toward the north-east and has a major impact on the geomorphology of the catchment, with the more resistant limestone beds forming a series of crenulated scarps and dip slopes.

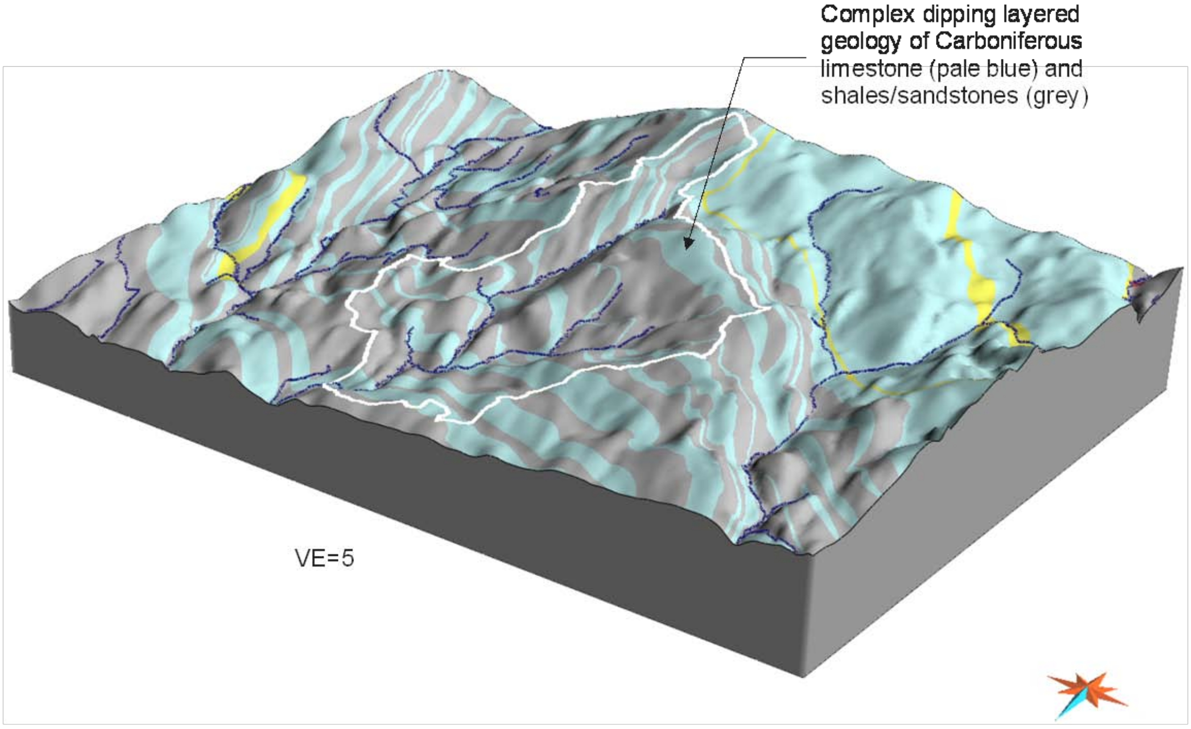
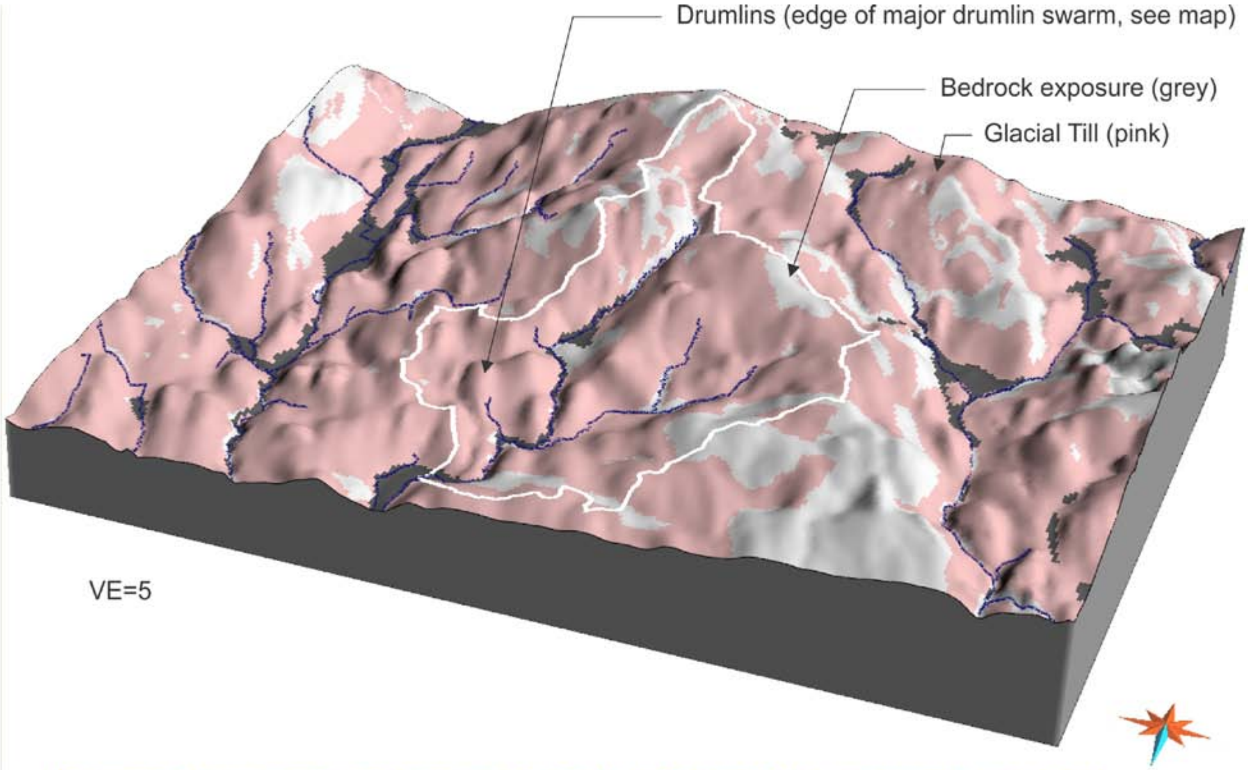


Figure 3.2 Bedrock geology of the Morland catchment showing interlayering of limestones (pale blue) and shales/sandstones (grey). Beds dip toward the NE producing a crenulated topography of scarps and dip slopes.

