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# Hydrogeology of Wales

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BRITISH GEOLOGICAL SURVEY

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## Articles

# Hydrogeology of Wales: Summary

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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Wales enjoys a humid westerly airstream which provides a plentiful source of water. Public supply largely depends on upland gathering and surface storage, but groundwater is also supplied. Approximately 250 Ml $d^{-1}$ (91 $Mm^3$ $a^{-1}$) or about 8 per cent of the total water in public supply in Wales derives from groundwater and a further 95 Ml $d^{-1}$ (34 $Mm^3$ $a^{-1}$) is abstracted for private consumption from about 21 000 boreholes, wells and springs. Private abstraction is limited and of a local scale because of the indurated and fractured nature and modest permeability of many of the aquifers. It is nevertheless of significant social and economic importance and is used for drinking water, farming, and light industry. Development of groundwater remains patchy due to a perception that it is unlikely to be present in useable quantities in areas such as the hard rock terrains typical, for example, of much of central and west Wales. Groundwater is also important as it maintains low river flows during dryer periods.

The traditional perception of groundwater in Wales is as an insignificant resource that has been a hazard to the mining communities. The Water Framework Directive (**European Community, 2000**) has brought new impetus to the understanding of groundwater in Wales as the Directive requires that the physical and chemical status of even the smallest producing aquifers be reviewed and remedial targets set. There are also several significant innovative groundwater schemes in Wales, including the Clwyd Augmentation/Abstraction Scheme and hydrogeological investigations carried out during the development of the Cardiff Bay Barrage.

Wales has a wide range of aquifers that reflect its diverse geology. These include the Triassic sandstone aquifer in the Vale of Clwyd in north Wales, the only aquifer designated as Principal A type by the Environment Agency Wales, the 'Old Red Sandstone' of the Brecon area and large areas of Carboniferous Limestone. Quaternary and alluvial deposits also provide some resource potential.

Much of central and upland Wales comprises Lower Palaeozoic and older bedrock. There are large areas of metasedimentary strata, typified by rocks such as mudstone, siltstone and sandstone which offer shallow fracture porosity and storage with no supporting intergranular storage. The Silurian and Ordovician rocks of west Wales, for example, sustain small springs and shallow boreholes enough to supply rural demand. The alluvial deposits that floor most valleys provide additional storage if they are in hydraulic continuity with the fractured bedrock. Deeper circulation occurs in the Llandrindod Wells area of central Wales where a number of chemically mature spring sources were used as Victorians spa resorts.

Devonian sandstones and mudstones crop out to the north and east of the South Wales Coalfield. Shallow weathering and fracturing provide storage and transport to groundwater although there is little intergranular storage. Nevertheless the aquifer is widely exploited from modest yielding springs and boreholes for rural and agricultural supply. The average transmissivity is 51 $m^2$ $d^{-1}$.

Carboniferous Limestone covers extensive areas in both north and south Wales. Groundwater flows through the Carboniferous Limestone via fractures and available karst features. Swallow holes are common in the main Carboniferous Limestone outcrops.

The Millstone Grit Facies is poorly represented at outcrop in Wales but the overlying Coal Measures are widespread in both the North Wales and South Wales coalfields. In north Wales groundwater transport and storage are limited to available fractures although there is some storage available in the sandstone horizons and in former mine voids. The working collieries all required to be dewatered, with shaft sump discharges generally of between 5 and 20 l $s^{-1}$, although some pumping rates fluctuated seasonally. Groundwater may be locally confined by till, and yields up to 5 l $s^{-1}$ have been attained in boreholes, exceptionally 15 l $s^{-1}$ at a borehole near Mold. However, both vertical and horizontal conductivity are poor and initial pumping rates may not always be sustainable.

In south Wales the Coal Measures comprise low permeability hydrogeological units composed of carbonaceous mudstones and sandstones with subordinate siltstones and coal seams. The Pennant Sandstone Formation is dominated by sandstone while the Lower and Middle Coal Measure formations are dominated by mudstone. Moreover the Pennant sandstones are generally thick, massive, feldspathic and micaceous and form the relatively high ground at the centre of the South Wales Coalfield. The permeabilities of the sand horizons are generally less than 1 m $d^{-1}$. Fracture permeability enhances the transmissive properties of these rocks although secondary deposition of silica may inhibit matrix permeability. Folding and faulting has produced some secondary fracture permeability, and mining activity tends to enhance fracture permeability in the overburden. At outcrop, borehole yields up to 8 l $s^{-1}$ are feasible, but the permeability of the sandstone horizons depends on the distribution and intensity of fractures within them.

The Triassic sandstone aquifer in the Vale of Clwyd is situated in a small graben some 5 km wide. The sandstone is concealed by up to 80 m of glacial till, and some fluvioglacial gravel material. The main aquifer is in the Ruthin and Denbigh area in which the central part of the aquifer was originally confined by till with an artesian head of about 6 m. Transmissivity is between 800 and 2000 $m^2$ $d^{-1}$ and storativity between $10^{-3}$ and $10^{-4}$.

Quaternary deposits include a variety of tills, both according to their depositional history and their lithology, and a complex array of fluvioglacial sands and gravels. There are also Recent alluvial and lacustrine deposits. The granular superficial deposits form shallow aquifers in low-lying areas such as valley bottoms. There are several important groundwater-dependent ecosystems including coastal dune-lands and significant domed peats, such as Tregaron in the upper Teifi catchment in west Wales.

Groundwater has stable physical and chemical properties, which are beneficial to a number of key industries. It provides a source of alkalinity when discharged as base flow to often acidic surface waters and the base flow maintains low river flows during dryer periods. Groundwater can also be a potential hazard and was of great concern to the metal and coal mining industries in their heyday. Coal production in south Wales peaked in 1926, the year of the General Strike, but declined steadily thereafter, the last working pit closing in 2008.

High rainfall and recharge coupled with low transmissivities, promote shallow water tables in many areas with a consequent complex relationship between surface water and groundwater. Contamination of groundwater by acid mine drainage in parts of south, west and north-east Wales, coupled with risks from contaminated land, the latter a legacy of the heavy industry that used to be prevalent in the valleys of south and north-eastern Wales, may have an adverse impact on groundwater (and surface water) quality. Diffuse pollution from agriculture and forestry is also a problem in some areas. Nevertheless, the resource is underexploited and considerable potential exists for abstraction of good-quality groundwater in much of Wales.

# Hydrogeology of Wales: Acknowledgements

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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Groundwater investigation in Wales has tended to be piecemeal with project reports and technical papers issued from time to time. The only holistic review of groundwater in Wales was written by **Bassett (1969)** although various regional compilations, such as the two available hydrogeological maps (**BGS, 1986; 1989**), have updated Bassett's work. More recently the regulator, Environment Agency Wales, has published catchment-scale reports and has commissioned a range of in depth studies, while others have worked at project-level providing insight into aspects of a variety of groundwater occurrence problems peculiar to Wales.

This report attempts to provide an updated review of the occurrence of groundwater throughout Wales. It is part of a series of regional- and aquifer-scale reports issued by the British Geological Survey, the Groundwater Programme Research Report series. An introductory chapter is followed by chapters on each lithostratigraphical system. These describe the outline geology and hydrogeology and highlight the availability of groundwater, its quality and any issues pertaining to the hydrogeology of the units within each system. In addition a concluding chapter describes the past and present regulatory framework in Wales and the modern-day management tools used by Natural Resources Wales with illustrations of some of the problems that need to be addressed.

The report draws on data available in the public domain, both published and unpublished. The reference list provides a valuable record of all these sources. In addition datasets held by both the British Geological Survey and Natural Resources Wales have been consulted along with data held by Dŵr Cymru Welsh Water and Cardiff University.

Although the report was compiled by Nick Robins and Jeff Davies, an important contribution was also prepared by David Jones Natural Resources Wales and Gareth Farr (previously of Environment Agency Wales) who drafted the bulk of the chapter on management and regulation. The principal authors are also grateful to Kay Roberts and Beth Davies and others at Natural Resources Wales for valuable peer review comments on the manuscript. Peter Neve is thanked for comments on hydrogeology in north east Wales. David Schofield and Colin Waters provided geological advice including validation of stratigraphical terminology.

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# Hydrogeology of Wales: Introduction

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
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Wales receives wet westerly winds and is consequently well-endowed with water resources. In addition to its surface waters, Wales also has a wide range of aquifers that reflect its diverse geology, and although groundwater cannot compete with the surface water resources in terms of volume, it does offer a valuable alternative or supplementary source, particularly in rural areas. Groundwater has stable physical and chemical properties, which are beneficial to a number of industries including brewing, distilling, fish farming and dairy processing and it provides a source of alkalinity when blended with the often-acidic surface waters derived from upland gathering grounds. Groundwater is not only an important resource but it also maintains low river flows during drier periods with continued discharge of groundwater base flow into surface waters. Groundwater is also a potential hazard — mine dewatering has taxed Welsh mining engineers ever since the Industrial Revolution. Coal production in south Wales peaked at the start of World War One only to decline during hostilities; recovery to full production was achieved by 1926, the year of the General Strike, but has declined steadily since (**Brabham, 2004**).

Groundwater is available throughout Wales, the more productive aquifers being the Carboniferous Limestone of north and south Wales and the Triassic sandstones in the Vale of Clwyd, the only aquifers designated as Principal type by Environment Agency Wales, and the Devonian age sandstones bordering Herefordshire and to the north of the South Wales Coalfield. There are, however, abundant surface water resources. Approximately 91 $Mm^3 a^{-1}$ or about 8 per cent of the total water in public supply in Wales derives from groundwater and a further 34 $Mm^3 a^{-1}$ is abstracted for private consumption from about 21 000 boreholes, wells and springs (**EA Wales, 2009**). The main water undertaking is Dŵr Cymru — Welsh Water. The estimated annual abstraction against likely overall annual renewable resource potential, based on an analysis by the then Welsh Water Authority undertaken in the mid 1970s when abstraction for industrial use was at its peak is shown in the **resource potential and annual abstraction table** (**Monkhouse, 1982**). This analysis shows that only about 10 per cent of the estimated groundwater resource potential was then used. However, the total estimated abstraction in the 1970s (111 $Mm^3 a^{-1}$) was only slightly less than that estimated for today (125 $Mm^3 a^{-1}$) and the groundwater resource potential remains to this day underutilised.

## Estimated annual renewable groundwater resource potential and annual abstraction in 1977 (after Monkhouse, 1982).

| Aquifer | Annual renewable resource potential ($Mm^3 a^{-1}$) | Annual abstraction ($Mm^3 a^{-1}$) |
|---|---|---|
| Quaternary deposits | 206 | 11 |
| Permo-Triassic age sandstones | 27 | 12 |
| Coal Measures facies | 412 | 37 |
| Basal Grits | 22 | 1 |
| Carboniferous Limestone facies | 376 | 46 |
| Devonian | 379 | 5 |
| Total | 1421 | 111* |
| *In 2009 the overall likely estimate by the Environment Agency Wales was 125 $Mm^3 a^{-1}$. | | |

Private abstraction is largely of a limited and local-scale because of the indurated and fractured nature and modest permeability of many of the aquifers. It is nevertheless of significant social and economic importance and is used for drinking water, farming, and light industry. There are several reasons why groundwater is important even in areas where surface water is abundant. Groundwater offers consistent and generally favourable quality and is readily accessible at least in small quantities. It is also inexpensive to develop and is largely abstraction license exempt. Overall development of groundwater is patchy, partly due to a perception that groundwater is unlikely to be present in usable quantities in areas such as the hard rock terrains typical, for example, of much of central and west Wales.

High rainfall and recharge coupled with low transmissivities, promote shallow water tables in many areas with a consequent complex relationship between surface water and groundwater (**Robins, 2009**). Karst conditions in the Carboniferous Limestone have created pathways between sinks and risings in which surface water may be diverted underground to emerge in an adjacent catchment. Contamination of groundwater by acid mine drainage in parts of south Wales, west Wales and north-east Wales, coupled with risks from contaminated land, the latter a legacy of the heavy industry that used to be prevalent in the valleys of the south and north-eastern Wales, may have an adverse impact on groundwater (and surface water) quality. Diffuse pollution from agriculture and forestry is also a problem in some areas. Nevertheless, the potential exists for abstraction of good-quality groundwater in much of Wales, particularly in remote areas where pollution risks are low.

Groundwater has also fostered a number of high-profile industries. At one time brewing relied on groundwater for make-up water, as the mineralisation of the water not only offset the need to add brewing salts but also provided a unique product flavour. Today there are still a few brewers using groundwater including the Felinfoel Brewery Company near Llanelli and the Penderyn Distillery near Aberdare, both drawing groundwater from Carboniferous strata. Welsh groundwater is also bottled at various locations and sold as Natural Mineral Water, and at a price significantly in excess of that of an equivalent volume of petrol or diesel.

# Hydrogeology of Wales: Introduction - geology and groundwater

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Author(s): N S Robins and J Davies, British Geological Survey
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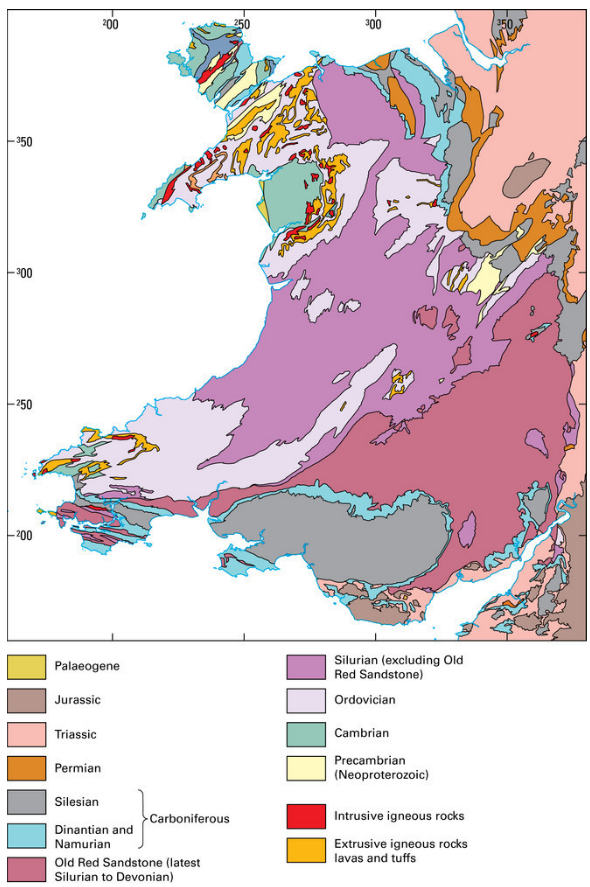
The geology of Wales is extraordinarily diverse; the geological descriptions in this report are based on those presented in the regional geochemistry atlas for Wales (**BGS, 2000**) although some terminology has since changed. The stratigraphical sequence in Wales extends from the Precambrian through to recent. The oldest rocks occur in north Wales and are mainly metamorphic and igneous Precambrian and Cambrian rocks (**Figure P841814**). Central Wales is dominated by Lower Palaeozoic age sediments (Ordovician and Silurian) trending south-west to north-east. The Precambrian and early Lower Palaeozoic rocks are overlain by Devonian sandstones, mudstones and conglomerates in east Wales and the Welsh Borderland. Carboniferous strata are present in south Wales and parts of the north, Triassic strata occur in the Vale of Clwyd and Jurassic deposits occur in the Vale of Glamorgan. Till and associated glacial material are widespread on the lower-lying ground but tend to be absent in many upland areas. Alluvium and glacial outwash material occur in many valleys and there are several large groundwater dependent peat bogs. Soil cover is typically thin on the higher ground, particularly in parts of Snowdonia where outcrop is extensive.




Solid geology in Wales. P841814.

Hydrogeological maps for northern and southern Wales (**BGS, 1986; 1989**) provide a valuable graphical summary of the occurrence and nature of groundwater in the Principality. Marginalia to these maps include cross-sections, hydrochemical information, selected hydrographs, rainfall distribution and a summary description of groundwater availability. However, such maps are not available for central Wales as the groundwater systems contained within the basement rocks in this area have not previously been considered in resource terms.

The Late Neoproterozoic, Cambrian, Ordovician and Silurian rocks have a low interstitial porosity and permeability, although many have a limited fracture permeability and porosity. Depth of weathering tends to be shallow especially on valley sides where glacial erosion has removed weathering products. Groundwater occurs within an otherwise shallow weakly permeable aquifer that is capable of maintaining rural domestic and limited agricultural and industrial demand.

The Upper Old Red Sandstone in south to mid Wales consists mainly of unconsolidated, well-cemented, flaggy sandstones with thin sandy marls. Most groundwater flow is limited to fractures, but marl bands limit vertical flow and promote hillside springs. The Devonian aquifer is regionally important in sustaining a large number of public and private water supplies, although groundwater yields and springs may decline during prolonged periods of dry weather and some may dry up completely. The Lower Old Red Sandstone is essentially mudstone and siltstone.

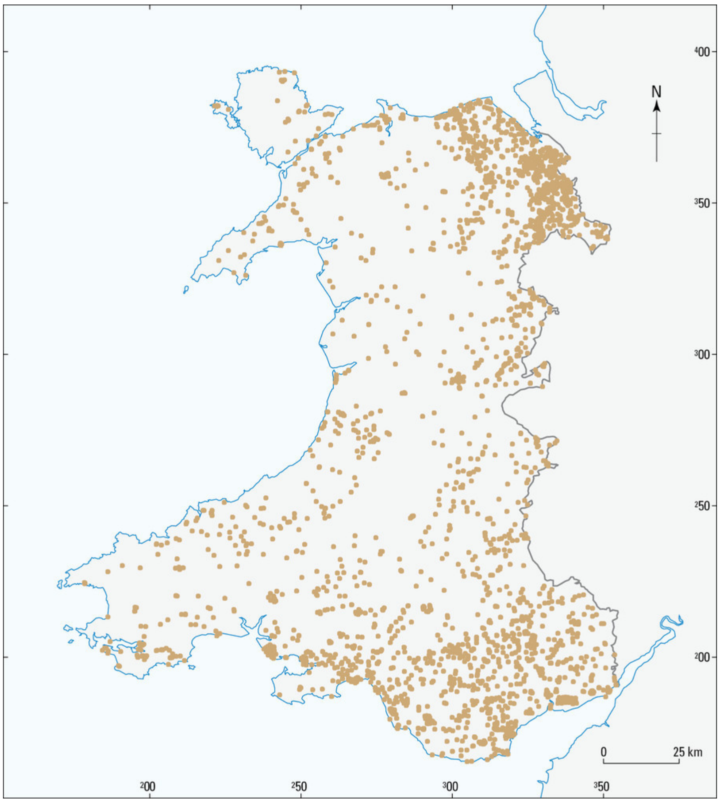
Carboniferous sediments, mainly limestones overlain by Coal Measures Facies, occur both in the south and north-east of Wales and in Anglesey. The limestones represent an important groundwater source and have a high fracture permeability resulting from a well-developed joint and fracture system, but with low matrix permeability. Karstic flow conditions occur throughout the limestones other than those in Anglesey. Significant yields are obtained from major spring resurgences that generally occur near the base of the sequence or along faults. Groundwater flow velocities can be rapid with movement taking place along a small number of large fractures. Recharge processes are supplemented by shallow holes or dolines that form point sources for recharge. Significant quantities of groundwater were formerly pumped from mainly fractured sandstones of the Middle Coal Measures and Pennant Sandstone Formation within the South Wales Coalfield both for mine dewatering and public water supply.

Triassic-age sandstones are found in north-east Wales in the Clwyd–Merseyside Basin and form a small aquifer that is exploited for public supply in the Vale of Clwyd. The strata comprise cross-bedded, well-cemented, fine- to medium-grained sandstones with thin lenses of mudstone. The sediments generally exhibit high fissure and intergranular permeability. Clay-grade superficial deposits cover the Triassic outcrop restricting recharge in some places and confining the underlying aquifer to generate artesian heads of up to 6 m above ground level.

Local Quaternary deposits (mainly glaciofluvial, alluvial and colluvial) throughout Wales are thin and variable in nature but have a high permeability and are useful in providing local domestic supplies especially in low-lying areas. They may be poorly protected and vulnerable to surface pollution.

Most of the aquifers in Wales are unconfined and have shallow flow systems. The groundwater is generally well oxygenated and weakly mineralised with calcium and bicarbonate forming the main ionic components. More strongly mineralised groundwater, depleted in oxygen, occurs in deeper aquifer systems. Groundwater from the Silurian and Ordovician strata is generally of good quality, varying from Ca-$HCO_3$ to Ca-Na-Cl types in relation to local geology, residence time and drift type. Deeper water from the confined Coal Measures facies is typically of poor quality due to the solution of iron and sulphate resulting from many years of mining below the water table. The Triassic strata are typically moderately mineralised and of the Ca-$HCO_3$ type.

Whereas the groundwater potential of much of Wales has traditionally been ignored (**Bassett, 1969**), the requirements of European Community Directives such as the Water Framework Directive have provided a new focus. Data are available on the Triassic and Devonian aquifers but remain scarce for much of the Carboniferous, other than the Carboniferous Limestone, and the fractured hard-rock aquifers which prevail in central and west Wales (**Robins et al., 2005**). The distribution of water boreholes based on British Geological Survey/Environment Agency records (**Figure P859258**) indicates a paucity of data outside north Wales and the Cheshire Basin and parts of south Wales.



Distribution of water boreholes recorded by BGS/EA. P859258.

Although Wales has never been dependent on its groundwater resources, there have been some significant innovative groundwater schemes. These include the Clwyd Augmentation/Abstraction Scheme (**Lambert, 1981**; **ESI, 2003**), the Dee Regulation Scheme and hydrogeological investigations carried out during the development of the Cardiff Bay Barrage (**Heathcote et al., 2003**).

# Hydrogeology of Wales: Introduction - topography, climate, land use and natural resources

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Author(s): N S Robins and J Davies, British Geological Survey
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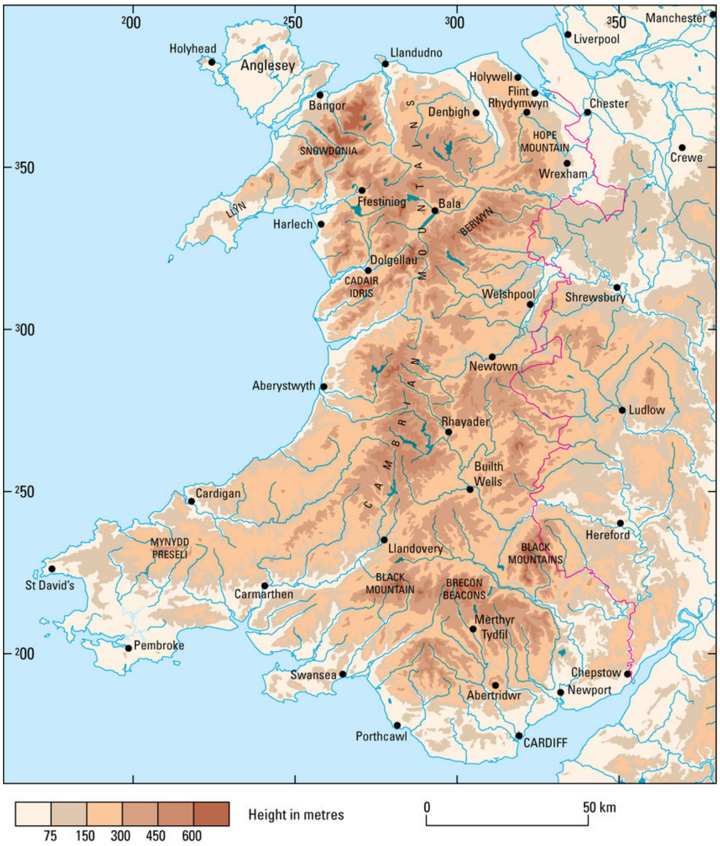
Wales is a principality which is governed from Westminster but which has its own Welsh Assembly Government that sits in Cardiff. The Principality covers an area of 20 000 km$^2$, about 8.5 per cent of the total UK landmass, and contains about 5 per cent of the total UK population.