The superficial geology of the catchment is dominated by glacial till which forms a relatively continuous cover on the bedrock. The till mostly has a low relief but in the NE corner of the catchment has been moulded by ice sheets into spectacular ‘whaleback’ drumlins which are elongated in a south-easterly direction. These drumlins form the western margin of a much larger field within the southern Eden catchment (Figure 3.3).

The Morland catchment lies on 1:50 000 scale geological map 30 (Appleby).



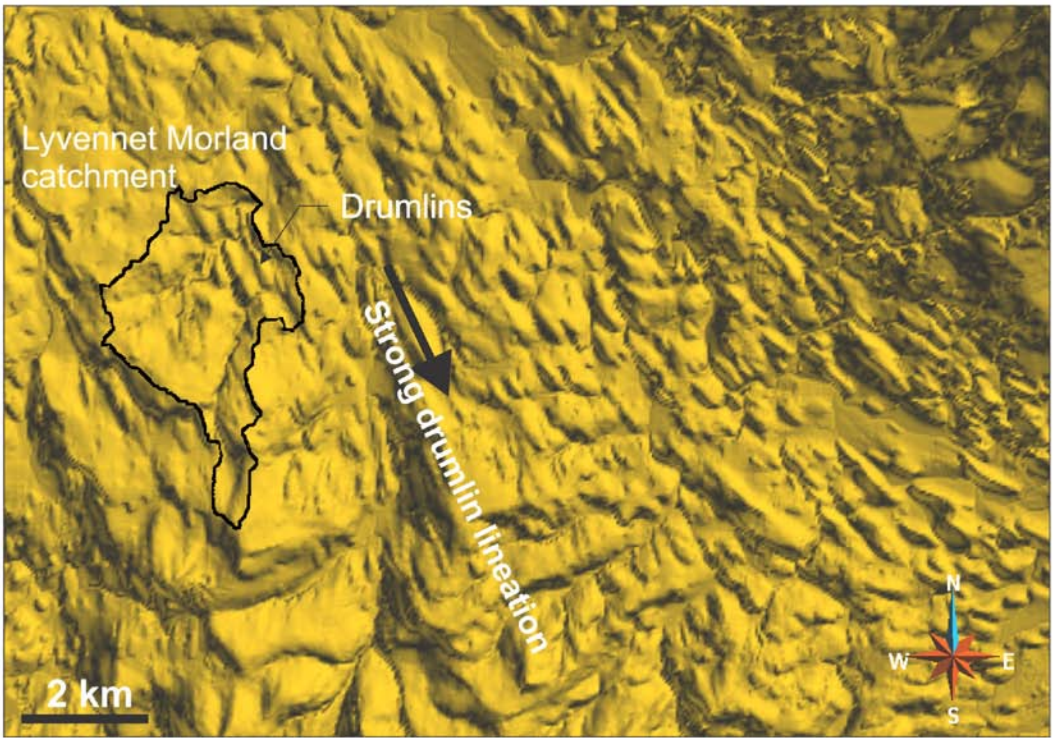


Figure 3.3 Superficial geology of the Morland Catchment. The block diagram shows the cover of glacial till (pink), alluvium (dark grey) and exposed bedrock (pale grey).
In the NE corner of the catchment the till is moulded into drumlins which, as shown in the shaded relief map, are the western limit of a much larger field in the southern Vale of Eden. The drumlins have a 'whaleback' form with a strong SE elongation recording the direction of ice flow.

3.3 HYDROGEOLOGY

3.3.1 Boreholes

Only one borehole is present in the catchment, at White Stone (NY 6056 2020) (Figure 3.4). This borehole encountered minimal superficial deposits (<1 m) before entering Carboniferous sandstones and mudstones. The rest water level in the borehole was 8.5 m below ground level, corresponding to an elevation of around 182 m AOD. Whether or not this implies hydraulic continuity with the river is unknown.

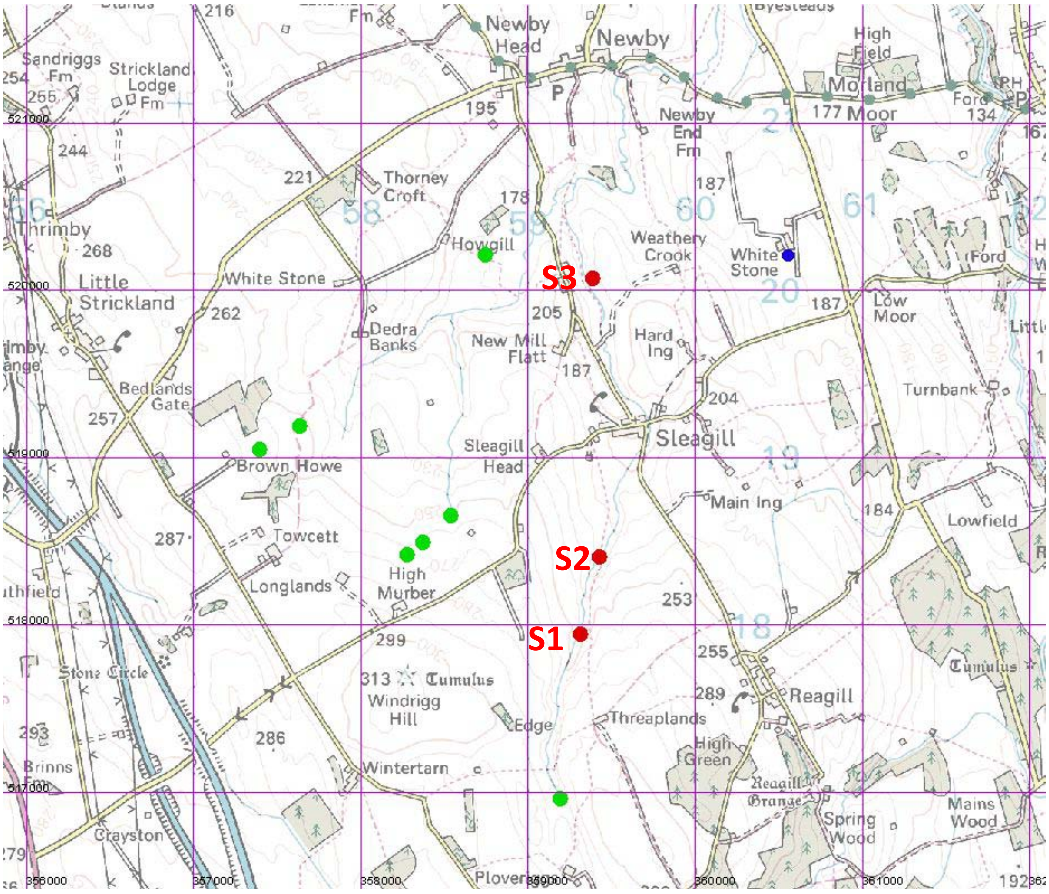
3.3.2 Springs and Issues

A number of springs and issues feed the Morland Beck via its tributaries. Figure 3.4 and Table 3.1 show those which drain to the river and its tributaries upstream of Newby. In addition several other issues rise and form streams which subsequently sink within the catchment.

Table 3.1 Locations of Springs and Issues in the Morland catchment

ID	Type	Easting	Northing	Comment
LS1	spring	359314	517942	Flows into Seagill Beck
LS2	spring	359428	518401	Flows into Seagill Beck
LS3	spring	359383	520070	Runs into Seagill Beck
	spring	*359390*	*517364*	*Spring feeding pond only*
LI1	issue	357397	519038	Flows into Long Sike
LI2	issue	357641	519187	Flows into Long Sike
LI3	issue	358746	520212	Flows into Sandwath Beck. Well also marked 40m to NW
LI4	issue	358275	518421	Flows into Gilmoor Sike
LI5	issue	358375	518491	Flows into Gilmoor Sike
LI6	issue	358539	518654	Flows into Gilmoor Sike
LI7	issue	359195	516957	Source of Plover Sike

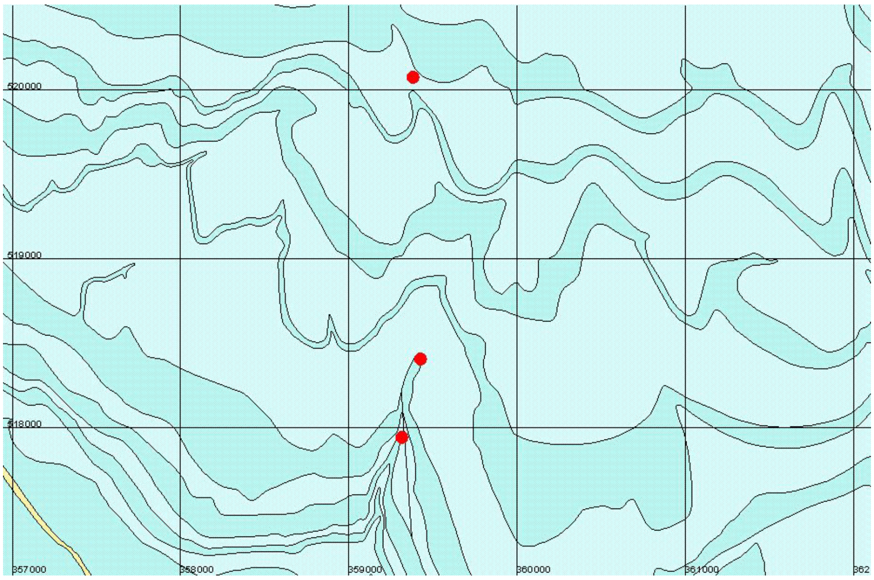
At the time of writing no information is available concerning the nature or flow patterns of the Morland Beck or its tributaries.



Borehole location, BGS © NERC. Based on OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010.

Figure 3.4 Location of Springs (red) and Issues (green) supporting the Morland Beck. Also shown is the borehole (blue). Grid lines at 1 km intervals.

Figure 3.5 shows the locations of the springs relative to bedrock geology and Figure 3.6 include superficial deposits. There may be an indication from Figure 3.5 that the two southernmost springs occur at the junction between limestone and shale/sandstone units i.e. possibly flowing out from limestone aquifers; however this supposition is very tentative at present.



Geological features, BGS, © NERC. Based on OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010.