Wales topography and place names. P841815.

Wales offers a rich environmental diversity. It is dominated by uplands, 25 per cent of the land is above 305 m in elevation, including ranges such as Snowdonia, the Cambrian Mountains and the Brecon Beacons (**Figure P841815**). The Principality has 1180 km of coastline with numerous bays, sandy beaches, peninsulas and cliffs (**Plate P802042**). It possesses large areas of National Parks with a variety of scenery, yet there are also numerous historical metal and coal mining industrial sites and large tracts of land contaminated from former industrial processes. The National Parks and five areas of outstanding natural beauty cover almost a quarter of the country. There are over 1000 sites of special scientific interest, nearly 100 nature reserves and six environmentally sensitive areas.


View from Aberaeron of the coast of Cardigan Bay extending north towards Aberystwyth. P802042.

With the exception of the major river estuaries in the north and south, Wales has no navigable rivers. The larger rivers such as the Taff, Teifi, Tywi, Usk and Clwyd flow from the central mountain ranges to the west coast. The Severn (the second longest river in the UK) and the Wye rise in the Cambrian Mountains and flow into the Bristol Channel. Wales has more than 400 natural lakes and more than 90 man-made reservoirs, many of which are used for water supply and some for hydroelectric power generation and

Elan Valley, Caben Cock dam in spate. P802061.


... and in drought, Pen-y-Fan, in the Brecon Beacons from wall of the Neuadd Reservoir north of Merthyr Tydfil during 1976. P802060.

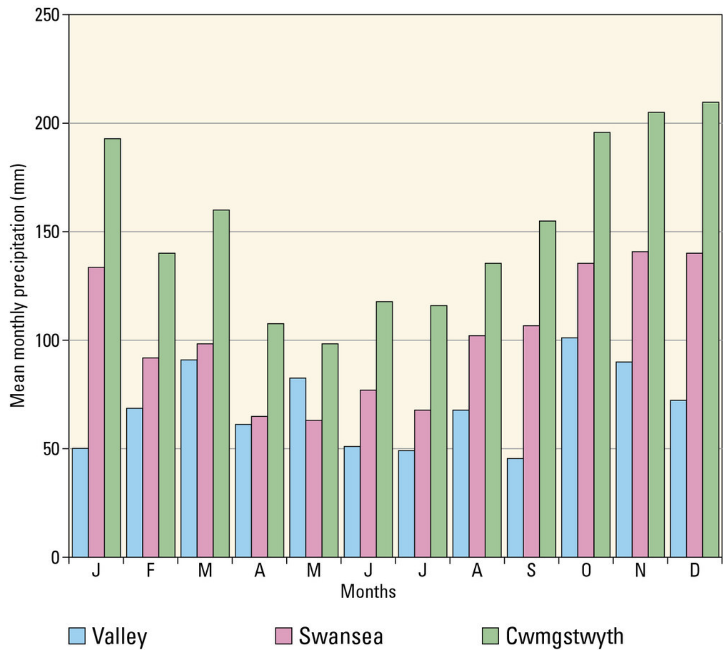
power storage (**Plates P802061 and P802060**). Bala in north Wales is the largest and deepest of the natural lakes and is 6.4 km long by 1.6 km wide. Some of the upland water storage is used to supply neighbouring English metropolitan areas notably Birmingham.

The main mountain chains are the Cambrian Mountains which are situated between the head of the Tywi catchment in central and west Wales, the Brecon Beacons/Black Mountains of south Wales and Snowdonia in the north of Wales (**Figure P841815**). In the north the highest peak is Snowdon (1085 m) with Cader Idris (892 m) in the central area overlooking the Mawddach Estuary near Barmouth where other peaks are generally below 600 m. In the south, the Brecon Beacons rise to 886 m and the Black Mountains to 811 m; both are more rounded in shape than the Cambrian Mountains. Radnor Forest (660 m) and Clwydian Range in central Wales in the north comprise rolling hills. Snowdonia is characterised by deeply incised valleys, whereas the valleys of west Wales are more open. South Wales is characterised by a coastal plain which varies from 1 km width at Port Talbot to 20 km in the Vale of Glamorgan.

Northern central Wales is drained by the upper reaches of the Severn feeding into the major reservoirs of the Elan valley upstream of Rhyadyr. Much of southern central Wales drains to the river Wye that flows through an interior plain centred on the town of Builth Wells. The lower course of the Wye is characterised by dissected lowlands divided by discontinuous lines of low hills. The river cuts a series of incised meanders into the Forest of Dean. The plateaux are broken up towards the north-east around the Teme Valley separating the Welsh Border hills from the uplands of central Wales. The high plateaux are strongly dissected in the south and drop to the coastal plain along the Severn Estuary.

Wales has a maritime climate, and the influence of Atlantic weather systems gives it somewhat changeable weather. Rainfall is plentiful — typically over 1000 mm $a^{-1}$ with the least usually recorded in May/June and the most in December/January (see http://www.metoffice.gov.uk/wl/print.html [1]). The distribution of rainfall varies widely, with the highest average annual totals being recorded in the mountainous areas of Snowdonia and the Brecon Beacons (**Figure P859259**). Snowdonia is the wettest part of Wales with average annual totals exceeding 3000 mm.

In the summer, Wales, other than the mountainous areas, has an average six hours sunshine per day, compared to between one and a half and two hours per day in winter months. July is normally the warmest month, with the highest temperatures inland away from the cooling influence of the sea. The mean temperature is 10 °C. Snow is rare at sea level, but more frequent over the hills. The average number of days each year when sleet or snow falls in Wales varies from about 10 or less in some south-western coastal areas to over 40 days in Snowdonia.



Mean monthly rainfall (mm) at Valley on Anglesey, Swansea and Cwmgstwyth in Ceredigion (after http://www.metoffice.gov.uk/wl/print.html [1]). P859259.

More than half of the population live in the industrial and commercial centres of south Wales, where the population density is around 500 $km^{-2}$. The industrialised area around Wrexham in north-east Wales is also a significant centre of population. The population of Wales is 2.9 million; the average population density is 140 people per square kilometre, which is roughly the same as the European average but half that for the United Kingdom.

Land use is dominated by agriculture. Approximately 80 per cent of the area of Wales is devoted to agriculture with some 30 000 holdings, the majority of which are dependant on livestock production. Grassland pasture for sheep and cows and rough grazing for sheep are the dominant agricultural features, but an additional 12 per cent of the land is forested.

Wales has numerous natural resources: coal and metal ores have been exploited from large deposits in the south, and to a lesser extent in the north. Coal remains the main mineral resource although mining has declined considerably and is now undertaken by opencast methods. Tower Colliery was the last working deep mine and this closed in January 2008. Extensive slate deposits exist in the north, and these have been exploited for roofing materials for many generations. Production continues today at a greatly reduced level. Metalliferous ores including sources of gold, silver, copper, lead and zinc were formerly mined at a large number of sites located throughout central and northern parts of Wales.

Light manufacturing forms the key industrial sector within the Welsh economy. Wales is also one of the most advanced automotive supply regions in the UK and food processing is another important industrial activity. Tourism and leisure are now increasing contributors to the economy, with Wales' popularity as a holiday destination mirroring the development of the tourist industry in the UK as a whole.

# References

[1] http://www.metoffice.gov.uk/wl/print.html

# Hydrogeology of Wales: Introduction - groundwater regulation

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The Water Act 1989 converted ten previously existing regional Water Authorities in England and Wales into privatised water and sewerage undertakings and created the National Rivers Authority as the new environmental regulator. The National Rivers Authority was subsumed into the newly formed Environment Agency in 1996. Several separate statutes, including the Water Act 1989 and the Water Resources Act 1963, were consolidated into the Water Resources Act 1991 to become the main statutory framework for the duties and powers of the Environment Agency. On the 1st April 2013 Environment Agency Wales was replaced with a new regulatory body, Natural Resources Wales. Natural Resources Wales combines the roles of Environment Agency Wales, Countryside Council for Wales and the Forestry Commission Wales.

Natural Resources Wales has a duty to secure the proper use of water resources. It is responsible for monitoring groundwater level and quality at 180 and 250 monitoring points respectively, and carries out additional monitoring work in the vicinity of groundwater-dependent terrestrial ecosystems. It issues licences for abstractions that exceed 20 $m^3 d^{-1}$ in order to regulate taking water from the environment, and to determine the volume that can be taken over a given period of time. Some rural areas of Wales remain license exempt because of the prevailing poorly yielding aquifers. Natural Resources Wales is also responsible for maintaining or improving the quality of fresh, marine, surface and groundwater and aims to prevent or reduce the risk of water pollution wherever possible, and to ensure that it is cleaned-up should pollution occur which could affect ecosystems or people.

Water quality standards for both public and private supply have been tightened in recent years and consolidated within the Water Supply (Water Quality) Regulations (2000). Some of the European directives have been implemented as Statutory Instruments whilst others became law as part of the Pollution Act, Part II. The Natural Mineral Waters Regulation (Statutory Instrument No. 1540 of 1999) provides for the recognition and exploitation of Natural Mineral Waters (as bottled groundwaters), their chemistry and potability.

The protection of surface and groundwater from pollution is provided for by the Environmental Permitting Regulations (2010), which define the requirements of sanitary landfill and other potentially hazardous activities.

The ongoing implementation of the Water Framework Directive (**European Community, 2000**) includes a need to assess the pressures and impacts affecting groundwater bodies with a view to determining the degree to which they are at risk from failing to meet Article 4 objectives. The Article 4 objectives in turn require that groundwater bodies achieve good chemical and quantitative status by the year 2015. Part of the assessment of whether a groundwater body is 'at risk' involves an evaluation of the likelihood that polluting activities will cause deterioration of the water quality in the groundwater body, to the extent that it will fail to have good chemical status by 2015.

The main water company operational in Wales is Dŵr Cymru Welsh Water. Since May 2001, Dŵr Cymru has been owned by Glas Cymru, a non-profit-making company, whose operational surplus is returned to customers as an annual dividend — £18 in the 2005/2006 fiscal year and up to £19 the following year. Dŵy Cymru is a management company with a small staff complement. Many of its service departments are contracted out, most to other UK water companies, including Thames, Severn Trent and United Utilities.

# Hydrogeology of Wales: Introduction - issues

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
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Wales faces broadly the same groundwater issues as the rest of the UK although its overall focus is different. The key management priority is currently the implementation of the European Community Water Framework Directive and satisfying the rigours of the European Community Nitrate Directive (**European Community, 1991**). The focus for both includes relatively minor aquifers including the fractured basement rocks of upland Wales. One of the key difficulties is uncertainty due to lack of data. The timeframe for the initial characterisation of groundwater bodies was such that new data could not be gathered and processed. An important goal, therefore, was that existing data be brought together and synthesised as a whole in order to support the characterisation process. A second aim was to identify methods by which data scarcity could be addressed, including rapid geological map revision, catchment modelling and intelligent use of interpolation.

Much of Wales is underlain by basement rocks of Lower Palaeozoic and older strata which were traditionally considered as only of marginal interest as an aquifer. The Water Framework Directive explicitly requires that all groundwaters be protected and these lesser aquifers have now come under the spotlight. Data are scarce for many areas and knowledge of recharge processes and interaction with surface water in most catchments is poorly understood. Investigation of upland catchment hydrogeology initiated by **Shand et al. (2007**) in the upper Severn valley, enables improved understanding of shallow groundwater systems in much of west and central Wales.

Much of the groundwater in Wales is vulnerable to surface pollution. Pressures from point source pollution include farmyards, sheep dips, septic tank systems, solid waste disposal, industry and mining. Diffuse sources due to agriculture include the application of inorganic fertilisers and landspreading of organic waste. Shallow fractured aquifers, karstic limestones and superficial granular deposits are subject to rapid groundwater transport and are at risk from the ingress of pollutants, both from the ground surface and from loosing stretches of rivers and streams. In the superficial deposits in west Wales nitrate concentrations can be as high as 40 mg/l ($NO_3$-N), although the fractured Ordovician and Silurian strata in the same area are hardly affected at all with a median value of less than 6 mg/l ($NO_3$-N). The European Community maximum admissible concentration for drinking water is 50 mg/l ($NO_3$-N). Most of the established nitrate vulnerable zones in Wales are in south-east Wales and in the Dee catchment in north Wales.

Acid mine drainage has been a significant issue in south Wales following the withdrawal from coal mining that took place in the 1990s. Most of the mine water risings have now reduced in strength and corrosivity, whilst others are treated by discharging over limestone chips and through reed beds to provide discharges that are more acceptable to surface watercourses. Acid mine drainage has long been a problem from abandoned metal mines in some valleys in west Wales. However, all but a few of these have now reduced to tolerable concentrations.

# Hydrogeology of Wales: Precambrian and Cambrian aquifers

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

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Precambrian strata crop out in Anglesey (**Plate P802417**)', in the Lleyn Peninsula and Bardsey Island, and in Pembrokeshire between St Brides Bay and Fishguard (P841814). They are nevertheless of limited areal extent.

Typical Cambrian coastal exposure looking towards South Stack, Holyhead Island. P802417.

The Monian Composite Terrain of Anglesey and the Lleyn Peninsula comprises a varied suite of tectonised igneous, metamorphic and sedimentary rocks. These diverse lithological elements were brought together in a belt of transcurrent faulting during the late Precambrian and early Cambrian (**Gibbons, 1983**). There are three main divisions of the Cambrian Monian Supergroup in Anglesey **(Greenly, 1919)**:

- the South Stack Group deformed metasediments – interbedded greywacke sandstones, siltstones and pelites
- the New Harbour Group greenschists and vocaniclastic sandstones – quartz-veined chlorite-mica schists grading upwards into metamorphosed massive, volcaniclastic sandstones and schistose pelites
- the Gwna Group comprising diverse clasts in a slaty mudstone and siltstone matrix

All three are present on Holyhead Island, Anglesey, while the Gwna Group also outcrops in central and eastern Anglesey and in the Lleyn Peninsula. In addition the granitic and dioritic Sarn Complex occurs in the Lleyn Peninsula whereas the Coedana Complex gneisses and Coedana granite are present in Anglesey. In north-western Snowdonia the Padarn Tuff Formation, the lowest part of the Arfon Group, comprises strongly welded, acidic ash-flow tuffs.

The Pebidian Supergroup of Pembrokeshire comprises a series of unmetamorphosed acid to intermediate tuffs, lavas and tuffaceous sediments, intruded by quartz porphyry and granophyric granite. These crop out with an east to west strike between the northern and southern extremities of St Brides Bay.

In north Wales, Cambrian rocks crop out to form the Harlech Dome, and form the flanks of the Precambrian Padarn Ridge in the Bangor area. Cambrian-age sedimentary rocks are also present north of St Brides Bay in Pembrokeshire where they flank a Precambrian inlier.

The Harlech Dome comprises 4.5 km thick sequence of Cambrian age rocks divided between the older Harlech Grits Group and younger Mawddach Group. The Harlech Grits Group is dominantly coarse deltaic and turbiditic sandstone which include manganese-rich beds, whereas the Mawddach Group comprises fine-grained sandstone, siltstone and black mudstone.

The late Precambrian to Cambrian Arfon Group forms the Padarn Ridge and its flanks in the Bangor area. The Precambrian Padarn Tuff is overlain by a varied sequence of sedimentary rocks of Cambrian age including, sandstones, siltstones and mudstones, conglomerates and greywacke grits, as well as the Llanberis Slate Formation.

The Cambrian strata in Pembrokeshire comprise shallow-water sediments which are intensely faulted. There are three groups: the lowest is Caerfai Group, followed by the Solva Group and the youngest is the Menevian Group, all of which are overlain by the Lingula Flags Formation. Lithologies include mudstones, siltstones, sandstones, conglomerates and shales.

# Hydrogeology of Wales: Precambrian and Cambrian aquifers - groundwater occurrence in the Precambrian and Monian Supergroup

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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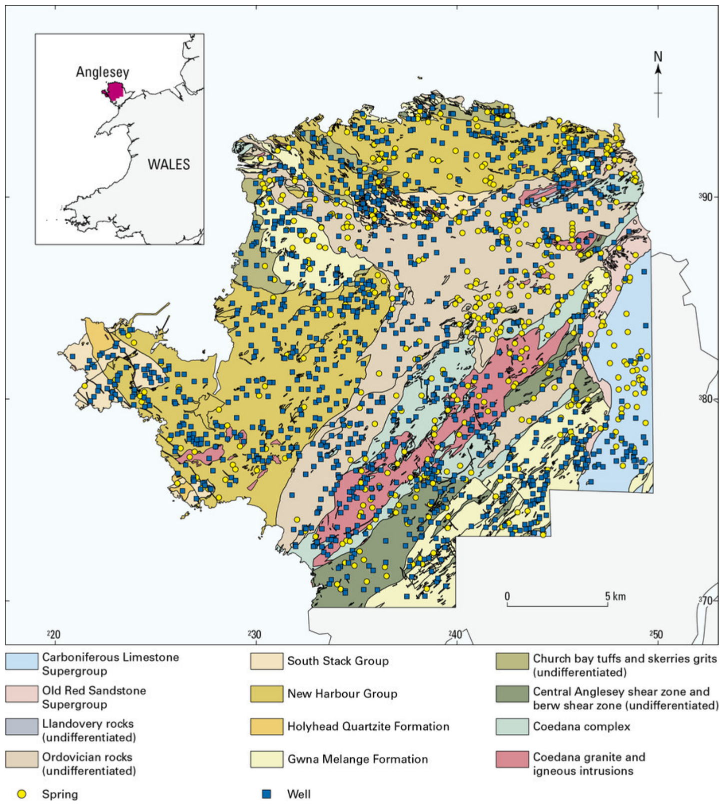
Awareness of the groundwater potential in the Precambrian was first documented by **Greenly (1919)** in his treatise on the geology of Anglesey. He identified the importance of contacts between different metamorphic lithologies and between the metamorphic rocks and the Silurian and Carboniferous sequences, especially low angle contacts and the contacts between dykes and country rock. Remarkably, Greenly also recognised the vulnerability of weathered fracture systems to surface pollutants.

Groundwater circulation in the crystalline basement rocks is shallow and restricted to short flow paths on a local catchment scale within selected fractures. Partial superficial cover of till may contain perched water but may also inhibit rainfall recharge to bedrock. There is little storage available in the basement and discharges to surface may be intermittent and quick to react to rainfall events. The hydraulic flow patterns are complex and application of conventional hydraulic theory is restricted. Even the effective transmissivity based on regional water-balance considerations may not represent a mean of transmissivity values determined in the regional flow regime (**Shapiro, 1993**). Nevertheless, crystalline rocks do contain some groundwater, and it is a resource which is often under-used in Britain whereas it has been widely developed in areas such as Scandinavia (**Banks and Robins, 2002**).

Yields from springs, wells and boreholes are general small and not easy to evaluate in terms of aquifer properties. Statistical analysis of hydraulic data provides the most appropriate means of comparing the performance of different lithostratigraphical zones in a given area. In general this is not carried out in the UK because of insufficient data, but a dataset collected for the Monian Supergroup in Anglesey for apparently unrelated reasons in the 1970s has allowed such an analysis (**Robins and McKenzie, 2005**). Data on the location, source type and geology of 1775 sources have enabled an analysis of the productivity of the respective lithostratigraphical zones.

Spring discharges from the basement rocks in north-west Anglesey and Holyhead Island are, for the most part, small, typically less than 2 l $s^{-1}$. An exceptional series of springs supplied the Twr Waterworks on Holy Island [SH 226 824] where three springs in close proximity discharge to surface with an average total yield of 5.5 l $s^{-1}$. Although few water boreholes have been drilled, the 10 m deep railway borehole near Holyhead Station [SH 261 812] yielded 1.5 l $s^{-1}$ for 12 hours per day.

Shallow wells in till offer prospects of perched water in gritty, moderately permeable horizons. Not all of the wells penetrate bedrock. Springs are common at the base of the unconsolidated till over bedrock. Blown sand deposits are well drained and unsaturated, and the alluvium is generally fine grained and weakly permeable.




Location of springs and wells in north-western Anglesey (after Robins and MeKenzie, 2005). P859260.

The well and spring dataset comprises three pieces of information: grid reference, well or spring, and geological observations for most data points. The geological observations identify some wells in till only, wells and springs at the junction between till and bedrock, and bedrock springs and wells in close proximity to a dyke or a stratigraphical or lithological contact.

The location of the springs and wells over the solid geology is shown in **Figure P859260**. When contrasting the intensity of field collected data for the area with that held in the BGS Wellmaster database (**Figure P859260**) a number of other features become apparent. The first is that the distribution of wells and springs are environment specific. The density of wells tends to be more concentrated around centres of population, more evenly distributed outside the towns and villages, and least concentrated in the vicinity of surface waters such as Llyn Alaw [SH 39 86]. Thus, for example, there are clusters of wells around Gwalchmai [SH 38 76] and between Llanfechnell and Mynydd Mechell [SH 36 90] as well as the northern outskirts of Llangefni [SH 46 76] which is at the margin of the survey area. The distribution of springs is constrained not by social needs but by geology and topography.

Analysis of the density distribution of both springs and wells for each bedrock formation is given in the **distribution of springs and wells table**. The dataset includes those wells and springs that derive water only from the superficial cover and from the contact between till and bedrock. As the till coverage is near complete, the drift wells and springs are likely to be roughly evenly distributed. The overall well and spring densities, be they in bedrock or drift, mainly reflect changes in bedrock properties, the Quaternary properties being areally consistent.

## Distribution of springs and wells in north-east Anglesey by geological formation (after Robins and McKenzie, 2005).

| | Bedrock geology | Area | Total wells and springs | | Wells | | Springs | | Total | Wells | Springs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ($km^2$) | number | % | number | % | number | % | $km^{-2}$ | $km^{-2}$ | $km^{-2}$ |
| Carboniferous | Carboniferous Limestone facies | 28 | 81 | 5 | 36 | 3 | 45 | 8 | 2.9 | 1.3 | 1.6 |
| Devonian | Old Red Sandstone | 8 | 21 | 1 | 10 | 1 | 11 | 2 | 2.5 | 1.2 | 1.3 |
| Silurian | Llandovery | 1 | 4 | 0 | 2 | 0 | 2 | 0 | 6.7 | 3.3 | 3.3 |
| Ordovician | Ordovician (undifferentiated) | 113 | 392 | 22 | 243 | 20 | 149 | 27 | 3.5 | 2.2 | 1.3 |
| Monian Complex | South Stack Group | 18 | 95 | 5 | 77 | 6 | 18 | 3 | 5.2 | 4.3 | 1.0 |
| | New Harbour Group | 133 | 465 | 26 | 373 | 30 | 92 | 17 | 3.5 | 2.8 | 0.7 |
| | Holyhead Quartzite Formation | 3 | 3 | 0 | 3 | 0 | 0 | 0 | 1.2 | 1.2 | 0.0 |
| | Gwna Group | 61 | 249 | 14 | 183 | 15 | 66 | 12 | 4.1 | 3.0 | 1.1 |
| | Church Bay Tuffs and Skerries Grits | 13 | 59 | 3 | 45 | 4 | 12 | 2 | 4.4 | 3.4 | 0.9 |
| | Central Anglesey Shear Zone and Berw Shear Zone | 28 | 91 | 5 | 58 | 5 | 33 | 6 | 3.2 | 2.0 | 1.2 |
| | Coedana Complex | 38 | 149 | 8 | 88 | 7 | 61 | 11 | 3.9 | 2.3 | 1.6 |
| | Coedana granite | 29 | 113 | 6 | 76 | 6 | 37 | 7 | 3.9 | 2.6 | 1.3 |
| | Totals | 480 | 1771 | 100 | 1225 | 100 | 544 | 100 | 3.7 | 2.5 | 1.1 |

The **distribution of springs and wells table** shows that there are 3–4 springs and wells per $km^2$ in north-west Anglesey. In the Precambrian, the density of wells is greatest over the South Stack Group and least over the Holyhead Quartzite Formation, whereas the springs are more evenly distributed across the Monian Supergroup although none were found over the Holyhead Quartzite Formation. This suggests that the New Harbour Group and South Stack Group and other formations in the Monian Supergroup offer more favourable conditions for shallow groundwater than the Holyhead Quartzite Formation. The Palaeozoic and Precambrian strata have a similar distribution density of wells and springs except for the Holyhead Quartzite Formation, which has poor hydraulic properties.