Figure 3.5 Bedrock geology and springs (red) in the Morland catchment. Limestones dark blue, shales/sandstones light blue. Grid lines at 1 km intervals

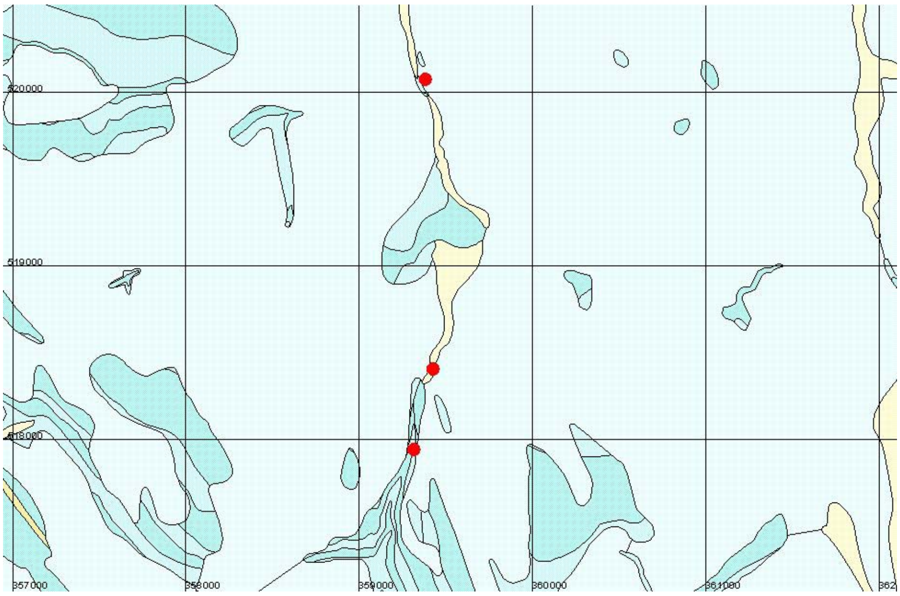


Figure 3.6 Superficial and bedrock geology and springs (red) in the Morland catchment. Limestones dark blue, shales/sandstones light blue, superficial deposits pale blue. Grid lines at 1 km intervals

3.4 CONCLUSION

The bedrock geology of the catchment consists of limestones, mudstones and sandstones and, therefore, aquifers may exist in the potentially more permeable units. However the dip of the sequence means that aquifers are likely to be localised across the catchment, and if groundwater flow follows the topographic gradient in the bottom of the catchment, i.e. to the north-east, then the aquifer outcrop is at right angles to the direction of groundwater flow, thus impeding it. The degree of any hydraulic interconnection between bedrock aquifers and the river is unknown, but the single borehole rest water level does not imply disconnection as in the Pow catchment. Glacial Till is extensive, and, therefore, likely to have an important (but as yet unknown) effect on the hydrogeology of the catchment.

4 Dacre Beck Catchment at Nabend

4.1 CATCHMENT SETTING

The Dacre Beck catchment lies in the west of the Eden Catchment, in an area with significant topographic variation to the north of Ullswater (Figure 4.1). The catchment drains to an outlet at Nabend, between Great Mell Fell (altitude 537 m) and Little Mell Fell (altitude 505 m).

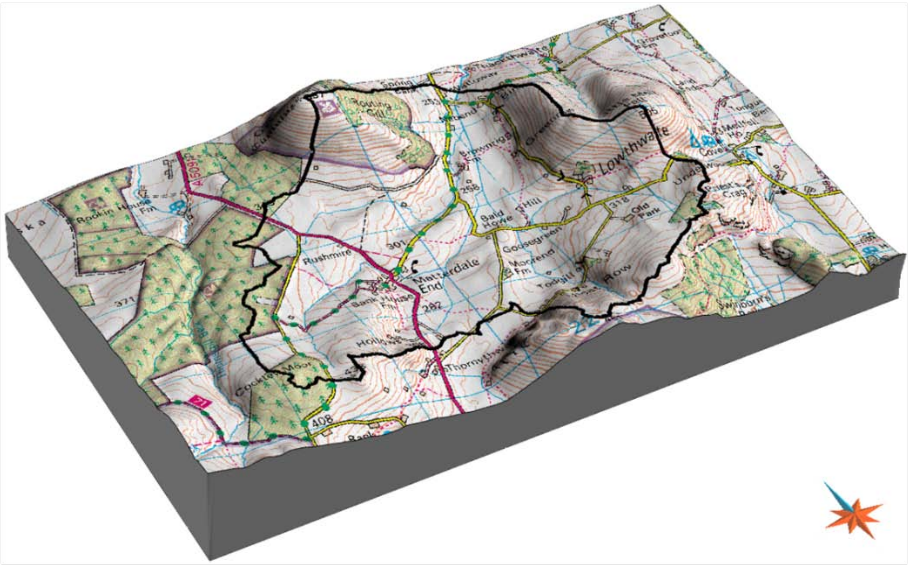


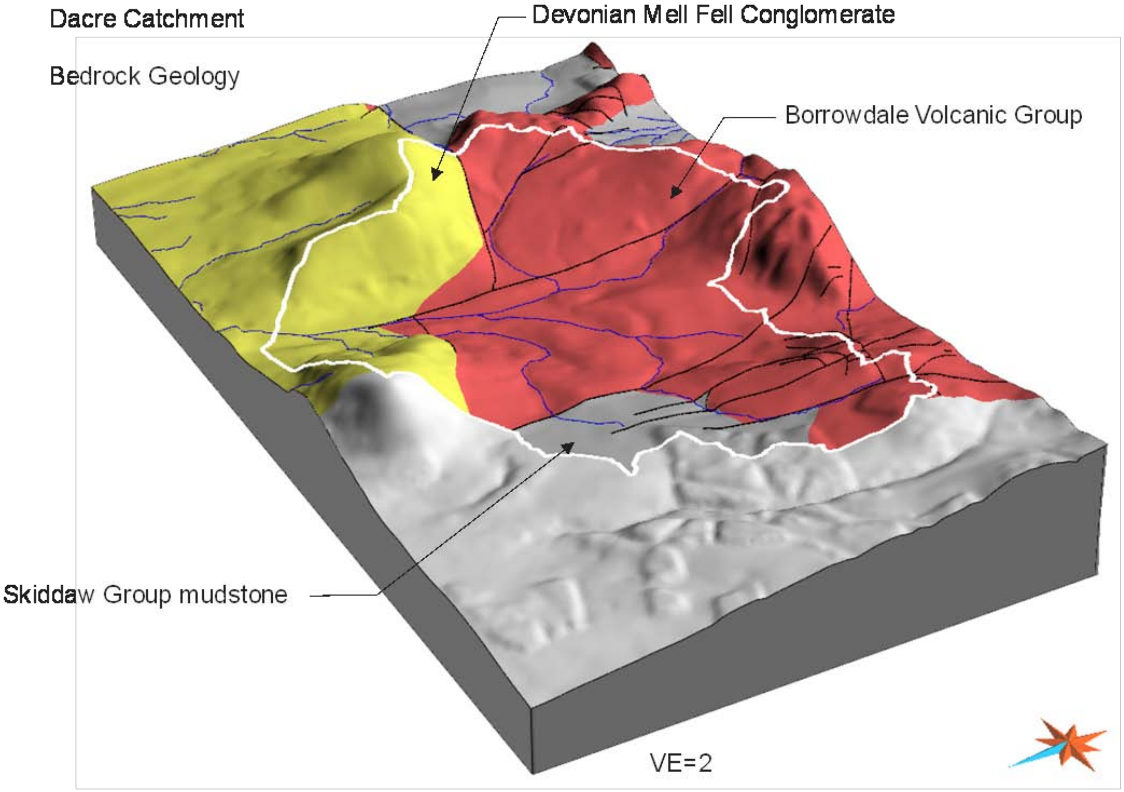
Figure 4.1 The Dacre Beck Catchment viewed from the SE. Long axis of block diagram is 6.5 km across. Vertical scale exaggerated by factor of two. Blue spine on orientation symbol indicates direction of North.

4.2 GEOLOGY

The Dacre Beck above Nabend is a hardrock catchment dominated by volcanic andesite sheets of the Birker Fell Formation (Borrowdale Volcanic Group). The andesites are extensively faulted and typically have thick autobrecciated margins (Stone et al. 2010). Devonian conglomerates form the conical hills of Great Mell Fell and Little Mell Fell at the catchment exit (Figure 4.2). The conglomerates result from the development of alluvial fans along the flanks of the Lake District massif in the Devonian and have an unconformable or faulted contact with the underlying Borrowdale Volcanic Group.

Devensian glacial till covers the central basin of the Dacre Beck catchment but is absent from much of the higher fells (Figure 4.3). The floor of the catchment has a dissected, hummocky relief with valleys and hollows locally infilled with sands, gravels, peats and silty alluvium.

The Dacre Beck catchment lies on 1:50 000 scale geological maps 29 (Keswick) and 30 (Appleby).



Geological features, BGS, © NERC. River network data from CEH, © NERC. © Crown copyright. All rights reserved. NEXTMap Britain elevation data from Intermap Technologies.

Figure 4.2 Bedrock geology of the Dacre Beck Catchment. Long axis of block diagram is 6.5 km across. Vertical scale exaggerated by factor of two. Blue spine on orientation symbol indicates direction of North.