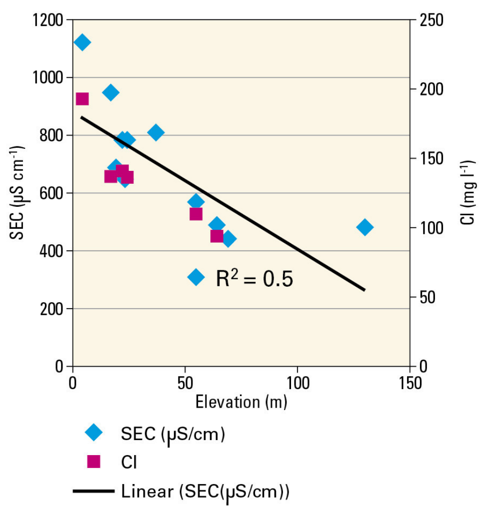
There are a number of additional features that the data illustrate. Increased fracturing in the vicinity of dolerite dykes accounts for the success of well digging in much of the South Stack Group, which has 4–5 wells per $km^{-2}$, but only 1 spring per $km^{-2}$, and the New Harbour Group, which has 2–3 wells per $km^{-2}$ and 1 spring per $km^{-2}$. The presence of distinct foliation in the Gwna Group and the Church Bay Tuffs and Skerries Formation also enhances the success of well digging in these rocks. In all the other formations the proportion of wells to springs is more equally divided, as there are fewer fractures and other minor discontinuities which favour the successful development of wells.

Available hydrochemical data for the Gwna Group indicate a weakly mineralised oxic group of waters that tend to be influenced by the prevailing maritime environment with elevated Na and Cl concentrations (typically 18 mg $l^{-1}$ and 31 mg $l^{-1}$ respectively). The waters are mostly Ca-$HCO_3$ type with subordinate Ca-Cl dominance with specific electrical conductance generally around 361 µS $cm^{-1}$ derived from 32 samples (**Banks et al., 2007**).

South of Bangor is the Padarn Ridge, stretching from Penygroes to Bethesda. It rises to just above 350 m above OD, and comprises hard tuffs and agglomerates of the Padarn Tuff Formation, the basal member of the late Precambrian to Cambrian Arfon Group. Small springs issue from the bedrock along the flanks of the ridge and many of these have been used for domestic supply. There are no water wells or boreholes recorded in the formation. The Ffynnon Springs [SH 4948 5642] lie at an elevation of 180 m on the north-western flank of the ridge. The major ion chemistry of the discharge (**Welsh Office Agriculture Department, 1986**) indicates a small catchment containing a young, immature, and weakly mineralised groundwater (Ca 14 mg $l^{-1}$; Na 16 mg $l^{-1}$; Mg 2.4 mg $l^{-1}$; Cl 25 mg $l^{-1}$; Na16 mg $l^{-1}$; $NO_3$ 16 mg $l^{-1}$; K 2.4 mg $l^{-1}$) These concentrations are typical of the short and shallow flow paths that occur in fractured basement rocks.

A small study of groundwater sources in the Gwna Group in Bardsey Island was reported by **Webb (2000)**. The island has an area of only 178 ha and is nearly 3 km long and 1 km wide, and rises from lowlands in the west to a summit at Mynydd Enlli of 167 m (**Plate P802418**). Many of the numerous springs are ephemeral with yields measured in September 1998 up to 2.0 l $s^{-1}$ but typically less than 0.3 l $s^{-1}$ (these spring yields may increase in the winter months). Surface drainage is only maintained throughout the year on some of the lower-lying areas in the west. Throughout the island the water table is nowhere deeper than 0.6 m although pumping water levels may be deeper. Slug tests at auger holes in the shallow weathered zone indicate that the hydraulic conductivity is of the order $10^{-3}$ m $d^{-1}$.

Bardsey Island.




Bardsey Island: Specific Electrical Conductance (SEC)/Cl to elevation relationship in groundwater (See Webb, 2000). P859261.

Sampling and analysis of selected sources for inorganic determinands indicates a generally weakly mineralised Na(Ca)–Cl type groundwater. Mineralisation is least at higher altitudes and greatest at lowest altitudes (**Figure P859261**) indicating a strong marine influence as indicated by the dominant Cl ion (cf. **Webb (2000)**).

Investigation of and information on the groundwater potential in the Precambrian rocks in Lleyn and in Pembrokeshire is limited. For the most part, stream flow run-off is neutral to marginally acid (**British Geological Survey, 2000**) with little buffering offered by weakly mineralised baseflow. However, outcrop areas are small and the controlling elements are the younger rocks that are present in respective catchments. There are no records of boreholes and wells in the Precambrian rocks in Lleyn and Pembrokeshire although it is likely that spring discharges draw on small groundwater catchments.

# Hydrogeology of Wales: Precambrian and Cambrian aquifers - groundwater occurrence in the Cambrian

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
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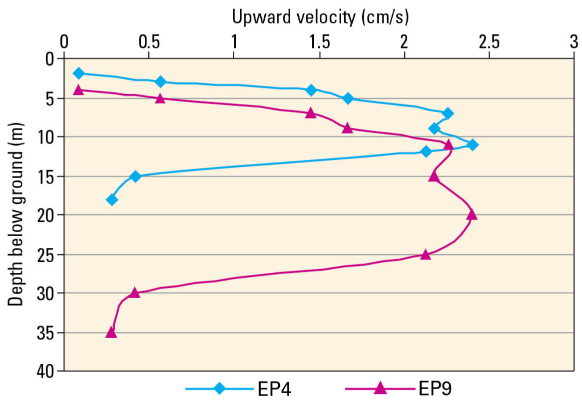
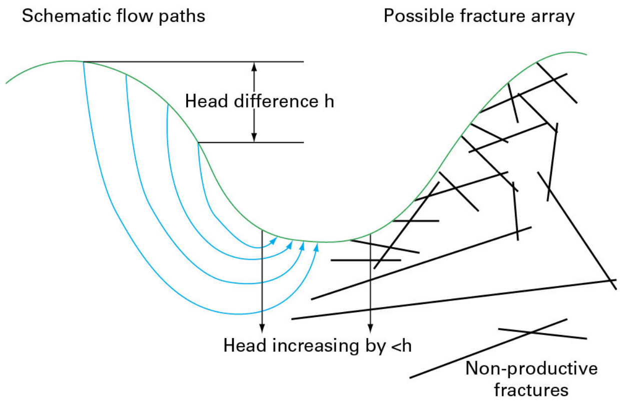
Llanberis slate quarry. P802416.

Groundwater occurrence and circulation in the Cambrian sedimentary rocks is much the same as it is in the crystalline basement rocks described ***above***. Groundwater is contained largely in the near-surface weathered and fractured zone of bedrock which offers little storage potential with transport via dilated fissures. Again, flow paths are typically short and shallow and are within catchment scale — usually down hill slopes towards valley bottoms. Spring discharges occur where fracture systems intercept the ground surface and along valley bottoms to provide base flow to surface waters. Steep topography over much of the Cambrian outcrop provides additional transport of 'groundwater', via soil or scree interflow, to discharge into valley bottom streams (**Shand et al. 2001**).

Although there are numerous springs associated with the Cambrian outcrops some are sourced partly, if not entirely, from overlying drift deposits. Collections from groups of bedrock springs have in the past been used for public supply. One example was the Nine Wells springs [SM 787 248] which were operated by the St Davids Water and Gas Company. The nine springs drained directly from bedrock slates into a chamber and delivered up to 225 $m^3 d^{-1}$. In the same area of Pembrokeshire at Solva [SM 7862 2507] a 10 m-deep, 1 m-wide shaft penetrating a clearly visible fault in well-jointed fine-grained sandstone belonging to the Menevian Group, was capable of yielding up to 35 $m^3 d^{-1}$. The static water level ranged between 1 m and 8 m below ground level depending on season.



Heat-pulse flowmeter logs for exploratory boreholes in Llanberis Slate Formation at Dinorwic (after Robertson, 1974). P859262.



Schematic cross section of a hard fractured rock upland valley such as Dinorwic, showing increasing head with depth in active fractures beneath valley bottoms. P859263.

In north Wales, detailed engineering investigations were carried out in exploratory boreholes in the Llanberis Slate Formation (**Plate P802416)** during the construction of the Central Electricity Generating Board's Dinorwic Pumped

Storage Scheme in the 1970s (**Robertson, 1974**). Heat-pulse flow logs of two of the boreholes in the valley bottom (see **Dinorwic exploratory boreholes table** ), measured under non-pumping conditions, are shown in (**Figure P859262**). These show upward movement of groundwater from the interception of the lowest active fracture in each of the boreholes EP4 and EP9. The upward flow continues to a point near the top of the water column in both boreholes. It demonstrates the increasing head with depth on active fractures in valley bottoms, and reflects the interception of successively longer flow paths, each upwelling along the valley bottom and derived from a higher recharge elevation on the valley side (**Figure P859263**.). By contrast, exploratory boreholes EP5 and EP7 in the same vicinity were static throughout the borehole column indicating constant head in the fractures penetrated reflecting poor contact with the overall fracture system.

## Exploratory boreholes at the Dinorwic Pumped Storage Scheme in the Llanberis

| Borehole | Grid Reference | Depth (m) | Rest water level on 5 March 1974 |
|---|---|---|---|
| EP4 | SH 5995 5875 | 36.8 | 1.2 |
| EP5 | SH 6007 5882 | 33.8 | 1.6 |
| EP7 | SH 6000 5881 | 52.3 | 1.8 |
| EP9 | SH 5983 5879 | 38.0 | 0.9 |

Boreholes EP4 and EP7 were also flow logged during pumping at 2 l $s^{-1}$. The flow logging was carried out with an impeller and fluctuating pumping rates caused some error to arise. However, the work showed that all the pumped water in EP4 derived from the uppermost 15 m of the borehole, reflecting the location of active fractures seen in the static log (**Figure P859263**.]). Borehole EP7 which showed no upward transport of water in the non-pumped state revealed its production zone to be located between 4 and 10 m below ground level, again demonstrating the shallow nature of active groundwater flow in these rocks.

Pumping was only maintained for brief periods at Dinorwic and sustainable yields are likely to be smaller than the recorded 2 l $s^{-1}$. Typical yields are about 0.5 l $s^{-1}$, for example from a 24 m deep borehole in the Ffestiniog Flag Formation at Criccieth [SH 5266 3991]. The static water table in this borehole is 1.3 m below ground level. However, it should be remembered that the distribution of springs and wells is significantly greater than that shown from the records in **Figure P859258**. as many sources have not been recorded.

# Hydrogeology of Wales: Ordovician and Silurian aquifers

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

## Ordovician and Silurian strata

Abergwesyn Pass between Aberystwyth and Llanwrtyd Wells, showing typical Silurian upland scenery. P802422.

Ordovician rocks crop out extensively in north and south-west Wales and in parts of mid Wales and the Welsh Borderlands (**Plate P802422**). Silurian strata crop out in mid and north Wales, east of the Tywi Anticline and Welsh Borderland Fault system and in parts of south Wales (**Figure P841814**.). The Ordovician dominantly comprises marine mudstones, siltstones and interbedded volcanic rocks with some breccia and fan deposits. The Silurian strata dominantly comprise a series of marine turbiditic mudstone and sandstone sequences with subordinate limestones.

The Ordovician succession formed within a subsiding basin between faulted margins defined by the Menai Strait and Welsh Borderland Fault systems. Deposition of black marine mudstones was periodically interrupted by lava and pyroclastic debris from volcanic centres in north and south-west Wales.

In north Wales both the Tremadoc Series and basal Arenig Series crop out in Snowdonia, the Lleyn Peninsula, Anglesey, around the Harlech Dome and in the core of the Derwen Anticline. The oldest strata are the grey mudstones and siltstones of the Tremadoc Series; up to 480 m thick with occasional sandstones in the upper part of the sequence. These are followed by a 1000 m-thick volcanic succession, the Rhobell Volcanic Group, which includes basic lavas, breccias, coarse-grained mass-flow units, and alluvial deposits. A marine transgression followed giving rise to the basal Arenig fan deposits: the Allt Llwyd Formation in Snowdonia and the Parwyd Grit Formation in the Lleyn Peninsula.

In Central Wales and the Welsh Borderlands there is an almost unbroken sequence of Ordovician sediments. These are also present in Powys in the Shelve Inlier. The Raglan Mudstone Formation comprises mainly mudstones and siltstones with subordinate cross-bedded sandstone horizons.

In Pembrokeshire and Carmarthen the oldest Ordovician strata are Arenig-age silty shales and subordinate sandstones. The principal strata that follow include the Treffgarne Volcanic Formation and the younger Fishguard Volcanic Group, which are varied sequences that are dominated by volcanic events with mudstones intercalated within the volcanic sequences. The Ordovician continues with graptolitic mudstone and subordinate sandstone sequences in the Haverfordwest to Llandovery area. A notable inlier of Llanvirn age volcanic strata occur in the Builth and Llanwrtyd areas. The overlying Silurian sequence continues with graptolitic mudstones and subordinate calcareous sandstone sequences in the Haverfordwest to Llandovery area and into the Welsh Borderland.

In north Wales the Silurian is represented by a thick sequence of mudstones in the Vale of Conwy. To the north the Clwydian Range and the Llangollen syncline contain similar strata. The Denbigh Grit Group is present in part of the area.

Much of Central Wales is now underlain by Silurian mudstones and turbiditic sandstones deposited in the so-called Welsh Basin. The arenaceous deposits are prevalent in the Aberystwyth area and are typified by the Devil's Bridge Formation which contains subordinate mudstones and which is nearly 500 m thick. The overlying Aberystwyth Grits Group occurs along the coast between New Quay and just north of Aberystwyth. The younger Cwmystwyth Grits Group forms the core of the Central Wales Syncline. At the close of the Wenlock, deeper water conditions brought the return of black mudstones and shales typified in the Builth–Llandrindod area by the Builth Mudstones. This depositional environment continued throughout the Ludlow producing mudstones and sandstones with subordinate siltstones and limestones.

# Hydrogeology of Wales: Ordovician and Silurian aquifers - groundwater occurrences

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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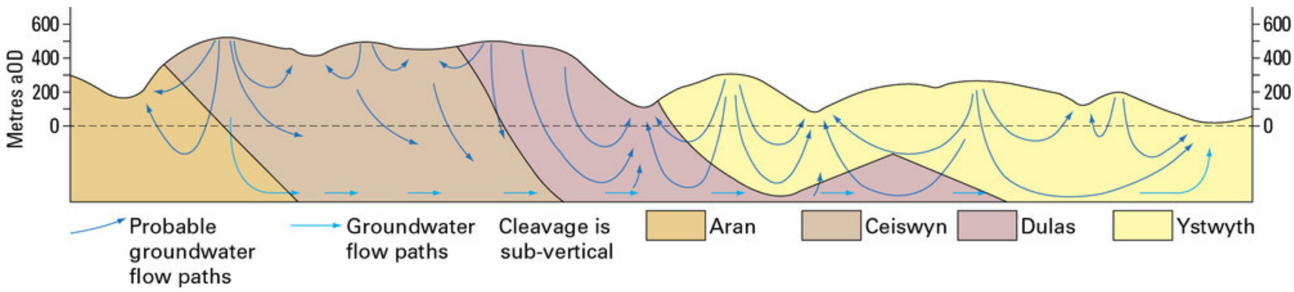
The diverse lithologies that are present in the Ordovician and Silurian strata in Wales support a range of hydraulic properties. This diversity contrasts with the Southern Upland massif of southern Scotland and south-east Northern Ireland where the dominant lithologies are sandstone, siltstone and mudstone. These areas offer more uniform hydraulic conditions, and the strata are described as weakly permeable and capable only of short and shallow flow paths supporting isolated springs and shallow wells (**Robins, 1999**). In Wales, some of the Ordovician and Silurian strata are also weakly permeable and cannot be considered as useful aquifers. However, there are other areas in which the strata are relatively productive and useable quantities of groundwater are available, for example from the Silurian sandstones, from which there is usually sufficient groundwater to support domestic and small-scale agricultural uses.

A weathered, frost-shattered and soliflucted horizon is well preserved in Wales. This is because the removal of the weathered zone by the ice sheets was less effective than it was in much of glaciated England and Scotland so that the weathered and fractured uppermost layer of rock is largely preserved in Wales south of Snowdonia. In some areas the effects of periglacial frost shattering enhance the near surface permeability of the rock. Tectonic activity has induced discontinuities throughout much of the Welsh succession where bedding plane fractures and subvertical breaks are commonplace. The boundaries between sedimentary lithologies and interbedded volcanic strata tend also to be marked by joints sufficiently dilated to allow groundwater transport. Significant groundwater storage, however, tends to be limited to coarser arenaceous deposits.

In general, the water table tends to be shallow where aquifer storage is not capable of receiving recharge from the available effective precipitation, a phenomenon known as rejected recharge. Flow boundaries may be defined by fracture orientation and the relationship between bulk-rock and fracture hydraulic conductivity. Dominant fracture orientation may also control groundwater flow direction (**Robins, 2005**).

Although awareness of the importance of groundwater in the Ordovician and Silurian strata is relatively new (e.g. **Haria and Shand, 2004**), its role in supporting low flow in upland streams has long been recognised. One of the earliest investigations into groundwater occurrence in the Ordovician and Silurian strata was a reconnaissance study of the Afon Dulas subcatchment of the Dyfi north of Machynlleth (**Glendining, 1981**). The catchment comprises a series of folded, well-cleaved and fractured turbiditic mudstones and slates with a north-easterly strike, younging towards the south-east. There are volcanic rocks in the north-west corner of the catchment. The superficial cover includes head and scree deposits, peat and valley alluvium. The cleavage planes trend north-easterly and are subvertical to 60° in dip, the main joints are normally vertical and are orientated between 120° and 140°, the faults also are subvertical. Surface drainage is strongly influenced by this structure, with the Tal-y-Llyn and Dyfi valleys following major fault lines and many first order streams following the 120° joint directions; groundwater flow is mainly constrained by the structure and jointing (**Figure P859264**).

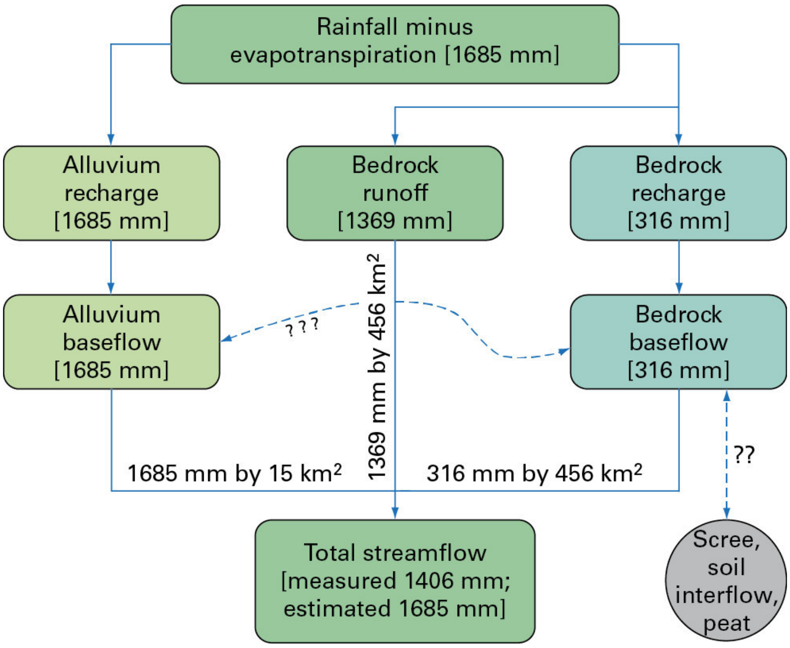



Schematic flow system for the Afon Dulas catchment controlled by topography, fracture orientation and fracture permeability (after Glendining, 1981. P859264.

## Effective infiltration (equal to base flow divided between alluvium and bedrock in the Afon Dulas catchment (after Glendining, 1981).

| Year | Total flow (mm) | Base flow (mm) | Effective rainfall (mm) | Alluvium (15 km$^2$) infiltration m$^3$ x 10$^6$ | Bedrock infiltration (456 km$^2$) infiltration m$^3$ x 10$^6$ | Bedrock infiltration (mm) |
|---|---|---|---|---|---|---|
| 1962–1963 | 1195 | 312 | 1393 | 21.0 | 126 | 276 |
| 1963–1964 | 1017 | 275 | 1201 | 18.0 | 111 | 244 |
| 1964–1965 | 1713 | 333 | 1842 | 27.6 | 129 | 283 |
| 1965–1966 | 1679 | 314 | 1909 | 28.6 | 119 | 261 |
| 1966–1967 | - | - | 1715 | 25.7 | - | - |
| 1967–1968 | 1656 | 444 | 2131 | 32.0 | 177 | 388 |
| 1968–1969 | 1224 | 399 | 1453 | 21.8 | 166 | 364 |
| 1969–1970 | 1410 | 417 | 1774 | 26.6 | 170 | 372 |
| 1970–1971 | 1355 | 382 | 1750 | 26.2 | 154 | 337 |
| Mean | 1406 | 396 | 1685 | | | 316 |

The bulk catchment properties suggest that total river flow equates to total effective rainfall. This assumes that changes in storage and soil moisture deficit are negligible over the long term and that underflow from the catchment is small. Base flow separation of the catchment run-off was calculated, and divided between alluvium (15 km$^2$ in area in the catchment) and bedrock (456 km$^2$). Infiltration into the alluvium was assumed to be equal to total effective rainfall (**Figure P859265**). The effective rainfall over bedrock was divided between the amount needed to make up the overall base flow (estimated from the base flow separation calculation minus base flow from or effective rainfall into the alluvium) and run-off (see **the effective infiltration table** ). This shows that the average annual infiltration to the bedrock is about 316 mm or 19 per cent of the effective rainfall (compared with 1685 mm or 100 per cent to the alluvium). This is likely to be an overestimate as it disregards soil and scree interflow, short flow-path discharge through the near valley-bottom weathered zone and the capacity of the rock to accept recharge.




Analysis of throughflow volumes in the Afon Dulas catchment (after Glendining, 1981). P859265.

**Glendining (1981)** assigned percentage flow to shallow, intermediate and deep flow paths using estimates of hydraulic gradients for each flow path. This enabled the overall hydraulic conductivity for the rock mass to be calculated. The value is of the order $10^{-3}$ m $d^{-1}$, however, this has little bearing on the majority of groundwater flow which takes place in the near-surface weathered zone and which may be of the order 1 m $d^{-1}$.

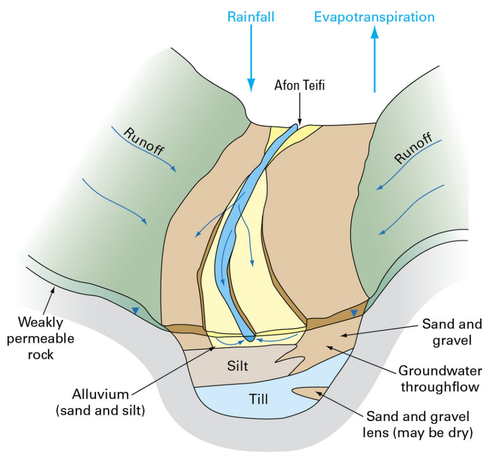
# Hydrogeology of Wales: Ordovician and Silurian aquifers - groundwater studies

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

Although the Ordovician and Silurian strata are recognised as being generally weakly permeable, there have nevertheless been a number of investigations into groundwater flow and occurrence within them. These case studies illustrate the specific hydraulic qualities of the rocks in different catchments.