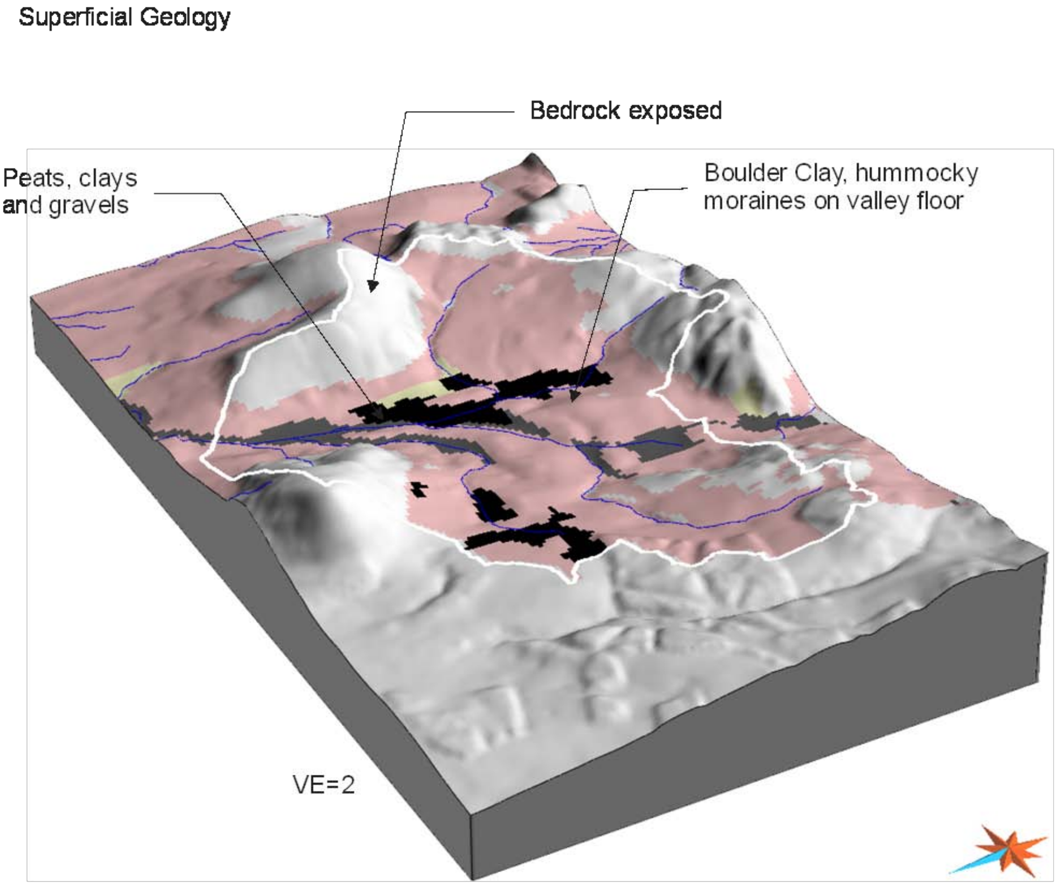


Figure 4.3 Superficial geology of the Dacre Beck. Long axis of block diagram is 6.5 km across. Vertical scale exaggerated by factor of two. Blue spine on orientation symbol indicates direction of North.

4.3 HYDROGEOLOGY

4.3.1 Boreholes

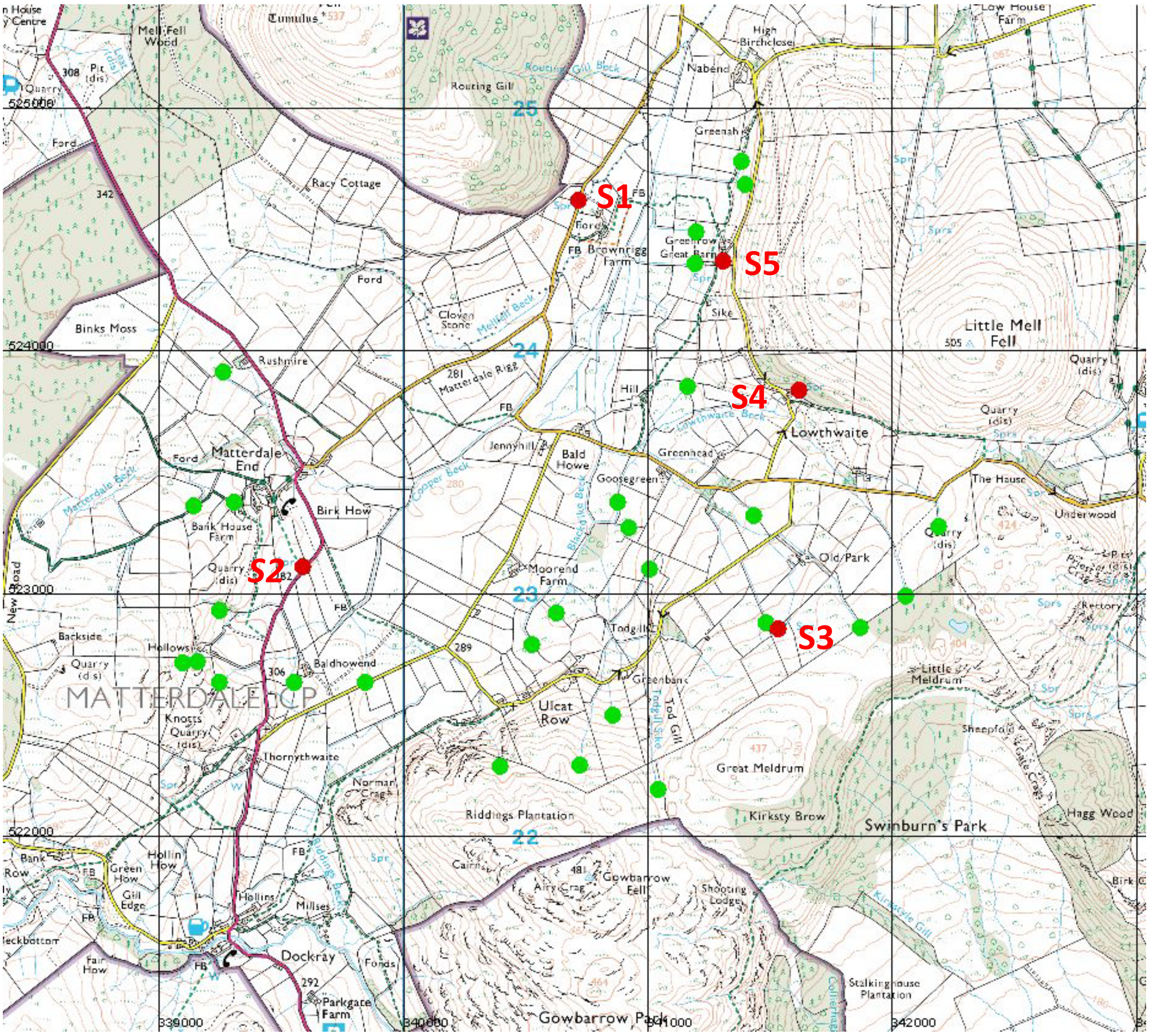
No boreholes are recorded in the catchment.

4.3.2 Springs and Issues

A number of springs and numerous issues feed the Dacre Beck. Figure 4.4 and Table 4.1 show those which drain to the river and its tributaries upstream of Nabend. In addition several other issues rise and subsequently sink within the catchment.

Table 4.1 Locations of Springs and Issues in the Dacre Beck catchment

ID	Type	Easting	Northing	Comment
DS1	spring	340719	524620	Flows into Mell Fell Beck
DS2	*spring*	*339586*	*523108*	*Not clear where this discharges to*
DS3	spring	341540	522850	Flows to Blackdike Beck
DS4	spring	341623	523838	Flows to Lowthwaite Beck
DS5	spring	341308	524366	Flows to Thackthwaite Beck
DI1	issue	339265	523911	Flows into Matterdale Beck
DI2	issue	339312	523374	Flows into Matterdale Beck
DI3	issue	339147	523358	Flows into Matterdale Beck
DI4	issue	339248	522927	Flows to Cooper Beck
DI5	issue	339161	522717	Flows to Cooper Beck
DI6	issue	339100	522711	Flows to Cooper Beck
DI7	issue	339249	522632	Flows to Cooper Beck
DI8	issue	339554	522631	Flows to Cooper Beck
DI9	issue	339846	522633	Flows to Cooper Beck
DI10	issue	340397	522286	Flows to Cooper Beck
DI11	issue	340527	522789	Flows to Blackdike Beck
DI12	issue	340626	522922	Flows to Blackdike Beck
DI13	issue	340722	522295	Flows to Blackdike Beck
DI14	issue	340860	522499	Flows to Blackdike Beck
DI15	issue	341042	522195	Flows to Todgill Sike
DI16	issue	341046	523097	Flows to Blackdike Beck
DI17	issue	340925	523271	Flows to Blackdike Beck
DI18	issue	340879	523374	Flows to Blackdike Beck
DI19	issue	341482	522878	Flows to Blackdike Beck
DI20	issue	341871	522860	Flows to Blackdike Beck
DI21	issue	341435	523319	Flows to Blackdike Beck
DI22	issue	341164	523847	Flows to Blackdike Beck
DI23	issue	342055	522988	Flows to Lowthwaite Beck
DI24	issue	342190	523276	Flows to Lowthwaite Beck
DI25	issue	341195	524360	Flows to Thackthwaite Beck
DI26	issue	341196	524486	Flows to Thackthwaite Beck
DI27	issue	341402	524685	Flows to Thackthwaite Beck
DI28	issue	341385	524776	Flows to Thackthwaite Beck



Based on OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010.

Figure 4.4 Location of Springs (red) and Issues (green) supporting the Dacre Beck. Grid lines are at 1 km intervals.

Figure 4.5 shows the location of the springs and issues in relation to the underlying geology. It may be noted that the three most northerly springs; DS1, DS4 and DS5 all appear to occur close to the junction of the Mell Fell Conglomerate outcrop and the overlying superficial deposits, which may imply that the conglomerate possesses some degree of permeability, although this is not expected to be high.

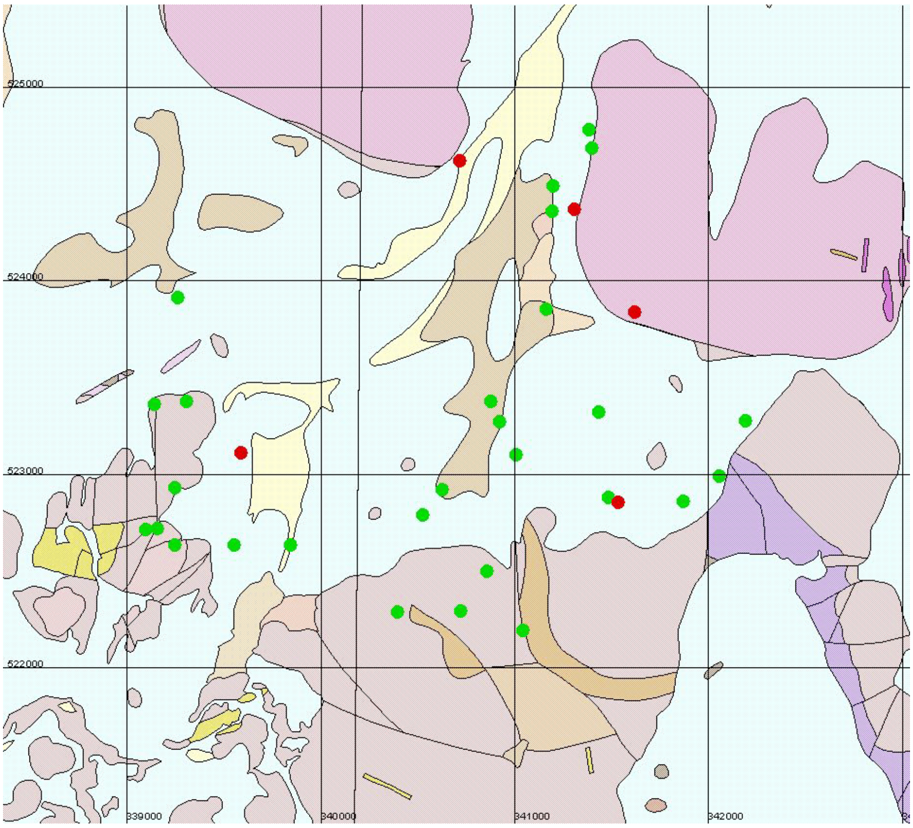


Figure 4.5 Location of Springs (red) and Issues (green) supporting the Dacre Beck related to geology (Mell Fell conglomerate shown in purple, superficial deposits in light blue). Grid lines are at 1 km intervals.

4.4 CONCLUSION

As with the other two catchments, the extensive superficial deposits in the Dacre catchment are likely to affect its hydrogeology to a significant extent. In the Dacre catchment the superficial deposits are also very variable. The underlying bedrock is unlikely to provide much aquifer potential, although the conglomerate may have limited permeability and any groundwater is likely to be mainly restricted to any arenaceous units within the Boulder Clay or to local gravel deposits.