The Afon Teifi at Cenarth flowing over on of several rock ledges that constrict the valley. P802420.




Schematic section of the central area of the lower Afon Teifi catchment showing the main flow components (after Robins et al., 2000). P859266.

Much of the work concentrates on shallow groundwater circulation on a catchment scale. Two studies were recently carried out in contrasting catchments in west Wales. **Robins et al. (2000)** investigated the occurrence of groundwater in the Silurian and Ordovician rocks of the Teifi valley (**Plate P802420**), whereas **Hiscock and Paci (2000)** concentrated on the more arenaceous deposits of the Rheidol catchment. Both these investigations highlight the interaction between groundwater in bedrock and in the superficial cover particularly along valley bottoms.

The bedrock in Afon Teifi comprises mudstones of Ordovician and Silurian age. Springs are common and issue primarily from weaknesses in the shale, or the contact between bedrock and the overlying superficial material. Many of the springs are seasonal reflecting low storage capacities. Storage may be enhanced where fissure storage is in hydraulic contact with overlying superficial deposits which possess intergranular storage, particularly in valley-bottom areas (**Figure P859266**).

Sustainable yields from bedrock are low, although adequate for many private uses. Spring flows occur up to 2 to 3 l $s^{-1}$, and exceptionally 5 l $s^{-1}$, but flows of less than 1 l $s^{-1}$ are more typical. Typical sustainable borehole yields are around 0.3 l $s^{-1}$; pumping rates of up to 1 l $s^{-1}$ invariably dewater boreholes. Boreholes are generally about 40 m deep; exceptions include one borehole which is 140 m deep. A short duration pumping test at Dan yr Allt [SN 1871 4162] indicates a transmissivity of 0.63 $m^2$ $d^{-1}$. A nearby boundary condition is apparent which reduces the transmissivity to 0.33 $m^2$ $d^{-1}$ after only 17 minutes pumping. A borehole at Tandderi [SN 5037 4354] indicates a transmissivity of 1.1 $m^2$ $d^{-1}$ from the early data, and 0.64 $m^2$ $d^{-1}$ from the later data, and a third test at Cyttir-bach [SN 2448 4838] suggests a transmissivity is about 0.49 $m^2$ $d^{-1}$.

Water levels are rarely more than 10 m from the surface, irrespective of the ground elevation. No clear piezometric surface can be created from water level data from boreholes and spring elevations. This reflects the nature of a fractured aquifer beneath relatively steep surface topography, and perching of groundwater bodies.

A best estimate of the quantity of groundwater abstracted from the catchment is based on data maintained by the Environmental Health Departments (see **Groundwater consumption table** ). Although it is not possible to estimate the proportions abstracted from the drift and bedrock aquifers the majority is believed to derive from bedrock (mains water is available throughout most of the catchment but private supplies are preferred by many on the grounds of cost). The majority of the private groundwater sources are springs. The analysis shows that less than 2 Ml $d^{-1}$ groundwater is being used in the catchment area.

## Groundwater consumption in the Teifi catchment (principally from bedrock) excluding the Alwen public supply source which draws from superficial gravels (source local Environmental Health Departments).

| | Estimated daily consumption ($m^3$) | Estimated number of sources | Total abstraction ($m^3$ $d^{-1}$) |
|---|---|---|---|
| Domestic – single property | 0.6 | 809 | 485.4 |
| Domestic – <25 people | 1.2 | 83 | 99.6 |
| Farm (livestock) | 1.5 | 68 | 102 |
| Farm (dairy) | 6.5 | 132 | 858 |

| | | | |
|---|---|---|---|
| Commercial (hotel, youth hostel, abattoir, quarry, etc.) | 8.0? | 20 | 160 |
| Total | | 1112 | 1705 |

Run-off and potential evaporation exceed precipitation (see **Precipitation, run-off and AE table** ), but run-off includes groundwater base flow (infiltration). As the BFI (base flow index) is 0.54 AT Glan Teifi (Centre for Hydrology and Ecology/British Geological Survey, **2003**), something of the order of 540 mm derives from groundwater discharge. This represents a renewable resource of 540 Ml $a^{-1}$ $km^{-2}$ of aquifer, a considerable surplus over the total estimate of just 622 Ml $a^{-1}$ withdrawn throughout the whole catchment from all the boreholes, wells and spring discharges.

## Representation precipitation, run-off and AE for Afon Teifi (source Hydrological data UK and Meteorological Office).

| | Precipitation (mm/a) | Run-off (mm/a) | Actual evaporation (mm/a) |
|---|---|---|---|
| IH: Glan Teifi (1959–1990) | 1349 | 999 | |
| IH: Llanfair (1971–1981) | 1446 | 988 | |
| MORECS (1961–1990) | 1102 | | 544.5 |

The magnitude of the groundwater through flow along the length of the valley based on Darcy's law is given by:

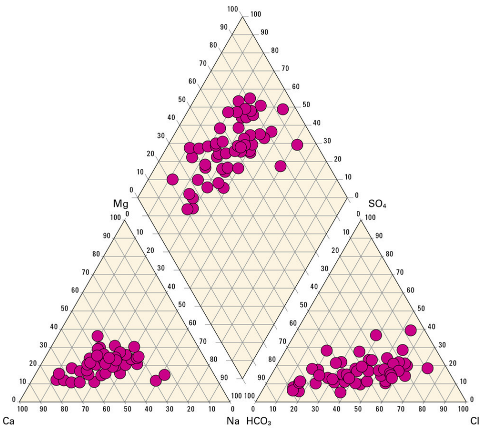
$$Q = T\ y\ i$$

where T is the transmissivity and y is the width of the catchment and i is the prevailing hydraulic gradient. Using a transmissivity value of 0.6 $m^2$ $d^{-1}$ (from pumping test analysis) and an average catchment width of 17 km, and estimating the hydraulic gradient to be equal to the gradient of the river (2.5 x $10^{-3}$), then:

$$Q = 0.6 \times 17\,000 \times 2.5 \times 10^{-3}$$

$$= 25\ m^3\ d^{-1} \text{ or only } 0.025\ Ml\ d^{-1}$$

This is a small amount compared to the total estimated base flow and the majority of the base flow component of river flow derives from local recharge and discharge via flow paths perpendicular to the axis of the valley, and not from longitudinal flow paths down the length of the valley. Abstraction and spring flow are small elements of the overall infiltration indicated by base flow indices.




Piper diagram showing major ion distribution in groundwaters in Afon Teifi (after Robins et al., 2000). P859267.

Temperatures do not vary significantly in the groundwaters in Afon Teifi with a median value of 9.6 $^{o}$C (**Shand et al. 2005**). Temperatures as low as 4 $^{o}$C were measured in some of the smaller springs implying short and shallow flow paths. There is a range in pH from 5.2 to 7.6, however, waters with pH less than 6 are confined to the catchment east of Llechryd (SN21794364). The waters are relatively low in total dissolved solids (TDS) and SEC varies from 117 to 662 $\mu$S cm$^{-1}$ with the highest values located close to the coast.

Bedrock groundwater quality ranges from Ca-$HCO_3$ to Ca-Cl type. The major cations show a tighter grouping than the anions on piper diagrams, typical of upland waters (**Figure P859267**). Mean concentrations of major elements for the boreholes are, in general, slightly higher than the springs and wells, but ranges are similar. Fe and Mn concentrations are low in most waters reflecting the presence of oxygen while Si concentrations are variable.

The Afon Teifi groundwaters show geographical variations in solute chemistry along the length of the catchment. This is particularly pronounced for SEC and the major elements Ca, Mg, $HCO_3$ and Si, which show a wide range of concentrations in the western part of the catchment but less variation and a slightly lower baseline for some solutes in the east. There is also a tendency towards higher Na and Cl, but less so for $SO_{4,}$ towards the coast in the Cardigan area. Most waters with low pH are confined to the eastern half of the catchment but are variable in both areas. The western enrichment is also matched to a similar degree by many of the minor and trace elements e.g. Br, Li, B and Sr, whilst others show no significant trend e.g. K, $NO_3$-N, Pb and Y. The close proximity of the western part of the catchment to the coast is shown by higher concentrations of Na and Cl in the area around Cardigan. Enhanced concentrations of these elements due to sea spray and salt deposition are typical of surface waters along the west coast of the UK, forming steep chemical gradients away from the coast (**Shand et al., 1995**). The dominant control over groundwater chemistry is, however, water rock interaction as illustrated by the normalised plot of the major ions which shows considerable enhancement of both Ca and $HCO_3$ (**Figure P859268**).

**Hiscock and Paci (2000)** studied the contrasting Rheidol catchment which enters the sea at Aberystwyth. The principal difference is that a more granular and generally better water-bearing bedrock is present in the Rheidol than in the Teifi. Other differences include surface waters polluted by mine-water discharge from former metal mining activities (see Management and regulation of groundwater), and stream-flow regulation for hydropower. Bedrock comprises Silurian Llandovery Series consisting of:

Aberystwyth Grits Formation

Borth Mudstones Formation

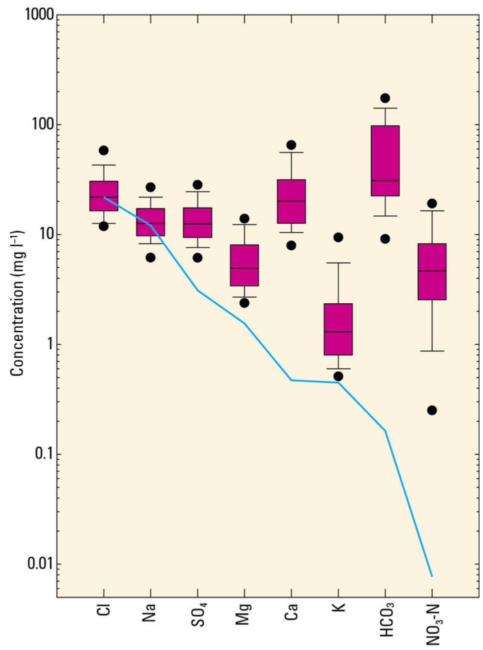
Devil's Bridge Formation

Cwmsymlog Formation

Derwenlas Formation

Cwmere Formation

The three uppermost formations are considered by **Hiscock and Paci (2000)** to offer the better conditions for groundwater occurrence in fractures and minor groundwater abstractions. This reflects a decrease in metamorphic grade and increase in depth of weathering in the younger formations coupled with occurrence of sandstones in the upper part of the sequence.




Box and whisker plot of major ion concentrations and the normalised sea water line. The mean 25th and 75th percentile are bars and the 5 and 95th percentile are dots (after Robins et al., 2000. P859268.

The overall porosity of the series is between 2 and 4 per cent. However, depth of weathering can be up to 20 m and brick-lined pits have been used effectively to capture springs and divert otherwise shallow groundwater to gravity-fed systems for domestic usage. These are commonly situated in bedrock at the junction between the Aberystwyth Grits Formation and the Borth Mudstones Formation, but may also occur at the base of the superficial deposits, drawing on the upper weathered zone of bedrock or within the superficial material itself, e.g. gravel over clay. In the Rheidol the majority of sources relate to contact with superficial deposits. In the upper parts of the catchment there are distinct spring lines parallel to the river. There are few sources recorded upstream of Devil's Bridge.

The Rheidol catchment covers an area of 182 $km^2$. Hiscock and Paci note there are 65 sources providing 3.6 Ml $d^{-1}$. Twenty-nine of the sources are in bedrock and a further ten occur in superficial deposits in contact with bedrock, tapping the upper weathered zone of bedrock. The estimated water balance for the catchment using an evapotranspiration value based on base flow separation and a BFI of 0.51 is shown in the **Comparative water balance table** .

**Comparative water balance estimates (mm $a^{-1}$) for the Teifi and Rheidol catchments (after Robins et al., 2000; Hiscock and Paci, 2000).**

| | Teifi | Rheidol |
|---|---|---|
| Rainfall | 1349 | 1790 |
| AE | 544 (Morecs) 350 (base-flow separation) | 753 (base-flow separation) |
| Run-off | 459 | 667 |
| Base flow | 540 | 363 |
| Groundwater abstraction | Small | 7 |

Investigation of the local-scale transport process in the Upper Severn catchment at Plynlimon provides further insight into the hydraulics of the Lower Palaeozoic aquifer. This work specifically tackles the issue highlighted by **Shand et al. (1999)** concerning the role of groundwater in sustaining base flow and its important contribution to storm flow as demonstrated by isotopic indicators analysed for groundwater and surface water both during dry and rainfall events.

**Neal et al. (1997)** identified the importance of base flow to the stream and recorded a damping of the rainfall chloride signal in base flow. Fractal analysis of the chloride output demonstrated that there was a range in travel times to groundwater arriving in the stream (**Kirchner et al. 2001**). **Shand et al. (2001)** have used isotopic evidence to show that the stream waters lie on a mixing line between groundwater and rainfall.

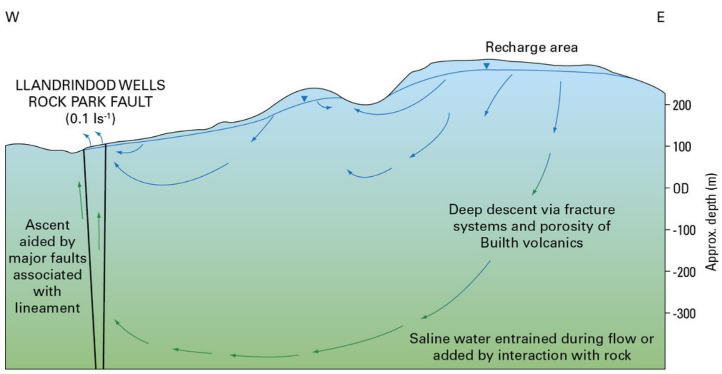
**Haria and Shand (2004)** carried out intensive investigations in the Hafren subcatchment of the upper Severn near Plynlimon. They used a transect some 50 by 10 m in area perpendicular to the stream with monitoring boreholes into weathered bedrock as well as soil piezometers. The time series physical and chemical data so gathered highlight the role of groundwater in stream flow generation. Key conclusions include:

- The system is complex with discrete flow paths in individual (confined) fractures which mix at the valley bottom.
- All fracture flow paths appear to respond rapidly to rainfall events.
- The upper weathered 1.5 m horizon of bedrock contributed significantly to stream flow.
- Groundwater from the less weathered zone to 10 m depth also contributed to stream flow.
- Some upwelling of ‘older’ groundwater into the soil zone suggests not all soil water is ‘new’.
- The stream is always gaining even at low flow.

The Chalybeate Spring of Llandrindod Wells. P802421.

In south-west Wales the Raglan Mudstone Formation offers transmissibilities in the range 4 to 13 $m^2$ $d^{-1}$. A 40 m deep borehole in the Usk valley at Llanilowell [SO 33955 19858] penetrating the Raglan Mudstone Formation has a specific capacity of 45 $m^3$ $d^{-1}$ $m^{-1}$ and a transmissivity of 60 $m^2$ $d^{-1}$.

There is evidence of some deep groundwater circulation in central Wales. The saline waters of the spa sources in the Llandrindod Wells [SO 0400 5102] and Builth Wells [SO 0589 6107] area of central Wales have been a focus of interest since Roman times (**Plate P802421**). The Builth Inlier is characterised by typically weakly permeable metasedimentary and volcanic rocks with a deeper than normal fracture system associated with the north-westerly trending Tywi Lineament, itself a south-westward extension of the Pontesford Lineament. Small volume discharges of iron-rich and sulphur-rich waters, some with total dissolved solids greater than 16 000 mg $l^{-1}$, suggest that some deeper-than-normal groundwater flow paths exist within this area of Ordovician and Silurian strata (**Edmunds et al., 1998**). The normal shallow active groundwater flow zone in weathered and fractured bedrock tends to dilute upwelling deeper-circulating and older waters suggesting that higher salinities may occur at depth.




Schematic cross-section of the Builth Inlier illustrating probable evolution of the Llandrindod wells spa waters (after Edmunds et al., 1998). P859269.

The discharge from all the springs including the nearby Llangammarch Wells [SN 9381 4725] and Llanwrtyd Wells [SN 8783 4661] sources are collectively < 1 l $s^{-1}$. The high salinities indicate a slow passage to considerable depth, there being no evaporite or hydrothermal deposits in the area. The discharge temperature is close to mean annual air temperature between 11 and 13 $^{o}$C, reflecting a slow upward journey of small flow volumes which equilibrate with the surrounding rock temperatures near surface before discharging. Stable isotope and radiocarbon evidence suggest the waters are of Late Pleistocene age. The Br/Cl ratio is enriched, suggesting that there has been prolonged water–rock contact with the Lower Palaeozoic marine shales to create a Br-rich composition. Some entrainment of Cl from ancient sea-water entrapped in the rocks may also have taken place. **Figure P859269** illustrates a probable flow system with upward flow concentrated in faults on which the spa springs occur.

Although the Builth Wells spa waters are more saline than those at Llandrindod Wells, the stable isotope data indicate that residence times of the Builth waters are shorter. Nevertheless the circulation mechanism is likely to be similar to that at Llandrindod (**Figure P859269**). The less mineralised waters at Llangamarch and Llanwrtyd derive from a shallower system. Mixing with locally derived near-surface systems tends to obscure the saline signature of the low-volume deeper waters as they rise to the surface. Thus, although no other sources of deep circulation in the Lower Palaeozoic aquifers of Wales have so far been discovered, there is every reason to infer that they may exist.

# Hydrogeology of Wales: Ordovician and Silurian aquifers - groundwater chemistry

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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The chemical composition of the groundwater in the Ordovician and Silurian strata is variable. This reflects the range of residence times as well as pH and redox. The rocks are dominated by poorly reactive minerals such as illite, chlorite and quartz, and the groundwaters tend to be weakly mineralised (**Shand et al., 2005**). The presence, locally, of sulphide and carbonate minerals form an important control on the evolution of the water chemistry. However, the largest variations are likely to occur with depth and boreholes that abstract waters from a variety of fractures at different depths produce waters of contrasting chemistry. The groundwaters are young, varying in age from weeks/months to a few decades.

The chemistry of the groundwater varies from very dilute waters dominated by Na, Cl and $SO_4$ (reflecting an important atmospheric input) to Ca-$HCO_3$ and mixed types. They vary from acidic to alkaline (pH 4.9 to 8.8) and from oxidising to reducing (Eh–79 to 514 mV). The pH is largely controlled by the degree of water–rock interaction, sulphide oxidation (producing acidity) and carbonate dissolution (producing alkalinity). The dominant process in most groundwaters is silicate dissolution, due to the lack of carbonate minerals present in the bedrock. In the western part of the Teifi Valley, the occurrence of carbonate shelly debris and calcite in the Irish Sea-derived drift has had a marked influence on the concentrations of Ca, Mg, $HCO_3$ and Sr.

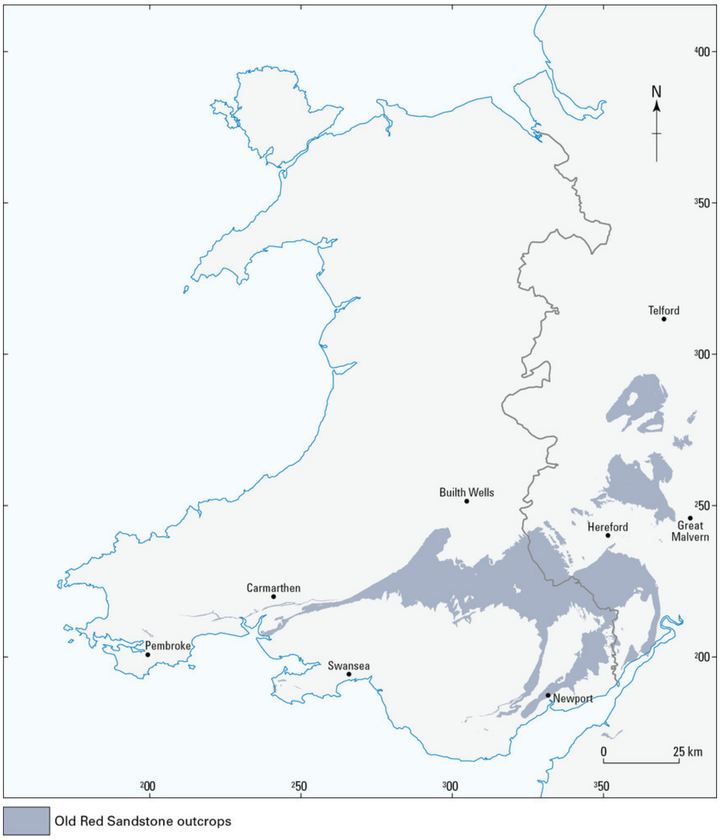
# Hydrogeology of Wales: The Old Red Sandstone aquifer

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

## Geological setting

The outcrop of the Devonian-age Old Red Sandstone in Wales and the Welsh Borders surrounds the north and east margins of the South Wales Coalfield to form a large tract of land that encompasses what was once called Breconshire, Herefordshire and a large part of Monmouthshire. There is a sinuous westerly limb that ends at Nab Head on the Dyfed coast while the eastern limit comprises the graben faults which mark the Worcester Basin (including the East Malvern Fault) and the Severn valley south of Bridgnorth.



Outline distribution of the old Red Sandstone outcrops. P859270.

The base of the Old Red Sandstone is conformable. In most of south Wales and the Welsh Borderland, the Silurian–Devonian boundary is situated in Old Red Sandstone facies, with the transition from marine to fresh-water deposition occurring in the late Silurian. This contrasts with south-west Wales, where Devonian strata lie unconformably on Precambrian to Wenlock age strata, and in Anglesey where they lie unconformably over Precambrian to Llandovery strata. Tournaisian to Visean strata (the Carboniferous Limestone facies) lie unconformably upon the Devonian-age strata except south of the Rhetic fault in south-west Wales where the Upper Devonian Skinkle Sandstones pass conformably into overlying Tournaisian to Visean strata.

The Devonian sediments of south Wales and the Welsh borderlands are continental deposits known as the Old Red Sandstone facies. They derive from detritus from a mountain front to the north draining towards the sea just south of the present location of the Bristol Channel. The shallow marine and coastal environment that developed in the late Silurian and Early Devonian was succeeded by terrestrial alluvial facies throughout the remainder of the Lower Old Red Sandstone. There is a major unconformity between the Lower Old Red Sandstone and Upper Old Red Sandstone. The principal lithostratigraphical components of the Old Red Sandstone are shown in the **Lithostratigraphical components table** and the outline location of the Old Red Sandstone strata is shown in **Figure P859270**.

## The main lithostratigraphical components of the Old Red Sandstone facies (after British Geological Survey, 2000).

| | Central south Wales | Forest of Dean<br>S Wales Coalfield E crop |
|---|---|---|
| Upper ORS | Grey Grits (21 m)<br>Plateau Beds (41 m) | Quartz Conglomerate Group (45–200 m) |
| Lower ORS | Brownstones Formation (490 m | Brownstones Formation (1220 m) |
| | Senni Beds (300–380 m)<br>Red Marls (1200–1375 m) | St Maughan's Group (380–610 m) |

In the Lower Old Red Sandstone the St Maughan's Formation comprises a cyclic succession of fluvial channelised sandstones, floodplain mudstones and siltstones. Associated calcrete deposits occur in some channel bottoms. The Senni Beds comprises fluvially deposited fine- to coarse-grained sandstones with associated calcrete deposits. The overlying Brownstones Formation is mainly red fluvial channelised sandstones within red/brown mudstones deposited as overbank material and it is these that form the Black Mountains and the Brecon Beacons.

The Upper Old Red Sandstone strata are more consistently arenaceous and conglomeratic as they young. The Plateau Beds cap the Brecon Beacons (**Plate P542858**), the Black Mountains and the western part of the north crop of the South Wales Coalfield. They are represented by an upward coarsening facies from mudstones through sandstones to conglomerate. The overstepping Grey Grits comprise a braided stream deposit which forms a quartzitic sandstone which may be grey, green or yellow in colour. The overlying Quartz Conglomerate Group develop from the quartzitic sandstones into higher energy, conglomeratic material interbedded with sandstones and red mudstones.