5 Discussion and conclusions

The hydrogeology of all three of the sub-catchments is likely to be dominated by the nature of the superficial deposits. In the Pow catchment, while significant bedrock aquifers are present (e.g. St Bees Sandstone, Penrith Sandstone), they do not appear to drain to the river and any river baseflow will be dominated by discharge from the superficial deposits. In the Dacre catchment the bedrock is likely to be weakly permeable and again river baseflow is likely to be dominated outflows from the superficial deposits. In the Morland catchment the aquifer characteristics of the Carboniferous bedrock are uncertain, as they consist of a mixture of limestones, shales and sandstones. However the dip of the bedrock is likely to result in any aquifers in the limestones being localised and also the catchment includes significant quantities of superficial deposits which are likely to have an important impact on groundwater movement to the river.

The current hypothesis of the nature of the hydrology of the catchments is, therefore, that the rivers draining the sub-catchments gain their flow from a set of sources with different residence times. Rapid surface runoff to the rivers and their tributaries undoubtedly occurs, and, given the argillaceous nature of much of the drift, is likely to dominate river flows. However delayed flow, resulting from near-surface or deeper groundwater flows is also likely to occur, probably over a spectrum of timescales, as a result of a range of subsurface flow mechanisms. For example relatively rapid shallow interflow may well occur, perhaps as outflows from shallow field drains. Also, given the lithological heterogeneity of the superficial deposits, there may be more delayed outflows from perched aquifers. Finally, deeper slower groundwater flowpaths through bedrock aquifers, perhaps especially in the Morland, may result in a component of older water in the surface outflows from the catchments. Understanding how these systems contribute to the integrated surface outflow from the catchment will be important if the effects of land use change on the river flows are to be evaluated properly.

On the basis of this study it is, therefore, concluded that it is quite possible that the groundwater component of the streams in all three catchments may have a range of ages, and, given the likely hydrogeological dominance of the superficial deposits, groundwater flows to the stream may substantially occur within the timeframe of the DTC studies. Changes to the concentrations pollutants carried by these shallow groundwaters as a result of farm measures may, therefore, be detectable in the stream outflows within the lifetime of the DTC programme.

The extent to which groundwater is a significant component of the stream discharge in any of the catchments is unknown at present, but measured baseflow indices in the Eden are commonly of the order of 0.3 to 0.5, suggesting that groundwater is important (and is likely to dominate summer streamflows).

It is, therefore, recommended that the hydrogeology of the catchments is investigated further, in particular to clarify the hydraulic role of the superficial deposits. Studies should include geological investigations, hydrological assessments of the nature and importance of baseflow, studies of the origin and nature of the springs and issues, and work to clarify the nature of and relationship between, surface flows and shallow and deep groundwater systems. In addition the role of the superficial deposits in groundwater recharge should be investigated.

All the conclusions of this report are based on a desk study only, and without field investigations are very speculative, however they do provide a basis for further work, some of which will be started in the second phase of the BGS study.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

ARTHURTON R S AND WADGE A J. 1981. Geology of the country around Penrith. *Memoir of the Geological Survey of Great Britain*, Sheet 24 (England and Wales).

BOTT M H P 1974. The geological interpretation of a gravity survey for the English Lake District and the Vale of Eden. *Journal of the Geological Society of London*. No 130, 309-331.

BUTCHER A S, LAWRENCE A R, JACKSON C , CUNNINGHAM J, CULLIS E L, HASAN K, AND INGRAM J. Investigating rising nitrate concentrations in groundwater in int the Permo-Triassic aquifer, Eden Valley, Cumbria. From: BARKER, R. D.& TELLAM, J.H. (eds) 2006. Fluid Flow and Solute Movement in Sandstones: The Onshore UK Permo-Triassic Red Bed Sequence. Geological Society, London, Special Publications, 263, 285–296. 0305–8719/06 The Geological Society of London 2006.

CHADWICK R A, HOLLIDAY D W, HOLLOWAY S AND HULBERT, A G. 1995. The structure and evolution of the Northumberland-Solway Basin and adjacent areas. *Subsurface Memoir of the British Geological Survey.* ISBN 0118845012.

HOLLIDAY D W. 1993. Geophysical log signatures in the Eden Shales (Permo-Triassic) of Cumbria and their regional significance, Proceedings of the Geological Society of Yorkshire 49, 4, 345-354.

INGRAM J A. 1978. The Permo-Triassic Sandstone Aquifers of North Cumbria, Hydrogeological Report, North West Water Authority.

KNOTT S D. 1994. Fault zone thickness versus displacement in the Permo-Triassic sandstones of NW England, *Journal of the Geological Society of London*, 151, 17-25.

MACCI L. 1991. A field guide to the continental Permo-Triassic rocks of Cumbria and northwest Cheshire, Liverpool Geological Survey.

MONKHOUSE R A AND REEVES M J. 1977. A preliminary appraisal of the groundwater resources of the Vale of Eden, Cumbria, Technical Note, Central Water Planning Unit. Reading, No.11.

STONE P, MILLWARD D, YOUNG B, MERRITT J W, CLARKE S M, MCCORMACK M AND KAWRENCE D J D. 2010. British Regional Geology: Northern England (Fifth Edition). Keyworth Nottingham: British Geological Survey.

VINES K J. 1984. Drift Recharge. North West Water Hydrogeological Report No. 145

WADGE A J. 1966 HYDROGEOLOGY (PP 23-29) IN ANON CUMBRIAN RIVERS HYDROLOGICAL SURVEY. MIN HO. LOC. GOVT. 117 PP HSMO