View of the Brecon Beacons capped by Old Red Sandstone Plateau Beds with the Neuadd and Pontsticill Reservoir in the Taff Fechan valley from the Twynau Gwynian north of Merthyr Tydfil. P542858.

Roberts (1966) described the joint patterns along the northern flanks of the South Wales Coalfield. Joint sets in the Brownstones Formation (shales and sandstones of the Lower Old Red Sandstone) are found at 350°, 330°, 270°, 240° and 220° (joint strikes being given as the larger of the two azimuths e.g. 350°–170° is recorded as 350° joint). The joints are best developed in the sandstone layers where characteristic joint sets with small dihedral angles predominate (350°–330°). They are reported to be smooth faced, planar, usually closed and persistent, with horizontal (strike) distances in excess of 15m being common. Succeeding members of the Upper Old Red Sandstone are jointed along the same trends but the coarser lithologies give rise to rougher, less rigidly parallel fractures. The topmost strata (Grey Grits) have a joint system with the master set striking at 340˚ and subordinate sets at 290°, 250° and 220°. These are smooth-faced, planar, with an average frequency of 15 cm and a horizontal and vertical persistence of 15–18m respectively. Roberts considers the majority of the joints to be shear fractures formed early in the deformational history of the area during the Variscan Orogeny.

# Hydrogeology of Wales: The Old Red Sandstone aquifer - groundwater occurrences

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

Although the Old Red Sandstone sequence approaches a thickness of 2 km in places, it offers little prospect for significant groundwater storage and transport. This is partly due to the interbedded weakly permeable mudstones, marls, and siltstones which tend to isolate the more permeable arenaceous sequences, inhibiting deep components of vertical flow. The channel-bottom calcrete deposits provide discreet zones of higher permeability and better prospects for groundwater transport. Nevertheless primary porosity is usually low, and the predominant groundwater-flow mechanism is via fractures.

Marls and siltstones predominate in the lowermost Old Red Sandstone strata. To these primary lithological controls are added the effects of poor sorting, frequent presence of micaceous material and induration arising from postdiagenetic compaction and burial. The primary porosity in some horizons of the Old Red Sandstone, for instance, is so low that they have long been used as flagstones. Associated cementation, both calcareous and siliceous, further decreases primary porosity, although this appears to be less the case in the Upper Old Red Sandstone, where the Quartz Conglomerate Group passes up into soft, poorly cemented fine- to coarse-grained sandstones (Holliday, 1986). In general however, the predominant Old Red Sandstone flow mechanism is via fractures, with much of the storage likely to occur in joint- and fault-related fracture systems.

Much of the strata are anisotropic and behave as a complex, multilayered aquifer with sandstone bands hydraulically isolated by interbedded mudstones, especially where there are no structural discontinuities. The effective saturated thickness, for most practical purposes, is only to about 40 m below ground surface, beneath which fracture dilation approaches zero. Steep regional hydraulic gradients of 0.01 to 0.1 reflect the low conductivity of the strata.

### Summary of aquifer properties data for the Old Red Sandstone of Wales and the Welsh Borderland – includes four sites in Raglan Mudstone Formation see Chapter 3 (after Jones et al., 2000).

| | Value | Population |
|---|---|---|
| Number of borehole records | | 148 |
| Transmissivity range | 0.000001 to 350 ($m^2 d^{-1}$) | |
| Mean transmissivity | 51 ($m^2 d^{-1}$) | 66 |
| Storage coefficient range | $1.9 \times 10^{-4}$ to $5.0 \times 10^{-2}$ | 3 |
| Specific capacity range | 0.000001 to 1226 ($m^3 d^{-1} m^{-1}$) | |
| Mean specific capacity | 39 ($m^3 d^{-1} m^{-1}$) | 135 |

The principal controls on permeability and transmissivity of the Old Red Sandstone are lateral and vertical heterogeneity arising from lithology changes, degree of induration/cementation, and extent/depth of fracturing along bedding planes, as joints or in association with faults or bed flexures. The range of transmissivity values available from pumping tests in the strata range up to 350 $m^2 d^{-1}$, with a mean of 51 $m^2 d^{-1}$ (see **Aquifer properties table**). The few storativity values that are available indicate that semiconfined to unconfined conditions are predominant

(**Jones et al., 2000**).

Nevertheless, the Devonian-age Old Red Sandstone is arguably the most important aquifer in Wales. The main outcrop of the aquifer contains at least 2650 abstractions and over 80 per cent of these are licensed for groundwater abstractions (i.e. >20 $m^3 d^{-1}$), either boreholes, wells or springs, the majority for domestic, agricultural and industrial supply (**Moreau et al., 2004**). Of the licences granted for agricultural purposes a significant proportion are for spray irrigation. In addition, there are over 2300 private water supplies from Old Red Sandstone strata that are registered with local government, although many small sources such as supplies to single dwellings remain unregistered. At least 50 per cent of the known private supplies are for domestic use only.

Holy Spring at Maen-Du, north of Brecon Cathedral. P802423.

The Brownstones Formation and the Senni Beds are the best yielding formations in the Old Red Sandstone because the more transmissive sandstone of the Upper Old Red Sandstone are locally poorly represented. There are some large springs at the base of the St Maughans Sandstone. Among the sacred springs located north of Brecon is that at Maen-Du [SO 0390 2963] that formerly supplied Brecon Castle (**Plate P802423**). Most of the waters from the Old Red Sandstone are hard (**Jones et al., 2000**). The hard water favours tufa formation and fractures are commonly lined with travertine in cuttings or excavations.

The Old Red Sandstone waters are moderately fresh and tend to have low conductivities compared with other British groundwaters reflecting shallow and rapid groundwater circulation in the aquifer. Most groundwaters are either at or approaching saturation with respect to both calcite and dolomite.

# Hydrogeology of Wales: The Old Red Sandstone aquifer - groundwater chemistry

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
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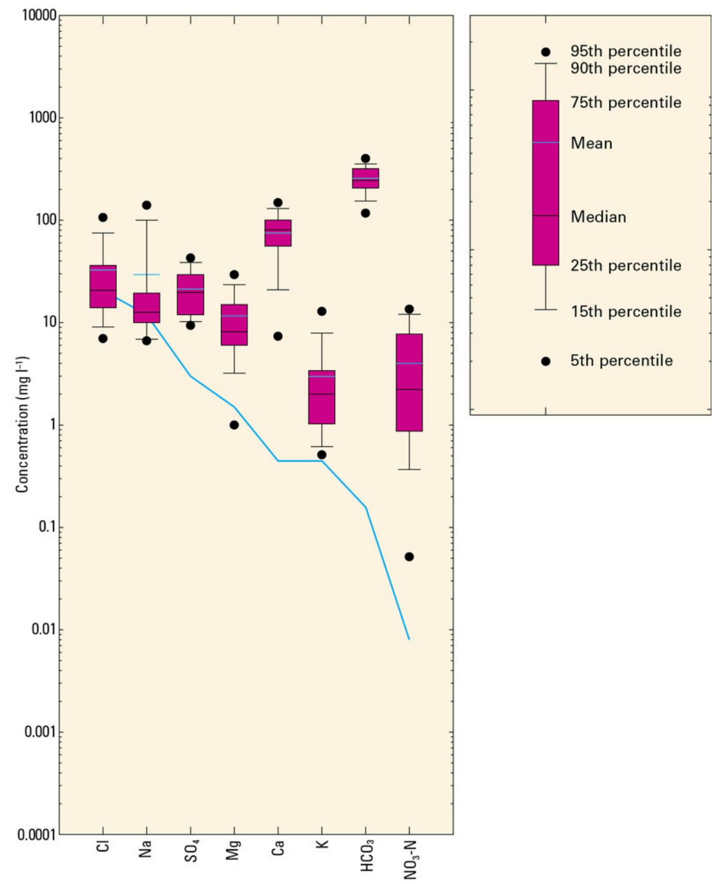
The chemistry of groundwater in the Devonian sandstone aquifer has evolved by natural processes of water–rock interaction (**Moreau et al., 2004**). The dominant process controlling the groundwater chemistry is carbonate mineral dissolution and, in the deeper groundwaters, ion-exchange. Slower silicate dissolution reactions are also important in providing Si, K and Na to the groundwaters. The groundwaters are mostly of Ca-$HCO_3$ type but Na-$HCO_3$ types are present in deeper parts of the aquifer (**Figure P859271**). Upland groundwaters show significant rock interaction even where residence times are short. In valleys this is complicated by mixing with older, locally confined groundwaters as well as surface pollutants.




Range of major ion concentrations in the Devonian sandstone in south west wales and parts of Herefordshire (after Moreau et al., 2004). P859271.

The groundwaters generally have low solute concentrations. The low salinities indicate shallow groundwater flow in uplands areas, where the aquifer is well flushed. Remnants of older formation groundwaters containing higher concentrations of Na, Cl, Br and I as well as salinity occur in valleys beneath mudstones horizons. In these areas ion-exchange of Na adsorbed on clays for solute Ca occurs leading to Na-$HCO_3$ type groundwaters.

There are some reducing groundwaters. Iron and Mn, however, are generally low reflecting the dominance of oxidising conditions in most of the aquifer but may be locally high (up to 3.2 and 0.95 mg $l^{-1}$ respectively). Trace metal concentrations are generally low, reflecting neutral pH and oxidising conditions over much of the aquifer.

# Hydrogeology of Wales: Carboniferous aquifers

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
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## Geological setting

The Carboniferous strata traditionally divide between the lowermost Carboniferous Limestone facies, the Millstone Grit facies and the uppermost Coal Measures facies. These names have now been superseded (**Waters et al., 2009**). In north Wales the sequence divides between the lowermost Clwyd Limestone Group, which is separated from the Millstone Grit Group by the Craven Group, the Pennine Coal Measures Group and the uppermost barren Warwickshire Group. In south Wales this translates into the lowermost Avon Group, the Pembroke Limestone Group, the Marros Group (of Millstone Grit facies), followed by the South Wales Coal Measures Group and the Warwickshire Group (formerly the Pennant Measures). The Warwickshire Group is absent in Pembrokeshire.

Lower Carboniferous rocks of Tournaisian to Visean age were deposited as warm water carbonates in marine shelf environments to form the Clwyd Limestone facies on the northern (north Wales) and the Pembroke Limestone Group on the southern (south Wales and Forest of Dean) flanks of the Wales–Brabant Massif.

The Clwyd Limestone Group occurs in Anglesey, north Wales and along the Menai Strait, on the west side of the Vale of Clwyd and adjacent coastal tract and along the eastern flank of the Clwydian range. Some local dolomitisation has occurred. The Pembroke Limestone Group in south Wales forms narrow outcrops peripheral to the South Wales, Pembrokeshire and Forest of Dean coalfields. The limestone is partly dolomitised on the east and south-east crop of the South Wales Coalfield.

The Namurian age Marros Group crops out around and underlies the South Wales Coalfield whereas in north Wales it forms a narrow belt of strata between Ruabon and Oswestry. These outcrops result from deposition on the flanks of the Wales–Brabant Massif. In the Gower Peninsula the Marros Group attains 55 m thickness, whereas there is less than 20 m of it in the east crop of the South Wales Coalfield. It is also thin in north Wales. The deposits are characterised by cyclic deposition with marine mudstones (**Plate P802427**) and deltaic and fluvial sandstones.

Waterfall on shales in the Afon Mellte Gorge north of Glyn Neath. P802427.

The Coal Measures groups crop out most extensively in the coalfields of south and west Wales, in the Flintshire and Denbighshire coalfields of north Wales and in the Forest of Dean. There are small outliers in Anglesey and in the Welsh Borderland. The sequence which equates to the Westphalian is divided between the South Wales Lower, Middle and Upper Coal Measures formations (the latter part of the Warwickshire Group) and mostly comprises cyclic sequences of fluviodeltaic origin. These consist of a coarsening upwards sequence of mudstones, siltstones and fine-grained sandstones which grade into seatearths which are succeeded by coals that derive from basin-wide peat mires. Periodic intrusion of the sea resulted in deposition of numerous mudstones characterised by marine bands with distinctive bivalve fauna.

Thicker sandstones also occur as valley infill deposits; thinner sandstones were deposited as levées, bars and deltas. Barren measures and the Warwickshire Group succeed the grey-coloured productive Coal Measures, the predominantly red beds being deposited in a more arid environment.

The Westphalian succession in the South Wales Coalfield (the Coal Measures formations and the Pennant Sandstone Formation) attains a thickness of over 2500 m towards the south-west (**Thomas, 1974**). It is dominated by mudstones and siltstones in the South Wales Lower and Middle Coal Measures formations, in which there are 20 to 25 principal economic coal seams. The South Wales Upper Coal Measures Formation and the Pennant Sandstone Formation are predominantly sandstones with persistent but thin mudstone and coal horizons. These rocks tend to form the plateau area of the central coalfield.

# Hydrogeology of Wales: Carboniferous aquifers - the Carboniferous Limestone aquifer

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

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The physical hydrogeology of the Carboniferous Limestone in Wales was first described by **Richards (1959)** and in south Wales was later summarised by **Allen et al. (1997)**, and north Wales by **Morris et al. (2000)**. The Carboniferous Limestone aquifers, the Clwyd Limestone Group in north Wales and the Pembroke Limestone Group in south Wales are used for public and private supply. A number of individual studies have been carried out in recent years on various aspects of groundwater occurrence and protection, particularly in south Wales. In addition there are some notable reports on speleological investigations which provide insight into the hydraulics of the karst aquifer. However, understanding of the regional flow mechanisms is patchy although considerable detail is available on a site specific basis.

Postdepositional faulting and folding took place in the Variscan Orogeny, and in north Wales coincident ore and gangue mineralisation occurred along some discontinuities. Solution channels may have begun to form along fractures as early as the Mesozoic, but the wetter climes of the Pleistocene produced most of the swallow holes and caverns, some collapsed as at Gwernymynydd in Flintshire, with many later infilled with rubble and detritus in the late- and post-glacial periods. Rapid solution of the limestone (**Plate P802429**) occurs mainly in the zone of active circulation which is in contact with the atmosphere, i.e. at the water table, or above the level of passages and caverns into which the phreatic water drains. Fossil karstic horizons, now submerged beneath the water table, may reflect past changes in base level (see box below: Development of Karst in the Carboniferous Limestone).

Karstic Avon Group strata at Mynydd Llangattog. P802429.

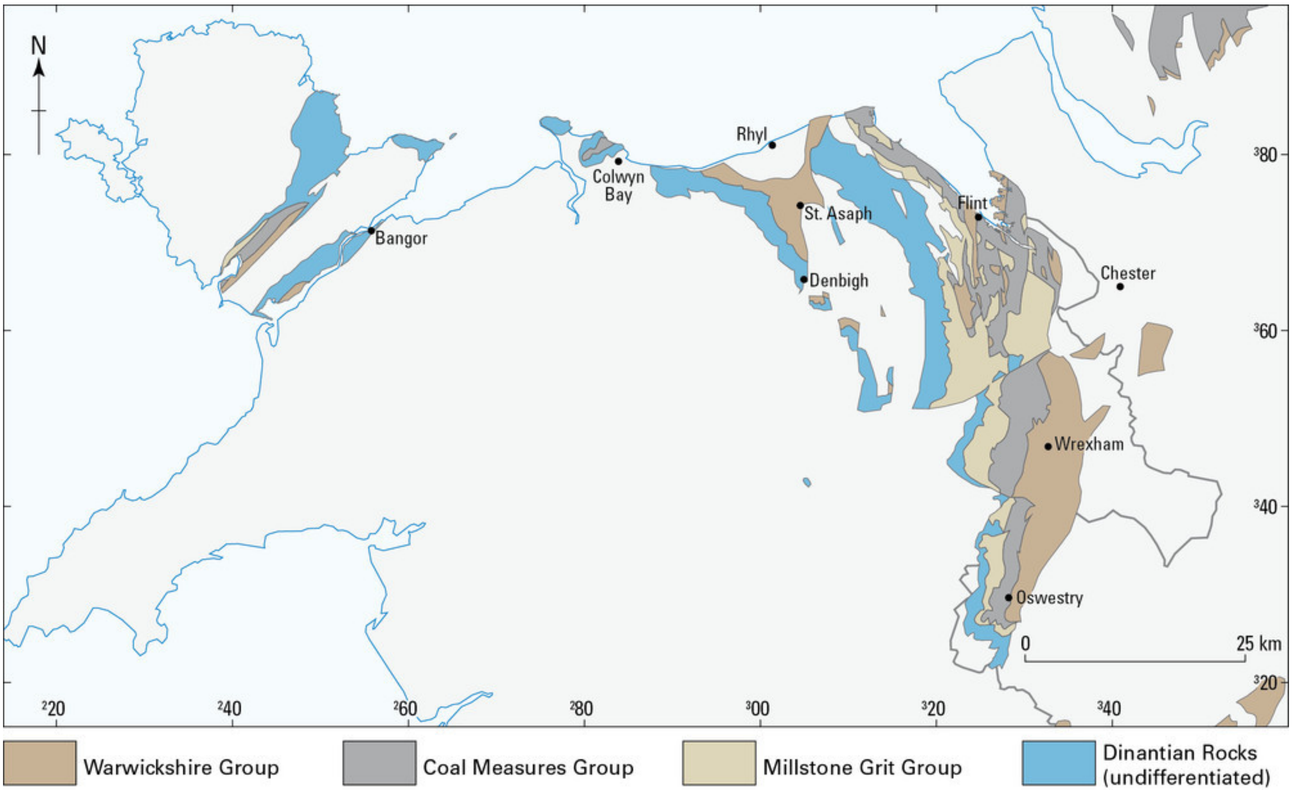
Speleogenesis is the origin and development of caves [1], the primary process that determines the evolution of karst features. The development of caves through limestone [2] is caused by water circulation with carbon dioxide [3] dissolved within it, producing carbonic acid [4] which permits the dissociation [5] of the calcium carbonate [6] in the limestone. Available $CO_2$ in rainwater can enable up to 33 mg $l^{-1}$ $CaCO_3$ to be taken into solution, increasing to 250 mg $l^{-1}$ wherever the rainwater has percolated through soil or peat to gain an enhanced $CO_2$ content. **Ball and Jones (1990)** argue that the solution of the limestone is inadequate to explain the tight stratigraphical positioning of solution tubes in the north crop, situated at the northern periphery of the coal field, and that shallow aerobic dissolution requires a bacterial catalyst to promote the reaction. That the purer oolitic horizons are generally left intact whereas the more impure sulphate-rich beds are the target of dissolution suggests a role for sulphur-loving bacteria, although mechanical attrition is also an important process in cave formation.

In addition, dolomitisation of some of the limestone in the periphery of the South Wales Coalfield effects a reduction in overall volume and the creation of vugs and fractures. Although these may be calcite or silica infilled they generally lead to an overall increase in permeability (**Thomas et al., 1983**).

## North Wales

In Anglesey the Clwyd Limestone Group aquifer is located in limestones that were deposited in faulted basins and have been extensively dolomitised and silicified. Flow occurs through open joints and karstic zones although mudstone horizons have inhibited the downward percolation of acidic rainwater and karstification is better developed elsewhere in north Wales. Transmissivities from test pumping at four sites reported values from 0.15 to 1.8 $m^2$ $d^{-1}$ with yields of about 1 l $s^{-1}$.

The Clwyd Limestone Group in north Wales crops out to the north of the Vale of Clwyd and in a narrow strip south towards Wrexham, and south of the Vale of Clwyd towards Colwyn Bay and Great Ormes Head, Llandudno (**Figure P859272**). There are basal units of grey and brown limestone and an upper unit of sandy limestone, but the majority of the sequence (c. 500 m thick) comprises white limestone. The limestone has been subject to brittle fracture and enlargement of secondary features by karstic dissolution. The limestone has a low intergranular permeability but substantial groundwater flow is possible through enlarged fissures. In the Clwyd catchment the limestone crops out without significant till cover and acts as a valuable indirect recharge source to the Triassic sandstones in the Clwyd basin, particularly in the area to the south of Ruthin (see Permo-Triassic and Jurassic aquifers).




The distribution of Carboniferous strata in North Wales. P859272.

Groundwater flows through the limestone in the Clwyd catchment via fractures and available karst features in a north-easterly direction to discharge to the sea. Swallow holes are common in the main Clwyd Limestone Group outcrop to the east of the Vale of Clwyd. Ffynnon Asaph [SJ 0752 7893] which flows at 4.3 Ml $d^{-1}$ traditionally supplied the town of Prestatyn. Local metal mining in the limestone has exposed a number of cave and conduit systems, some of which have had a direct effect on mine dewatering.

In the Halkyn Mountain area, around Caerwys, between Cilcain and Llanferres and in the Gwernymynydd district, fossil swallow holes containing sands, clays and weathered cherts have been exposed during mining.

Other surface waters with low flows subject to loss into the limestone include the Afon Clywedog, a tributary of the Dee to the west of Wrexham, and the Afon Alyn which is dry on average for 170 days per year between Loggerheads and Rhydymwyn some 4 km above Mold (**National Rivers Authority, 1993**). The Afon Alyn otherwise often disappears into a swallow hole north of Plas-yr-esgob [SJ 188 644] and re-emerges into the dry river bed just above the confluence with the Cilcain stream [SJ 187 652], below which it can be intermittently dry as far as Hesp Alyn [SJ 188 653]. The Ogof Hesp Alyn cave system has only been discovered in recent years (**Appleton, 1974**) and its description illustrates the complex processes of capture, solution and attrition that combine to create such underground features. The Afon Alyn water loss is not a new phenomenon, and legend has it that a giant, when set on fire by St Cynhafal, jumped into the river to extinguish the flames whereupon the river, which was turned to steam, ceased to flow, and has only flowed intermittently ever since.

Caverns also occur west of the Vale of Clwyd at Cefn and Plas Henton and to the east at Ffynnon Beuno and Bae Gwyn. The elevation of these cave systems relative to today's base level suggests that they all originated in the Pleistocene when sea level was about 15 m higher than it is today.

Attempts to prevent water from the River Alyn from entering the Halkyn Mine via swallow holes during the 1930s were largely unsuccessful (**Water Resources Board, 1973**). A number of drainage schemes were implemented to protect the mines and their drainage used to supply industry:

- the Halkyn Tunnel, 8 km in length across Halkyn Mountain

- Government (War) Drainage Scheme – pumping from Taylor's Shaft, North Hendre at 300 l $s^{-1}$ into the Halkyn Tunnel
- Milwr Sea Tunnel which was designed to lower the water table in the limestone across the Halkyn Mountain area. The minimum yield is about 55 000 $m^3$ $d^{-1}$ representing run-off from the surrounding hills onto the limestone as well as lost river water.

Borehole yields are highly variable and unpredictable, with good supplies only obtained if water-filled fractures with access to recharge are intersected. For example, a borehole drilled in Anglesey into a mixed sedimentary sequence in Carboniferous strata at Llanbedrgoch [SH 493 803] to a depth of 65 m yielded only 2.5 l $s^{-1}$ over a two-hour pumping day. Two previous drilling attempts in the same vicinity at Llanbedgroch, however, had failed to find any trace of water. **Robins and McKenzie (2005)** showed that the density of occurrence of wells on Anglesey in the Clwyd Limestone Group was 1.3 $km^{-2}$ and of springs was 1.6 $km^{-2}$. Yields are typically small with many springs being little more than minor seepages.

Groundwater chemistry on Anglesey is consistently of the Ca-$HCO_3$ type, with a small subset tending towards Na, Mg and Cl dominance. The groundwater is oxic (Eh >127 mV) has near neutral pH, Ca ranging from 60 to 130 mg $l^{-1}$ and $NO_3$ typically < 25 mg $l^{-1}$ (**Banks et al., 2008**).

## South Wales

In Carmarthenshire, the basal Avon Group, with thin shaly and muddy limestones, are overlain by karstic massive crystalline, fossiliferous to dolomitised limestones up to 100 to 150 m thick. These are overlain by the Oystermouth Formation (formerly the Upper Limestone Shales). The limestone has a low primary porosity. Transmissivity is between 10 and 20 $m^2$ $d^{-1}$ and storage coefficients of between 4 and 9 x $10^{-4}$ have been obtained from a small number of borehole pumping tests. Boreholes at Trapp yield 144 $m^3$ $d^{-1}$ to 240 $m^3$ $d^{-1}$. The source of the Loughor, located on a faulted contact of limestone and Marros Group grits, flows at 60 to 1000 l $s^{-1}$ with a connection to caves 7 km away.

The Pembroke Limestone Group outcrop is thin both north and east of the coalfield, and to the south of the coalfield it has been eroded into a broad platform in the Vale of Glamorgan, the Gower and parts of Pembrokeshire. The strata are characterised by a basal shaly mudstone, followed by thick massive dolomitic, oolitic and bioclastic limestones and an upper mixed sequence of shale and muddy limestone. Chert may be abundant within the main limestone. In Pembrokeshire, the Pembroke Limestone Group aquifer discharges into the Bosherton ponds via spring systems at Frainslake and Bosherton. Groundwater is abstracted at Pendine for use in public supply.

Various attempts have been made to establish the water balance over all or part of the limestone outcrops. Work by **Aspinwall and Co (1993)** focussed on the Vale of Glamorgan and the capture zones of the Schwyll Spring [SS 888 771] and the Pwllwy Borehole and springs [SS 992 766] noting that the water balance calculations showed that a large part of the recharge could not be accounted for and was presumably lost as offshore submarine springs. Schwyll and Pwllwy near Bridgend are believed respectively to derive from a variety of sinks on the rivers Ogmore, Ewenny, Alun and Methyr Mawr up to 7 km away (**Hobbs, 2000**), whereas the Pwllwy has a more local catchment. Although rarely used for public supply, Welsh Water retains an abstraction license for 7.955 $Mm^3$ $a^{-1}$ from the Schwyll Spring sources, although they are not currently in use and **Hobbs (1993)** estimated the total yield of the spring at 12.3 $Mm^3$ $a^{-1}$ derived partly from influent rivers, the Ogmore and to a lesser extent the Ewenny, and partly from groundwater. These springs periodically had to be disconnected from supply during very wet weather when the outflow became turbid. The springs can also suffer from reversed hydraulic head during periods of exceptional high spring tides when dirty surface water can ingress some of the spring heads. **Aldous (1988a)** used detailed site specific knowledge to attempt to delineate flowpaths and likely transport fields for contaminant movement in the aquifer. **Hobbs (1993)** identified a number of sinks and risings in the area:

> Merthyr Mawr sinks [SS 8901 7763] on the western bank of the Ogmore river and rise at two springs which flow into the Merthyr Mawr Mill Leat [SS 88657763]

Pitcot Pool [SS 8955 7443] is spring fed

Jacobs Well [SS 9121 7480] a series of springs alongside the Afon Alun

Byeastwood Springs [SS 9298 8099 and SS 9258 8060] flow eventually into the River Ewenny

Hoel-las stream sink [SS 9288 8267], now concealed beneath the M4 motorway, and smaller sinks to the east take water draining off the Coal Measures

Tymaen sink [SS 8943 7705]

Ewenny Fach sink [SS 9542 7990] a sink in the bed of the River Ewenny

In the area of the Schwyll Spring and Pwllwy Borehole and springs the Pembroke Limestone Group is over 500 m thick comprising a southward thickening alternating bioclastic and oolitic limestone 700 to 800 m thick. This is underlain by the basal Avon Group shales which are about 100 m thick. Aquifer transmissivities range between 4 and 130 $m^2$ $d^{-1}$, and hydraulic conductivity range between 0.1 and 5 m $d^{-1}$. The effective porosity of the upper 8 to 10 m of the aquifer ranges between 6 and 8 per cent, reducing to 0.5-2 per cent below this. Among other sources, boreholes drawing from the concealed Pembroke Limestone Group at Bridgend contribute to public supply.

One of many springs flowing from boggy ground at the junction of the basal Namurian grit and the underlying Avon Group near Trefil, north of Tredegar . P802428.

Near Llandybie at Pant-y-Llyn on the north-western limb of the coalfield is a small turlough, the only known active turlough in Wales. Pant-y-Llyn [SN 60167] is a small depression in the limestone which fills with water rising from the Pembroke Limestone Group along its faulted boundary with the Devonian Brownstones, usually in the autumn, and drains to estavelles in the late spring (**Campbell et al., 1992**). In flood it is some 160 by 60 m in area and up to 4 m deep.

Swallow holes are common over much of the limestone outcrop and also occur beneath a thin cover of the basal beds of the Marros Group grits. Particularly large examples with collapsed caverns occur at Mynydd y Glog north of Hirwaun, whereas linear developments of swallow holes occur along lines of weakness at Ystradfellte and east of Trefil. Numerous examples are present on the Twrch Sandstone Formation (formerly the Basal Grit) on the Llangattwg and Llangynidir mountains, some blocked by fine detritus to form small ponds such as Pwll Mawr which is situated on the interfluve between the Neath and the Tawe valleys.

There are numerous closely spaced swallow holes on the north crop, some of which are nothing more than open fractures. There are some 80 000 dolines on the north crop alone (**Crowther, 1989**), and collectively these provide drainage to the limestone outcrop. The swallow water tends to flow southwards down dip and beneath the cover of the Bishopton Mudstone Formation. In wet conditions it rises up through the shale to emerge above Blaen-Rhymney, and much like a Chalk bourne, creates river flow where normally the bed is dry. A similar, but less ephemeral discharge near Blaen-Sirhowy was once used for public supply. There are also a few springs on the northern scarp slope. In addition there are a number of caverns beneath the north crop especially around the headwaters of the rivers Tawe and Neath.

Some caves reflect past sea levels; Little Hoyle and Hoyle's Mouth near Tenby are about 15 m above sea level reflecting the Pleistocene sea level. The Bacon, Minchin and Paviland caves in Gower were also formed during the Pleistocene when the sea level was elevated relative to the present level.

There are numerous examples of sinks and risings (see **Active karst systems table** and **Plate P802428**). The headwaters of the Neath, including the Hepste, Mellte and Nedd-Fechan all come off the Devonian sandstone and disappear into sinks in the limestone. At the head of the Swansea valley the Llynfell flows out of the Dan-yr-Ogof cave whilst nearby the River Giedd disappears into a swallow hole. There are show caves in the Tawe Valley at the mouth of the Dan Yr Ogof cave system. The caves drain the Sink y Giedd [SN 810 179] and Waun Fignen-felen [SN 826 177] with a combined discharge of between 0.15 and 0.30 $m^3 s^{-1}$ depending on weather conditions (**Coase and Judson, 1977**). Average flow rates of 0.14 and 0.13 km $hr^{-1}$ respectively have been demonstrated with dye testing (see **dye tests table** ). A number of dolines (e.g. the 'Crater') and other hollows overlie the cave system, but the remnant dry valleys occasionally flow during exceptionally wet weather.

## Selected active karst systems within the north crop (from east to west), see Gascoine (1989).

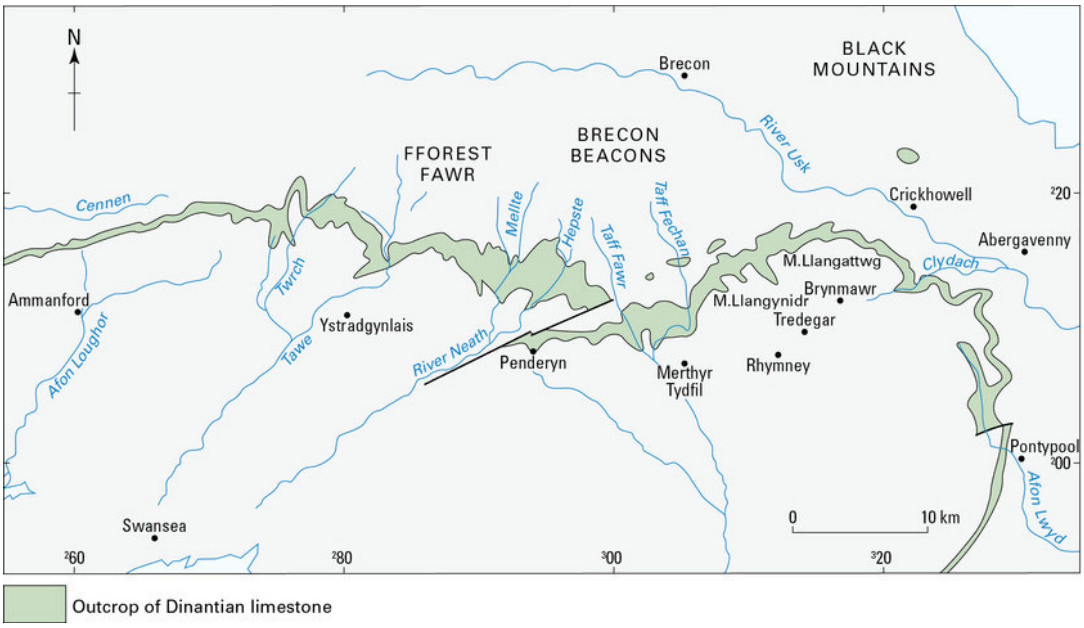
| Area | Grid Square | Comments |
|---|---|---|
| Afon Lwyd | SO 20 | A series of sinks and caves leading to four resurgences. Pontnewynydd Risings typically issue at 6 Ml $d^{-1}$. |
| Llangattwg | SO 21 | Dye tracing has proved relationship between a series of sinks and risings. |
| Mynydd Llangynidr | SO 21 | The main resurgence is Fynnon Shon Sheffrey [SO 1265 1188]. Dye tracing has proved the relationship between various sinks and risings (**Figure 5.2**). |
| The Rhymney Valley | SO 01 | Dye tracing has proved relationship between a series of sinks and risings. |
| Taff Fechan and Taff Fawr | SO 01 | Includes Nant y Glais caves and resurgences, otherwise connections proven by dye tracing. |
| Cwm Cadlan and Penderyn | SN 90 | Llygad Cynon is source of the Afon Cynon. An adjacent borehole [SN 9524 0774] reported an 'underground lake' at 55 m and is pumped at 5 Ml $d^{-1}$. |
| Afon Hepste | SN 90 | Upper Hepste Main Sink [SN 9541 1208] discharges back to the river at Hepste Main Resurgence [SN 9360 0973] in under 24 hours. |
| Afon Mellte | SN 91 | The main Mellte Sink [SN 9315 1332] has proven connections to five resurgences. Contributions also from smaller sinks. |
| Nedd Fechan | SN 91 | Dye tracing has proved relationship between a series of sinks and risings. |
| Glyntawe and the Black Mountain | SN 81 | Two main cave systems behind main resurgences at Glyntawe |
| The Twrch valley | SN 71 | Fault-controlled resurgences. |
| Black Mountain – western area | SN 61 | 7 km from main sink to resurgence proven by dye tracing. |

## Relationship between dye tests from Waun Fignen-felen and Sink y Giedd, after Coase and Judson (1977).

| | From Waen Fignen Felen | From Sink y Giedd |
|---|---|---|
| Distance from sink to resurgence (km) | 3.5 | 4.7 |
| Time for dye to reach resurgence (hours) | 25 | 36 |
| Average flow rate (km $hour^{-1}$) | 0.14 | 0.13 |
| Elevation of sink above resurgence (m) | 248 | 218 |

Other celebrated groups of caves include the Nant y Glais caves to the south of the Vaynor Moors on the north crop: Ogof Robin Goch [SO 0392 1076], Ogof y Ci [SO 0403 1051], Ogof Dŵr Dwfn [SO 0415 1022], Ogof Rhyd Sych [SO 0416 1021], Ogof Pysgodyn Gwyn [SO 0416 1016] and Ogof Jonny Bach [SO 0420 1000]. The Nant y Glais river disappears underground altogether as it traverses the cave system except in exceptionally wet weather when flow also occurs through a narrow gorge at surface (**Ford, 1989**).

**Gascoine (1989**) reviewed other cave systems within the north crop. Many of the sinks are situated at the feather edge of the Marros Group where it is only a few metres thick above the limestone (**Figure P859273**), whilst others provide connections from the Avon Group shales and the main limestone. One of the longer and more complex cave systems is Ogof Draenen [SO 2467 1176] at the eastern edge of the north crop. Numerous dolines and stream sinks are present in the area and speleological investigation recognises numerous underfit streams in large passages. **Maurice and Guilford (2011)** have identified a watershed within the system whereby flow occurs both to the north to Clydach Gorge and to the south to the Afon Lwyd. The latter is in a different topographical catchment some 8 km distant and tracer testing indicates velocities of 4 km $d^{-1}$.




Sketch map of the Pembroke Limestone group outcrop along the North Crop (after Gasgoine, 1989). P859273.

A wide range of borehole yields have been established depending on the hydraulic contact with productive fractures. Drilling is always speculative as targeting useful fractures is not easy. The average yield from Carboniferous Limestone Supergroup boreholes across the UK was shown by **Monkhouse (1977)** to be just 4 l $s^{-1}$, but there is no record of the numbers of boreholes that were abandoned as dry, while other boreholes may have a significantly higher yield.

Although fractures and karstification rapidly decreases under the cover of the Marros Group there is some evidence of deep groundwater circulation beneath the coalfield. Taff's Well [ST 1193 8364] discharges groundwater at about 1 l $s^{-1}$ from the South Wales Coal Measures Group with a temperature of 21.6 $^{o}$C, the only thermal spring in Wales (**Farr and Bottrell, 2013** . Previous measurements reported a variety of temperatures all less than 20 $^{o}$C but these were subject to mixing with water from the River Taff which is now prevented by new flood works. Simple inspection of the geothermal gradient and of the discharge water chemistry suggests a deep flow path, probably in the Pembroke Limestone Group, which is believed to travel to a depth of about 700 m (**Squirrell and Downing, 1969**; **Thomas et al., 1983**). Dissolved inert gas analysis indicates that the water infiltrated the ground some 500 m higher in elevation than Taff's Well, suggesting a recharge source somewhere along the north crop (**Burgess et al., 1980**; **Edmunds, 1986**). The water is between 5000 and 10 000 years old based on $\delta^{18}$O and $\delta^{2}$H age indicators (**Farr and Bottrell, 2013**).

A major spring was encountered in the concealed limestone in 1879 during the excavation of the Severn Railway Tunnel. Here a spring discharge of 1000 l $s^{-1}$ was encountered, the Great Spring, which has been pumped to surface ever since (**Drew et al., 1970**). Of good quality, it has been used for a variety of purposes including supply to a paper mill and brewery however its only current use is for public supply.

Water quality in the limestone is typified by slightly alkaline pH up to 7.6, and alkalinity concentrations (as $CaCO_3$) ranging upwards to 230 mg $l^{-1}$. The lower values reflect immature waters that have not attained Ca saturation. In north Wales, local mineralisation in the limestones promotes the solution of metals but at barely detectable concentrations. There are distinct tidal influences on some low-lying coastal areas of south Wales (including the Schwyll Spring) and a marine mixing zone in selected fractures is indicated by enhanced concentrations of Na and Cl at some sources.

A number of detailed site-specific investigations have been carried out on the limestone aquifer in south Wales which provide insight into its hydraulic processes. One such study was carried out between Porthcawl and Port Talbot looking at the environmental impact of extending local quarries in the Pembroke Limestone Group on a wetland area within adjacent superficial deposits (**Cheney et al., 2000**). This work drew on extensive monitoring and analysis carried out previously in the area but was unable to develop a robust groundwater flow model due to data scarcity and the complex nature of flow in a karstic system. In addition 95 per cent of the water balance was unaccountable, suspected to drain to submarine springs in the Bristol Channel.

Groundwater is typically of the Ca-$HCO_3$ type, with $HCO_3$ typically in the range 90 to 550 mg $l^{-1}$, the weakest mineralisation occurring along the north crop. The pH is almost always alkaline with values up to 8.2. Cl concentrations are generally low (<50 mg $l^{-1}$) except on the coast near Porthcawl at Rest Bay where some private sources suffer from saline intrusion (**Jones, 2007**) and in parts of the Gower Peninsula where sea spray may be the cause of elevated Na and Cl concentrations. The same pattern emerges in Pembrokeshire where Ca-$HCO_3$ type is dominant with subordinate Na/Mg-Cl type but here it is possibly caused by ion exchange in waters that are older than in the limestone around the South Wales Coalfield (**Fahrner et al., 2008**).

**Development of Karst in the Avon Group**

The development of the karst features found today in the Avon Group in south Wales reflects a continuing process which commenced almost as soon as the rocks were laid down. The most active zone of karstification is the vadose zone where unsaturated water can move freely through bedding planes and other discontinuities, but the phreatic zone may also be active when groundwater chemistry changes due to long-term effects of mixing. There were three intensive phases of karstic development: the Lower Carboniferous, the late Triassic and the Palaeogene through to the Quaternary.

The Lower Carboniferous palaeokarstic surfaces developed as the limestone initially rose out of the sea. Clay and mudstone beds, representing fossil soils, overlie the hummocky erosion surface, with discrete fissures in the limestone infilled with the soil material below. This is characteristic of both south Wales (**Wilson et al., 1990**) and north Wales (**Davies, 1991**) where relief varies between only a few centimetres to a few metres.

Uplift during the late Carboniferous Variscan Orogeny initiated a protracted period of erosion which lasted through to the Jurassic Period. By Late Triassic times a network of fissures and caverns had been created, some of which had already been partly infilled with rubble and clay. Mineralised hydrothermal waters may have added to the process leading to the deposition of galena and barites on fissure walls. **Wilson et al. (1990)** recognised three types of karst feature in south Wales: dilated joints, irregular shaped cavities developed along bedding plains, and subvertical cylindrical pipes.

During the Palaeogene and Quaternary periods, large periodic fluctuations in sea level caused fluctuations also in the location of the vadose zone, and new and some pre-existing conduit features were developed, many now below the present-day water table. Three types of feature were created: dolines (collapsed caverns), linear fissures and large cavities. These features are commonly backfilled with silt and rubble debris. **Gunn (1992)** asserted that the larger features could only develop where they were fed by a river or stream sink, and the Dan yr Ogof system was once fed by the River Haffes which has since been captured and redirected.

Reactivation of karst conduit systems has been recorded at a number of sites. At Stormy Down Quarry [SS 845 800] discharging into a doline reactivated the karst system such that extensive remedial action was required in the vicinity during the construction of the M4 motorway (**Aldous, 1988b**).

## References


[1] http://en.wikipedia.org/wiki/Cave
[2] http://en.wikipedia.org/wiki/Limestone
[3] http://en.wikipedia.org/wiki/Carbon_dioxide
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# Hydrogeology of Wales: Carboniferous aquifers - the Marros Group

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**


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The Marros Group is thickest near its southern limit of outcrop around Oswestry. It comprises a varied sequence of sandstones, shales and cherts, of which the uppermost 90 m, the Gwespyr Sandstone offers the most favourable conditions for groundwater transport. Borehole yields are generally modest although a yield of 25 l $s^{-1}$ was attained in a public supply borehole near Oswestry [SJ 2759 3405].

In south Wales, the Marros Group forms a relatively thin horizon at the base of the South Wales Coal Measures Group. The dominant lithology is fine-grained shale and mudstone which tends to act as a barrier between the Pembroke Limestone Group and the overlying South Wales Coal Measures Group. Along the north crop of the South Wales Coalfield is a sandstone unit, the Twrch Sandstone Formation, which with the Bishopton Mudstone Formation and an upper sandstone unit, the Telpyn Point Sandstone Formation, is collectively up to 150 m thick. To the south and east the sequence thins to only 20 m and is finer grained. The sandstones are hard, massive and quartzitic with low porosities and intergranular permeabilities. Transport of water is dependent on fracture flow with fracture density reducing in intensity away from outcrop and with increasing depth. Borehole yields are small, typically only a few l $s^{-1}$ with overall permeability no better than the South Wales Coal Measures Group sandstones, although occasional higher yields have been found where boreholes intersect an open fracture system.

# Hydrogeology of Wales: Carboniferous aquifers - modelling the South Wales Coalfield

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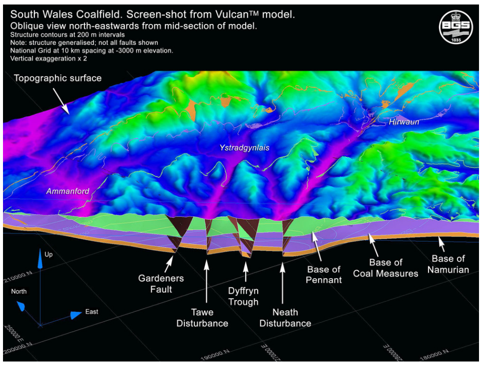
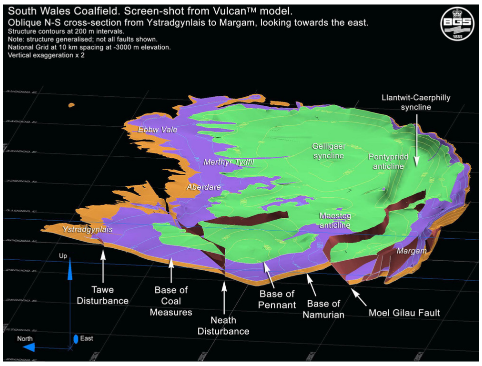
In order to determine the overall groundwater flow patterns within the coalfield and given its complex structure, **Robins et al. (2008**) created a 3D visualisation model (see blue box below: 3D visualisation techniques). The model was constructed from the BGS digital 1: 250 000-scale geological geoline dataset which was draped over the digital terrain model for the area (**Figure P859290**). The model incorporated cross-sections from the 1: 50 000-scale geological map sheets and base of Marros Group, South Wales Coal Measures Group and the Warwickshire Group data derived partly from interpreted geophysical data and partly from available borehole data.

The basic geological model reinforces understanding of two key aspects of the coalfield, firstly the significance of major structural divides across the region, and secondly the different nature of the coalfield east and west of the Neath Disturbance (**Figures P859291 and P859292**). The shallow coalfield of the eastern area contrasts with the much deeper coalfield in the west, itself illustrating why the partly metamorphosed low-sulphur anthracite coals are only available in the deeper part of the coalfield. It is also apparent that the deep western coalfield pinches out towards the west, and that it does not connect with the South Wales Coal Measures Group in Pembrokeshire beneath Carmarthen Bay.

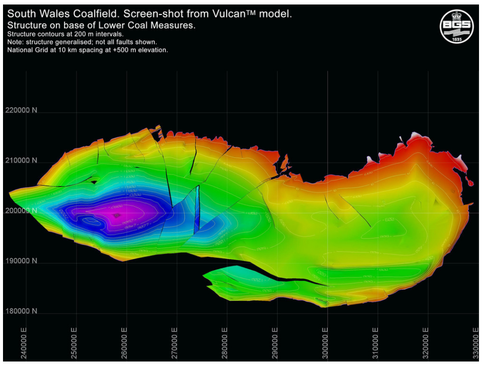



Oblique west–east screen shot from VULCAN model along national grid northing 200000 looking towards the north-west. P859290.

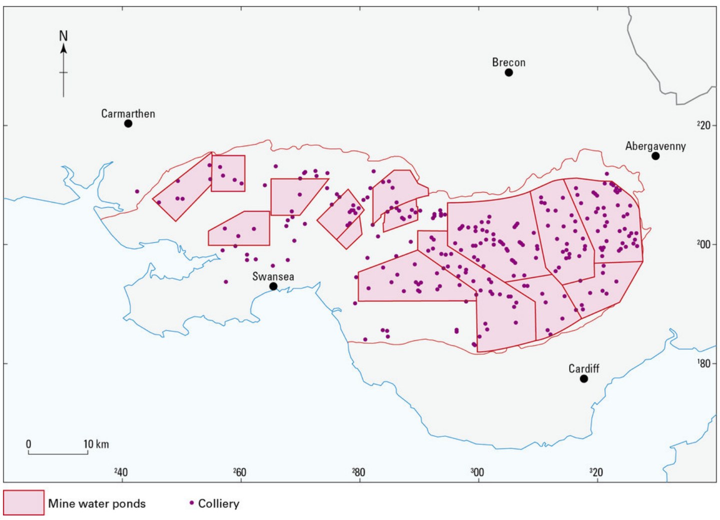
The available piezometry, derived largely from pumping water levels in working shafts for the pre-1990 era when intensive mining still took place, and from limited borehole monitoring data for the more recent period illustrates two significant points. The first is that the piezometric surface, both during mining and subsequent to abandonment of the coalfield, is relatively flat compared with the topography and is largely controlled by the elevation of valley bottoms. The second is that the regional influence from mine dewatering on the water table in the South Wales Coal Measures Group and the Warwickshire Group was negligible, i.e. mine dewatering affected the immediate area around a mine or group of interconnected mines, and there was a steep hydraulic gradient away from the mined area over a limited area of influence. This is known to be case elsewhere (*Whitworth, 2002*) as the transmissive properties of the undisturbed coal measures are small, the horizontal permeability derived from sandstone and grit bands being considerably higher than the vertical permeability. Undermining generally increases the vertical permeability of the strata as a result of collapse and fracturing of otherwise weakly permeable fine-grained but brittle horizons (*Booth, 2002*).




Screen shot showing an oblique north-south section through Margam looking west and illustrating the low angle Moel Gilau fault. P859291.




Screen shot showing the structure on the base of the South Wales Lower Coal Measures Formation with contours at 200 m intervals: dark purple -2500 m OD; green -1000 m OD; orange 0m OD. P859292.




The discrete drainage ponds within the former operational South Wales Coalfield (after Lewis et al., 2000). P859274.

The hydraulic interconnection of mine workings has been investigated, and a set of discrete 'ponds' defined from historical pumping and water level data in former mine workings (**Lewis et al., 2000**). Each pond represents a cluster of voids which have a common water level and overflow at a single lip. Much of the shallow eastern coalfield falls into one of eight hydraulic systems whereby abstraction in one mine ultimately affects levels in adjacent mines in the same pond (**Figure P859274**). In the deeper coalfield to the west of the Neath Disturbance the pond effect is lessened due largely to the smaller number of mines and their more dispersed distribution. The work demonstrates that the hydraulic interconnection is generally of limited scale with the normal area of each pond, typically only about 10 x 10 km. This contrasts with the much larger scale interconnections found, for example, in the South Nottinghamshire Coalfield where interconnections typically exceeded a distance of at least 20 km (*Dumpleton et al., 2001*).

Overlaying the ponds onto the 3D geological and topographical visualisation model showed that the controlling hydraulic boundaries within the eastern part of the coalfield are all topographical divides. Structure seems to play no part in separating the various ponds other than prescribing the courses of the rivers. From west to east the ponds fall within the catchments of the Afon, Rhondda, Taff, Rhymny and Lwyd with the three eastern catchments divided into subcatchment ponds on either side of the axis of the Pontypridd Anticline.

The ponds suggest that much of the groundwater transport in the coalfield is limited to the catchment and subcatchment scale. Mass exchange of groundwater, by definition, has never been observed between one pond and another, although transport of water from one colliery to another within the same pond can occur freely. This partly reflects the interlinking between different pits by roadways and adits which may be used to transport water from one area to another, but it also reflects the prevailing groundwater flow system within a given pond or catchment.

Although the historical dewatering information for the coalfield indicates short catchment-scale flow paths within much of the eastern part of the coalfield, there is only limited evidence that this is the case in the deeper western coalfield. This is due to the smaller number of mines and their uneven distribution. Nevertheless it is likely that the same is the case in this area and that the dominant shallow groundwater system is limited to the catchment scale throughout the whole coalfield.

A small proportion of the groundwater in circulation may adopt a deeper and longer flow path via suitable discontinuities offered by the complex structure of the region. Deeper flow may emerge down-gradient to discharge as base flow to rivers and streams. However, it will be mixed with shallow groundwater and any chemical or isotopic signature it may have gained is obscured by the time it reaches the surface. Such older and deeper circulation is, therefore, difficult to locate, although Taff's Well [ST 120 836] is one such example (**Plate P802426**).

Taff's Well - a warm spring rising from faulted Avon Group strata on the bank of the Taff, now housed in an enclosed bath. P802426.

**Rae (1978)** calculated a water balance for the coalfield based on returns made for 1975 under the Water Resources Act 1963 and a survey of mine drainage carried out by the National Coal Board in 1972. He calculated annual outflow from effective precipitation on the South Wales Coal Measures Group to be 988 mm or 2100 $Mm^3\ a^{-1}$ but did not attempt to separate base flow and run-off. He did, however, provide values for intercepted groundwater flow as:

| | |
|---|---|
| abstraction from wells, boreholes and springs | = 16 $Mm^3\ a^{-1}$ |
| drainage from abandoned mines | = 62 $Mm^3\ a^{-1}$ |
| drainage from disused mines | = 25 $Mm^3\ a^{-1}$ |

Base-flow indices derived from low-flow calculations (Centre for Hydrology and Ecology/British Geological Survey, 2003) allow an approximate separation of run-off. Base-flow indices for the major rivers traversing the coalfield (e.g. the Rhymney at Llanedeyrn [ST 224 821], the Ogmore at Bridgend [SS 896 790] and the Ebbw at Rhiwderyn [ST 263 881]) are all 0.48 suggesting that some 48 per cent of total outflow leaves the system as base flow, i.e. some 1008 $Mm^3\ a^{-1}$. This also represents the likely volume of recharge, given that there is no long-term change in groundwater storage. The recharge volume is equivalent to a depth over the area of just less than 500 mm $a^{-1}$. This estimate compares well with the long-term rainfall data and monthly MORECS data for the area which indicate that the long-term average annual rainfall ranges from 1200 to 2000 mm across the coalfield, of which some 400 to 600 mm is lost to evaporation. The effective rainfall thus ranges from 600 mm to 1600 mm, of which 48 per cent, or between 290 and 770 mm, again represents recharge depending on the exact location within the coalfield. This method suggests a likely overall value of about 530 mm essentially similar to the value derived from Rae's historical data.

The overall water balance for the area of the coalfield can be approximated to:

| | |
|---|---|
| Rainfall | = Evaporation + run-off + recharge ± change in storage |
| 1500 mm | = 500 mm + 520 mm + 480 mm ± change in storage |

The water balance is currently at equilibrium with input balancing output. This reflects the present-day status of mine water rebound still taking place in the coalfield with little additional demand on recharge needed for additional storage.

Hydraulic connection with the underlying Avon Group is feasible in a number of localities most notably where the South Wales Coal Measures Group thins towards the northern and eastern boundaries of the coalfield. Reports of water breaking through the floor of some passageways in these parts of the coalfield suggest an inrush of confined groundwater contained in the Avon Group below. Away from the margins of the coalfield the risk of water inrush is less but may still occur where faulting or other discontinuities allow hydraulic contact between the workings and basal sandstones in the South Wales Lower Coal Measures Formation. Flow rates of inrushes generally diminished quite rapidly reflecting limited storage. Roof and wall inrushes have also occurred in the coalfield margins due to connectivity with surface waters in some of the shallower mines. However, rising groundwater from the Avon Group through the Marros Group is unlikely to affect significantly the water balance of the South Wales Coal Measures Group in its present postmining, near-equilibrium state.

## 3D visualisation techniques

Given the complex structural setting of the overall coalfield, 3D visualisation techniques provide a useful platform with which to investigate the available geological and piezometric data. The key benefits of the visualisation process were summarised by **Robins et al. (2008)**. The process:

- provides a formalised means of assembling diverse and complex datasets into a comprehensive and tangible model
- can be added to and improved upon, as new data become available
- provides a data platform on which subsequent analytical models can be developed
- allows analysis of the geometric logic of planes between lithostratigraphical units
- allows visual inspection of the data in 3D format and assists in graphical presentation of data for reporting and demonstration and for informing nongeologists
- can accentuate and help identify structural features for analysis by exaggerating the vertical scale
- allows the investigation of the relationship between lithostratigraphy and piezometric surfaces.

A variety of software is available to the user including VULCAN [1], EARTHVISION [2] and GoCAD [3]. VULCAN was selected as the most appropriate for the south Wales analysis as it incorporates various mining specific tools that may be required in some future study.

VULCAN is a complex suite of software modules that allow the creation, assimilation, manipulation and visualisation of varied datasets within a common 3D environment. The VULCAN 3D visualisation software not only provides a platform for data assembly, but also a means of inspecting spatial configuration.

The software was developed by Maptek/KRJA Systems Limited for the Australian mining industry, in order to portray mineral deposits in 3D, to assist in the creation of the optimum underground design, but the software is now also used to solve groundwater problems. The VULCAN Modeller is the core of the toolkit. It includes a Graphical

User Interface and 3D graphics environment, CAD and visualisation options. Triangulation and grid mesh modelling and contouring tools allow the creation and modelling of most terrain. Geological and block modelling tools augment the Modeller package for geologists. Lithological, analytical, structural and hydrogeological data are all stored and co-ordinated, available to be displayed, manipulated and analysed.

## References

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[2] http://www.dgi.com/earthvision/evmain.html
[3] http://www.gocad.org/w4/

# Hydrogeology of Wales: Carboniferous aquifers - the Coal Measures facies

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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The study of groundwater occurrence in the Coal Measures facies of the south and north Wales coalfields has mainly been related to problems of mine drainage and possible inrushes of groundwater into workings from fracture zones and flooded old workings. However, Carboniferous strata also form significant aquifers in both south and north Wales. The hydrogeology of the South Wales Coal Measures Group was first described by **Ineson (1967)** who had the benefit of access to a large number of then active coal mines and the National Coal Board records research departments, now superseded by the Coal Authority. The hydrogeology of the coalfield was later revisited by **Rae (1978 a or b?**).

The general hydrogeological character of the Coal Measures Facies consists of low permeability hydrogeological units composed of carbonaceous mudstones and sandstones with subordinate siltstones and coal seams. The Pennant Sandstone Formation is dominated by sandstone whilst the Lower and Middle Coal Measure formations are dominated by mudstone. Moreover the Pennant Sandstone Formation is generally thick, massive, feldspathic and micaceous and forms the relatively high ground at the centre of the South Wales Coalfield. The permeabilities of the sand horizons are generally less than 1 m $d^{-1}$, typical of tight sandstone layers; **Ineson (1967)** provided transmissivity values for sandstone horizons ranging from $10^{-1}$ to 20 $m^2$ $d^{-1}$. Fracture permeability enhances the transmissive properties of these rocks although secondary deposition of silica may inhibit matrix permeability. Folding and faulting has produced some secondary fracture permeability, and mining activity tends to enhance fracture permeability in the overburden. At outcrop, borehole yields up to 8 l $s^{-1}$ are feasible, but the permeability of the sandstone horizons depends on the distribution and intensity of fractures within them.

## North Wales Coal Measures

The Coal Measures crop out along the Dee Estuary, from the Point of Ayr, south eastwards through Flint and south towards Wrexham and Oswestry. The strata are faulted and broken but there is a small regional dip towards and beneath the Cheshire Basin to the east. The productive Pennine Coal Measures Group typically comprise up to 600 m of pyritic shales and mudstones with subordinate sandstone horizons, thin ironstone bands and coal seams. The sandstone horizons tend to become more significant towards the Wrexham area. The unproductive Warwickshire Group overlies the coaliferous strata:

| | | |
|---|---|---|
| Halesowen Formation | sandstone and subordinate marl<br>calcareous sandstone | 900 m<br>160 m |
| Etruria Formation | marl | 330 m |
| Pennine Coal Measures Group | includes sandstone horizons | 600 m |

Groundwater transport and storage is largely limited to available fractures, although there is some storage available in the sandstone horizons and in former mine workings. Yields up to 5 l $s^{-1}$ have been attained in boreholes, exceptionally 15 l $s^{-1}$ at a borehole near Mold [SJ 24186348]. All the collieries required to be dewatered during their working life, usually through shaft sump pumping, and occasionally by adit drainage to a valley side. Shaft discharges were generally of between 5 and 20 l $s^{-1}$, some shafts with pumping rates that fluctuated seasonally. However, both vertical and horizontal conductivity are poor and initial pumping rates may not always be sustainable. In places, groundwater is confined by the till, as a borehole at Bryn-y-Cwm in Flint [SJ 23687159] testified, and which overflowed for a while after completion at 0.1 l $s^{-1}$ having penetrated 40 m of till over Coal Measures sandstone.

Water quality, particularly in the productive coal measures facies is poor due to the availability of soluble hydrous products of pyrite within the worked coal seams, which had been oxygenated whilst dewatering took place and later flooded on abandonment of the collieries. Quality is better in the Warwickshire Group, with total dissolved solids concentrations up to 2000 mg $l^{-1}$, and some spring sources, drawing on shallow circulation perched groundwater in individual sandstone horizons, yield relatively weakly mineralised but generally small volume discharges.

## South Wales Coalfield

The main shaft and buildings at Tower Colliery prior to closure in 2008. The dark green area is reclaimed opencast land and contrasts with the yellow-green natural vegetation in the foreground. P802424.

The South Wales Coalfield is an exposed synclinal basin some 87 km long by 30 km wide with an overall area of some 2200 $km^2$. Coal production in south Wales peaked at the start of World War One, but declined steadily after the general Strike of 1926 (**Brabham, 2004**). Wholesale closure of the coal mines took place subsequent to the political decision to reduce dependency on the UK coal mining industry in the late 1980s and early 1990s. The last working pit, Tower Colliery [SN 939 054], near Hirwaun, was closed in January 2008 ( **Plate P802424**) while two pits have been reopened in the Vale of Neath. As with many of the South Wales collieries, Tower was part of a large interconnected mine complex, with connections between shafts up to ten miles apart being common.

Mine-water rebound is now well advanced over much of the coalfield and there are no ongoing deep mine dewatering schemes. Steady state conditions have occurred in some areas where piezometric levels are now controlled by gravity discharges from the mines. Some of these require treatment (see Management and regulation of groundwater) – there were eleven mine water treatment schemes operating in 2009 at abandoned flooded coal mines in south Wales. Morlais [SN 572 023] is of note since the high flow of iron rich mine water required construction of (at the time) the largest constructed wetland in Europe by the Coal Authority (see www.coal.gov.uk [1]).

Erosion and down-cutting by major rivers has created incised valleys along major fault zones. These valleys are significant areas of groundwater/surface water interaction. The Vale of Neath divides the coalfield into a lower lying area to the west, over the anthracite field, although rising to the north and the Black Mountains, and a higher area to the east, over the bituminous coals, where topographical divides rise to over 600 m elevation.

The South Wales Coal Measures Group thickens west of the River Neath, there being about 600 m present in the Ferndale–Taff Valley whereas there is 1500 m in the Gower at Gorseinon. The sandstones tend to form the higher ground and form the steep valley sides of many of the incised rivers. The South Wales Coal Measures Group are partly concealed by glacial till and outwash deposits which range up to 100 m in thickness in the Tawe Valley, but are generally less than 30 m thick. They are partly concealed by estuarine coastal flats in the south which are up to 30 m thick.

Within the central and eastern parts of the coalfield the South Wales Lower Coal Measures Formation ranges between 120 m and 210 m in thickness. The South Wales Middle Coal Measures Formation ranges between 210 m and 260 m in thickness. Both formations comprise fluviodeltaic sediments that consist of coarsening-upwards cycles of mudstones, siltstones and sandstones with siltstones containing ironstone layers, siderite and pyrite. Each cycle is capped by a coal seam underlain by seatearth:

*Seatearth* – including clay and coarse sandstone with ironstone bands

*Arenaceous* – quartzitic sandstones ranging upwards to coarse pebble layers

*Striped beds* – comprising quartzitic siltstones and mudstones

*Argillaceous* – ranging from clays to silty mudstones

The Warwickshire Group consists of 670 m of strata, mainly of the massive Pennant Sandstone Formation. The Pennant Sandstone Formation comprises thick, cross-bedded units with some coal.

A study of the Pennant Sandstone Formation at Merthyr Tydfil indicates that the intergranular permeability of these well-cemented sandstones is small and that transport and storage is largely limited to fractures. Undermining may enhance tensional fracturing and increase the overall hydraulic conductivity of the sandstones. The majority of infiltrating rainwater penetrating the sequence is diverted by shale and mudstone horizons to emerge as hillside springs and discharge to surface waters as base flow ( **Plate P802425**).

Throughout the South Wales Coal Measures Group there appears to be little significant vertical flow along faults, although flow from the shallower sandstones has managed to penetrate some of the deeper mines. The coal mines of south Wales were some of the wettest in England and Wales requiring eight tonnes of water to be pumped on average for every tonne of coal recovered. However, **Rae (1978 a or b?)** reported that this figure may be misleading as 30 per cent of the south Wales mines pumped at <4 $ls^{-1}$, a further 40 per cent <20 $l\ s^{-1}$ and only 15 per cent were very wet mines which required to pump at discharges >50 $l\ s^{-1}$.

St Mary's Well at Penrhys – a spring issuing from Pennant Sandstone on the side of the Rhondda Fach above Fernadale. P802425.

Severe problems were occasionally encountered with water inrushes in collieries situated towards the northern and eastern margins of the coalfield. Inrushes could occur through the roof or the floor of workings and were worst in collieries situated some considerable distance from outcrop. Inrush risk focused on an area that was sufficiently distant from outcrop for mine dewatering to attain sufficient pressure differential to create a burst, but not so deep that fracture dilation was reduced and groundwater transport inhibited. The area east of a line between Ebbw Vale and Caerphilly was the critical area. Initial flows were typically between 50 and 80 $l\ s^{-1}$, exceptionally 200 $l\ s^{-1}$ and they generally declined with time (see detailed listing in **Ineson, 1967**, pp.6-8). A few inrushes stabilised with significant yields up to 30 $l\ s^{-1}$, reflecting greater fracture storage than those systems which quickly dropped off in yield. In the eastern part of the coalfield the thickness below the lowest worked seams and underlying sandstones in the South Wales Lower Coal Measures Formation and the Marros Group can be as little as 10 m, and floor bursts were not uncommon; in some cases the source may have been from the Pembroke Limestone Group wherever faulting was present to provide a suitable conduit.

## References

[1] http://www.coal.gov.uk/

# Hydrogeology of Wales: Carboniferous aquifers - groundwater quality in the South Wales Coalfield

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

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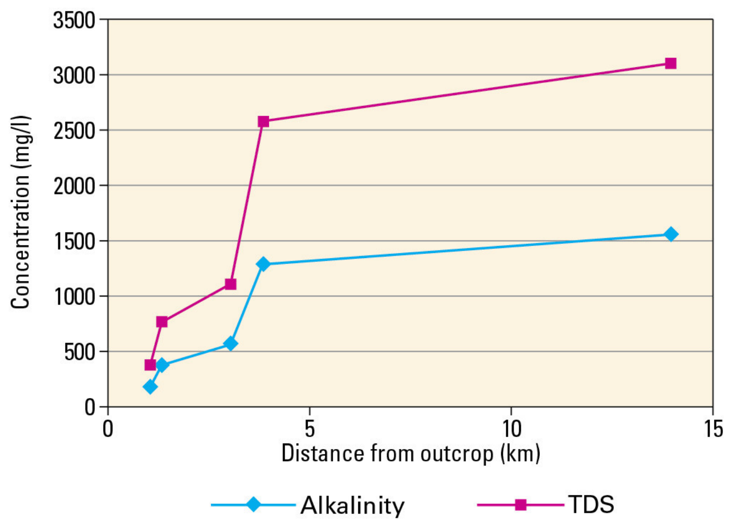
The groundwater in the South Wales Coal Measures Group is characteristically less mineralised than groundwater found in other British coalfields. Total dissolved solids are commonly <1000 mg $l^{-1}$, exceptionally approaching 10 000 mg $l^{-1}$. The more saline groundwaters tend to be of the Na-$SO_4$ type, whereas Na-Cl type waters are notably absent in south Wales. The South Wales Upper Coal Measures Formation is typically Ca-$HCO_3$ type. In the argillaceous horizons Ca and Mn rich groundwaters occur near outcrop with salinity increasing down-dip. The increase in alkalinity and total dissolved solids away from the Pennant Sandsone and Warwickshire Group outcrop down-dip through Tirpentwys, Crumlin, Celynen and Penallta collieries shows a similar increase for samples collected in the Old Coal horizon (**Figure P859275**). Ion exchange tends to create Na dominated waters (Na-$HCO_3$ and Na-$SO_4$) towards the main syncline but the availability of Na is small compared with that in major coalfields elsewhere.



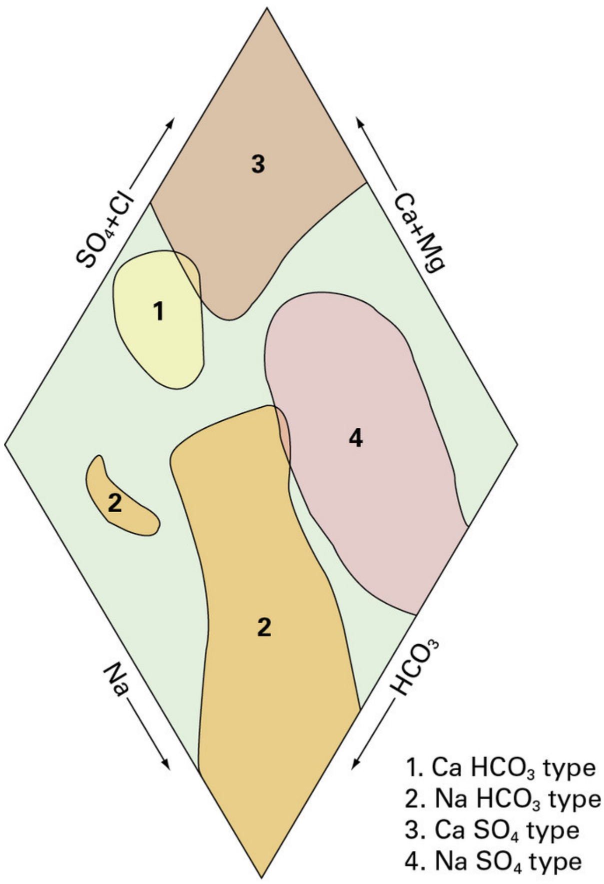
Alkalinity and total dissolved solids evolution down dip in the Old Coal Horizon (after Ineson, 1967). P859275.

Although analytical data for mine water discharges are plentiful, few of these data represent specific horizons or even groups of horizons. Most represent mixed waters draining from colliery sumps. In addition many contemporary analyses focus on acid mine drainage rather than groundwater uncontaminated with soluble products of Fe and S.

The uppermost shallow groundwater circulation which discharges locally to springs and as base flow to streams and rivers is weakly mineralised Ca-$HCO_3$ type groundwater with a total dissolved solids concentration typically <300 mg $l^{-1}$. This is a young and immature groundwater which reflects short transport pathways and relatively short transit times.

Groundwaters circulating deeper into the South Wales Coal Measures Group are more highly mineralised than the shallow groundwaters. A survey of 178 samples for the eastern part of the coalfield gathered by **Ineson (1967)** showed a high percentage of moderately mineralised discharges with little over one in eight of the samples exceeding 1000 mg $l^{-1}$ total dissolved solids. Four types of groundwater are present (**Figure P859276**): Ca-$HCO_3$, Ca-$SO_4$, Na-$HCO_3$ and Na-$SO_4$ groundwaters. There are also isolated occurrences of Mg-$HCO_3$ groundwater found in Ebbw Vale. The Na-$SO_4$ type tends to be the most mineralised. All of these waters contrast with those typical of the coal measures facies in Scotland and England where Na-Cl groundwaters tend to prevail. A number of explanations have been put forward for the relative scarcity of the Cl ion, the most likely that any connate sea water has long been flushed from the system. This is a probable explanation which relates to the deep burial of the coal measures subsequent to deposition, so creating the anthracite beds of the western coalfield, and of subsequent uplift and exposure.

The most common groundwater type in the South Wales Upper Coal Measures Formation is Ca-$HCO_3$ and in the South Wales Lower and Middle Coal Measures formations is Na-$HCO_3$. The progression from Ca to Na dominance reflects cation exchange occurring with increasing residence time and transit down dip, starting from a relative immature and weakly mineralised groundwater and developing into the older, more mature groundwaters that are found in the South Wales Lower and Middle Coal Measures formations. There are also abundant mudstones in these deeper strata to aid the cation exchange processes. The Na-$SO_4$ type water is likely to represent an intermediate phase. Occurrence of Fe in solution is widespread although concentrations rarely exceed 10 mg $l^{-1}$.



Piper diagram showing the distribution of the four main groundwater types in the South Wales Coal Measures Group (after Ineson, 1967). P859276.

The work by **Ineson (1967)** is valuable as it can no longer be replicated. Wholesale abandonment of the coalfield has allowed mine-water rebound to occur. Rising mine waters have since taken soluble hydrous products of pyrite into solution to produce acid sulphate-rich mine waters (identifiable at surface by the ochreous deposits that form once the discharge emerges into contact with the atmosphere).

The natural groundwater chemistry recorded as discharge to working collieries contrasts with the quality of the mine waters that have emerged at surface as acid mine drainage following coalfield closure. *Brown et al. (2002)* studied these discharges and found that they fell into two distinct groups. Those deriving from the South Wales Upper Coal Measures Formation remained as Ca-$HCO_3$ type, with increased salinity and reduced pH. Those from the South Wales Lower and Middle Coal Measures formations were of the Na-$SO_4$ type, with greatly increased salinity, anoxic, and again with low pH, but having reverted from Na-$HCO_3$ type to Na-$SO_4$ type due to the availability of soluble products of S that had formed in the previously aerobic environment of the mine workings.

Ongoing groundwater monitoring carried out by the Environment Agency concurs that the dominant groundwater type is Ca/Mg-$HCO_3$ with subordinate dominance of Mg and $SO_4$. Maximum observed concentrations of $NO_3$ are 22 mg $l^{-1}$.

# Hydrogeology of Wales: Permo-Triassic and Jurassic aquifers

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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## Geological setting

In North Wales Permo-Triassic age strata are limited to part of the Vale of Clwyd on the edge of the East Irish Sea Basin and the western margin of the Cheshire Basin. Much of the Triassic sequence comprises red beds, deposited in an arid desert-like environment, which are uniform, cross-bedded, generally well cemented, fine to medium grained with occasional mudstone horizons but no pebble beds. Halite, gypsum and anhydrite lenses are common and there are occasional wadi-type channel deposits.

Jurassic Lias limestone cliffs at Nash Point, South Glamorgan. P802430.

The Jurassic Lower Lias is present in a limited area between Cardiff and Porthcawl. Here the Blue Lias Formation comprises up to 90 m of thinly bedded argillaceous marls and calcareous mudstones, increasing in subcrop towards Bridgend to a thickness of 150 m where marginal oolitic limestones are present (**Plate P802430**).

# Hydrogeology of Wales: Permo-Triassic and Jurassic aquifers - Vale of Clwyd

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
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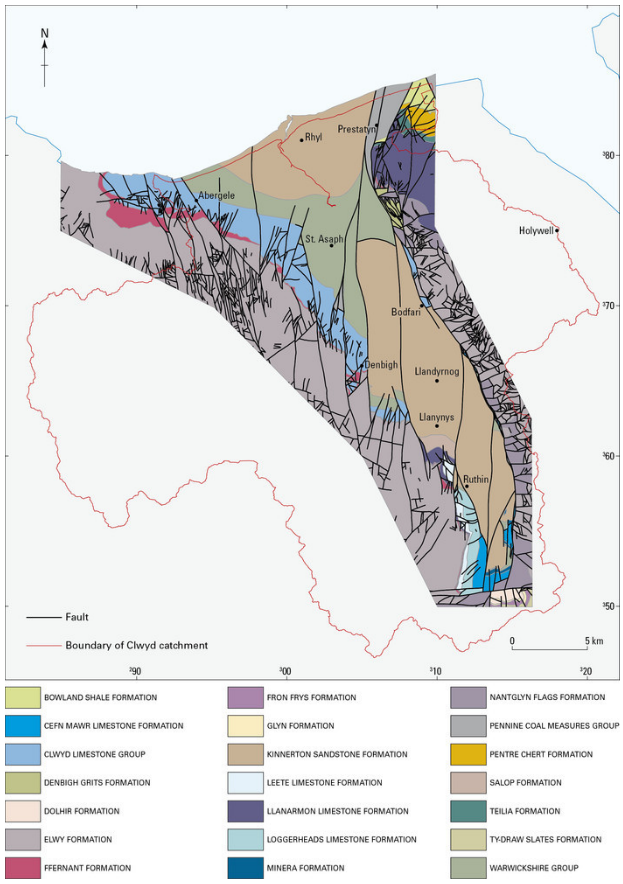
The Triassic sandstone aquifer is situated in the central part of the Clwyd catchment in north Wales. The catchment comprises some 800 km$^2$, and lies between the Conwy to the south and the Dee to the north and east. The Triassic aquifer occupies the central lowland area of the catchment with surface elevations rising to 115 m aOD inland towards its southern extremity. The sandstone is divided into two parts by a shoulder of Carboniferous strata: the northern block widens to 13 km at the coast and the southern block, which is twice as big in area, is 5 km wide and 22 km long, oriented north-north-west to south-south-east beneath the Afon Clwyd (**Figure P859277**).



Vale of Clwyd—geological setting. P859277.

The main aquifer unit is the Kinnerton Sandstone Formation of the Triassic Sherwood Sandstone Group. The principal lithology is a sequence of variously cemented fine- to medium-grained aeolian sandstones which are generally well laminated and in places cross-bedded. The northern block is fault bound to the east by the Denbigh Fault while the unconformity with Carboniferous strata forms the southern and western boundaries. The Vale of Clwyd Fault, with a downthrow to the west of 1500 m, forms the eastern boundary against the Carboniferous. The western boundary is mostly defined by an *en chelon* series of north–south trending faults, each with throws up to 300 m, the Triassic strata lying directly but unconformably on the Carboniferous (**Warren et al., 1984**). The aquifer continues offshore to the north. **Wilson et al. (2002)** suggest that the Kinnerton Sandstone Formation may be as thick as 350 m onshore although the greatest thickness proven is 152 m in a borehole at Foryd [SH 9945 3799]. **Wilson et al. (2002)** postulate that fault gouge along parts of the boundary faults may inhibit cross-flow. The sandstone crops out only in a small area towards Ruthin, being for the most part confined by the glacial cover material.

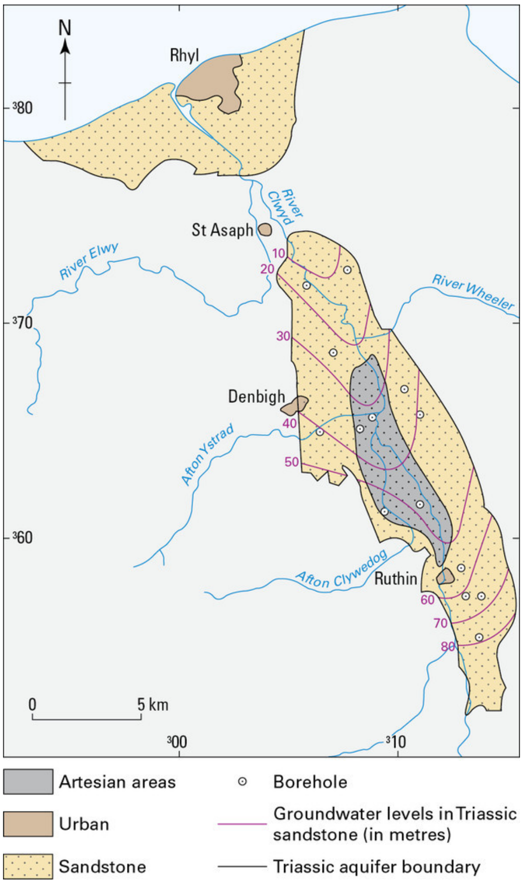
The Silurian stata to the east essentially comprise folded and cleaved mudstones with subordinate medium-grained sandstone.

The Carboniferous strata include the Warwickshire Group which for the most part underlies the Triassic sandstone aquifer. It comprises mudstone, siltstone, micaceous sandstone, seatearth and thin seams of coal. The older Carboniferous Limestone crops out to the east of the Coal Measures facies strata. The limestone includes cyclical sequences of thin- to thick-bedded limestone, the upper part also with thick sandstone at the top of each cycle of deposition. The lower part of the succession includes mudstone, siltstone and sandstone.

The lower part of the catchment is largely covered in glacial deposits, principally till, which may be up to 90 m thick. The superficial strata on top of the northern block lie in a broad steep-sided trough whereas the southern block is covered by infill of a broad palaeochannel of the Clwyd which was deepened by ice scour. The northern part of the aquifer lies beneath the Irish Sea Till while south of Denbigh the Welsh Till came down to meet it. Both ice sheets deposited fine-grained rock flour comprising silty and sandy clay although the sandy faces predominate in an area between Ruthin and Denbigh and outwash fan deposits are also present in the south, much of this, however, has been reworked into fluvial terraces. The river lies on a strip of alluvium and the lower part of the northern block also has postglacial marine clay above the till.

The Kinnerton Sandstone Formation comprises well-laminated and dune-bedded aeolian red, brown and yellow weakly cemented, fine- to medium-grained sandstones with subordinate coarser beds and silty horizons, although there are no coarse basal beds (**Warren et al., 1984**). Individual grains vary from well rounded to subangular and consist predominantly of quartz with subordinate feldspar and lithic grains. The sandstone is generally friable and borehole abstraction water is commonly turbid and red at the start of pumping.

The main aquifer is in the Ruthin and Denbigh area (**Figure P859278**) in which the central part of the aquifer was originally confined by till with an artesian head of about 6 m (**Lambert et al., 1973**). The sandstone aquifer is partly confined by overlying superficial deposits, causing artesian conditions in the centre of the southern basin. Confinement is not total, since leakage occurs elsewhere through the superficial deposits, which may be in hydraulic contact with some reaches of the river. Transmissivity was estimated at between 800 and 2000 $m^2 d^{-1}$ and storativity between $10^{-3}$ and $10^{-4}$. Coal Measures strata crop out to separate the upper part of the aquifer from the coastal area of Triassic sandstone centred on the town of Rhyl. Natural discharge from the upper aquifer to the surface-water system was estimated at 20 Ml $d^{-1}$ (**Lambert, 1981**).




The Vale of Clwyd Triassic aquifer (after ESI, 2003). P859278.

Boreholes at Llanerch Park [SJ 057 720], near St Asaph, confirm the upward flux of groundwater in the confined central portion of the aquifer. Test pumping undertaken in 1976 showed that the upward flux could be maintained by pumping at 7 Ml $d^{-1}$ and the water used for both public supply and for river augmentation in order to maintain a prescribed minimum flow for the benefit of fisheries in the River Clwyd (see also Section 8.2). Direct rainfall recharge to the sandstone aquifer was suggested by **Lambert et al. (1973**) with a likely focus via the gravel deposits and possibly also from cross-flow derived from the adjacent Carboniferous Limestone strata. **ESI (2003)**, however, report that cross-flow from the Carboniferous strata is likely to be limited to the western boundary of the aquifer as flow in the sandstone is unlikely beneath depths of about 200 m precluding upwelling from beneath much of the aquifer. In isolated locations where the Carboniferous Limestone is faulted against the sandstone some cross-flow may occur but the extent of the contacts is small and the potential cross-flow, if any, likely also to be small. Indeed borehole yields from the limestone are generally only modest.

*The Vale of Clwyd is an important Welsh aquifer.* The Llannerch Park public supply boreholes have a collective abstraction licence of 3400 Ml $a^{-1}$. At Afon Clwyd to the south-west of Llannerch Park are five river augmentations boreholes with a collective licence of 2290 Ml/$a^{-1}$, and these are used seasonally as required.

Laboratory determined hydraulic conductivity on drill core samples ranges from $3x10^{-4}$ to 3.0 m $d^{-1}$ and a mean of 0.21 m $d^{-1}$ (**Allen et al., 1997**). The more permeable sands are the clean, well-sorted medium-grained sands, and the poorly sorted but laminated sands in which the coarse laminae have clean rounded grains. Well-cemented and compacted fine-grained sands are the least permeable (**Lovelock, 1977**).

**Lambert et al. (1973**) demonstrated that there is an inverse correlation between the degree of cementation and permeability but that there is little significant relationship between grain-size distribution and laboratory-determined physical properties. It was also noted that the median horizontal hydraulic conductivity, 0.29 m $d^{-1}$, was double the vertical median value, increasing to four to eight times vertical values in some borehole cores (**Lambert et al., 1973**). Fracture flow was demonstrated with downhole geophysical logging.

Pumping tests were conducted at eight sites as a component of the Groundwater Resources Study by the Dee and Clwyd River Authority and the Water Resources Board (**Lambert et al., 1973**). The mean tranmissivity is 130 $m^2$ $d^{-1}$, but values range from 20 to 1200 $m^2$ $d^{-1}$ depending on the degree of fracturing penetrated in each borehole. These values equate to bulk hydraulic conductivities of 0.17 m $d^{-1}$ to 20 m $d^{-1}$ with a mean value of 2.4 m $d^{-1}$. The minimum values are consistent with mean intergranular hydraulic conductivity values obtained from core samples but the higher values suggest that the borehole discharge is almost entirely derived from fracture flow drawing on intergranular storage in the sandstone matrix.

Core porosity data for the eight boreholes tend to a normal distribution within the range 19 to 31 per cent, with a mean of 23.6 per cent. This is higher than many other Triassic sandstones and reflects the generally low degree of cementation within the aquifer. Specific yield, determined from core samples by centrifuge techniques, is estimated as 4 to 17 per cent intermediate between confined storage values and the porosity values (**Lambert et al., 1973**). Storage coefficients calculated from six pumping tests range from $1x10^{-4}$ to $2x10^{-3}$ with a mean of $3.8x10^{-4}$. The higher values reflect seepage from the weakly to moderately permeable superficial strata that overlie the sandstones.

The original water balance for the aquifer (**Lambert et al., 1973**) suggested a deficit was likely if abstraction exceeded leakage from the River Clwyd that could take place at the lower margins of the aquifer (see **Water balance table** ). Subsequently **ESI (2003)** suggested that the Clwyd and its main tributary the Afon Hesbin are hydraulically disconnected with bedrock except where they cross the Carboniferous Limestone at outcrop in the upper part of the catchment where some river loss may be occurring. The till cover controls the occurrence of direct rainfall recharge to the sandstone aquifer while the terrace sands and gravels in the south contain a significant shallow groundwater resource. Observations on the Llanerch Park well field showed that under static conditions the head on the sandstone is greater than that in the weakly permeable glacial sands and clays above. However, under pumping conditions the head declines in the sandstone aquifer so that water can be drawn down from the superficial deposits, principally from a basal gravel layer. It is possible that after extensive pumping the connection can be made via the gravel to the river. At Glan y Wern [SJ 090 695] there is a gravel layer in a borehole at 75 m depth which overflows, probably driven by the head in the underlying sandstone.

## Water balance for the Vale of Clwyd sandstone aquifer (Ml $d^{-1}$) based on data from Lambert et al. (1973).

| Inflow | | Outflow | |
|---|---|---|---|
| Infiltration to the Triassic sandstone aquifer | 15.2 | Base flow to the River Clwyd and tributaries at Pont-y-Cambyll gauge | 20.0 |
| Probable cross boundary flow to the sandstone aquifer from the Carboniferous Limestone aquifer | 4.2 | Base flow between Pont-y-Cambyll and Pont Dafydd | 5.0 |
| Leakage from storage in overlying superficial strata | ~7.0 | Groundwater abstraction minus effluent returns to surface waters | 1.5 |
| Leakage from River Clwyd | ?? | Abstraction | ?? |
| Total | ~26.4 | | 26.5 |

Borehole hydrographs in the sandstone show annual variation up to 1.5 m, with a long-term but slow downward trend in the vicinity of the Llanerch Park boreholes. Pumping in these boreholes also induces a reduction in water level in the overlying glacial deposits in the vicinity (**ESI, 2003**). The greatest seasonal range in water level occurs on the eastern edge of the aquifer, 5 m at Pentre Mawr, which is likely to be a reflection of recharge through the local granular superficial material. Groundwater chemistry data also suggest that the groundwater on the eastern side of the aquifer is youngest with nitrate concentrations greater than 40 mg $l^{-1}$ whereas concentrations of only about 4 mg $l^{-1}$ persist elsewhere. Intermediate concentrations occur south of Ruthin. Available piezometry in the southern block shows an overall hydraulic gradient falling away to the north, varying from 0.01 to the south of Ruthin to 0.003 north of Ruthin.

Transmissivity appears to increase from 20 $m^2$ $d^{-1}$ in the south increasing to 100 $m^2$ $d^{-1}$ near Ruthin, and increasing again to the north where values of between 660 $m^2$ $d^{-1}$ and 2200 $m^2$ $d^{-1}$ have been demonstrated at and around Llanerch Park (**ESI, 2003**). Laboratory analyses of core material consistently yield permeability values less than field values reflecting the important role of fracture flow in the system. Transmissivity values in the older strata surrounding the sandstone are small, consistently less than 10 $m^2$ $d^{-1}$, supporting the hypothesis that there is little likelihood of any significant cross-flow from these strata to the sandstone aquifer.

**ESI (2003)** describe a conceptual model and water balance for the southern block aquifer. However, it was not feasible to isolate the sandstone baseflow component to surface waters to establish a recharge volume. The recharge estimate was based on the likely processes and recharge mechanisms prevalent within different typological zones within the catchment, for example, the principal recharge zone is taken as the eastern periphery of the aquifer. Elsewhere the aquifer is divided between unconfined and confined zones in which recharge can and cannot normally occur. **ESI (2003)** indicate that the long term depth of water passing beneath the soil zone above the superficial strata is equivalent to 340 mm $a^{-1}$ or 84 Ml $d^{-1}$. However, only a small component of this will access the sandstone aquifer. **ESI (2003)** suggest that longitudinal flow in the essentially confined aquifer could be as little as 2.1 Ml $d^{-1}$ at Ruthin and between 2 and 7 Ml $d^{-1}$ further to the centre of the aquifer. In perspective this is tiny compared to the river flow which ranges between 133 and 584 Ml $d^{-1}$.

The water balance assumes an upwelling of groundwater from the confined sandstone which discharges as base flow. This flow may amount to only 10 per cent of the overall base flow component in the river which includes spring discharges from the older strata within the entire catchment area and base flow from the superficial strata. **ESI (2003)** further conjecture that the likely recharge rate to the southern sandstone aquifer block is about 22 Ml $d^{-1}$ with some three times that value recharging the superficial deposits and discharging directly as base flow. They further determine that the current long-term average abstraction for the sandstone aquifer is about 10 Ml $d^{-1}$, suggesting that the aquifer is currently underutilised. The recharge estimate (22 Ml $d^{-1}$) compares favourably with the 26.4 Ml $d^{-1}$ postulated by **Lambert et al. (1973**).

Three different groundwater types have been identified in the southern block of the aquifer (**Fahrner et al., undated**): Ca/Mg-$HCO_3$ type occurs in the north, Ca-$HCO_3$/Cl type in the central western part of the aquifer with the more common Ca-$HCO_3$ type, generally associated with a dynamic actively recharged system, in the central eastern part of the southern block. Major ion concentrations, with the exception of higher concentrations of $NO_3$ in the east, remain reasonably consistent across the aquifer. $HCO_3$ concentrations range from 160 mg $l^{-1}$ to 350 mg $l^{-1}$, and the specific electrical conductivity varies from 336 to 978 μS $cm^{-1}$.

# Hydrogeology of Wales: Permo-Triassic and Jurassic aquifers - Cheshire Basin - Dee catchment

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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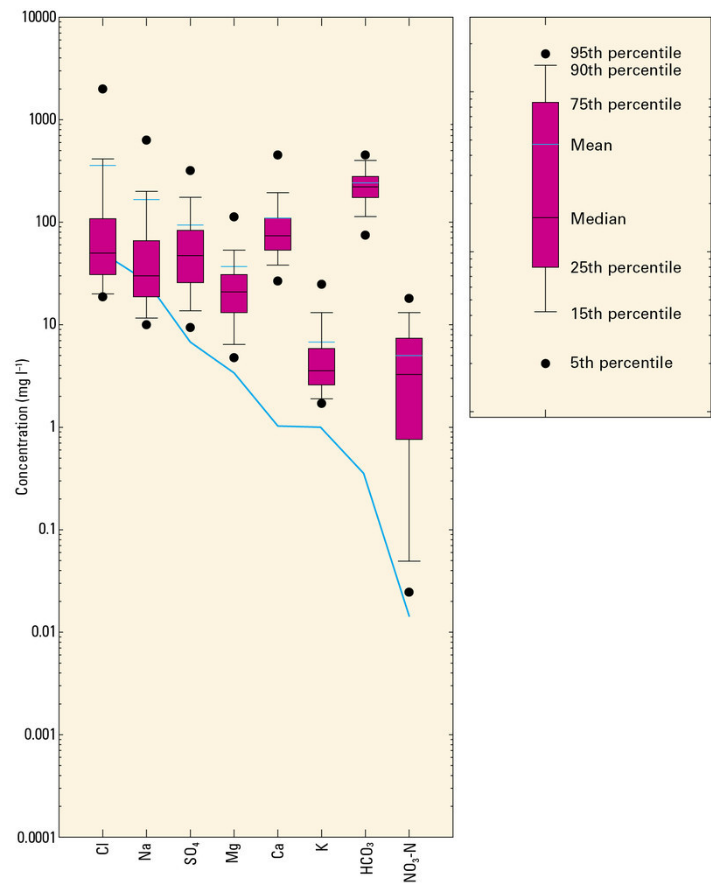
The feather edge of the Cheshire Basin crosses the Dee into Clwyd from near Chester to a point to the south of Wrexham. The Triassic Kinnerton Sandstone Formation is present overlain by the Chester Pebble Beds Formation and together they form a single hydraulic unit. There are numerous silty horizons which impede vertical flow but otherwise the porosity in the sandstone usually lies within the range 20-30 per cent, and in the pebble beds between 11 and 29 per cent. Hydraulic conductivity in the sandstone is typically in the range 4 x $10^{-5}$ to 10 m $d^{-1}$ and for the pebble beds 2.5 x $10^{-4}$ to 15 m $d^{-1}$. In the Chester area saline groundwater is present at depth. For the most part the aquifer is concealed by thick glacial deposits but significant yields are abstracted from the aquifer.




Range of major ion concentrations in Permo-Triassic groundwaters in West Cheshire and Dee catchment (after Griffiths et al., 2002). P859279.

Groundwater flow is essentially longitudinal towards Chester, but local flow in the glacial deposits may be lateral towards the River Dee. Available monitoring data for the aquifer indicate a Ca-$HCO_3$ type groundwater indicative of an actively recharged system (**Figure P859279**). The mean specific electrical conductance for 109 analyses in the aquifer is 768 µS $cm^{-1}$ and the mean $HCO_3$ concentration is 258 mg $l^{-1}$ (**Griffiths et al., 2002**).

# Hydrogeology of Wales: Permo-Triassic and Jurassic aquifers - South Wales

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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The Triassic strata that lie to the east of Porthcawl comprises marginal basal facies deposited in a shallow coastal environment (**Plate P802431**). Lithologies include sandstone, conglomerate and subordinate dolomitised limestone. The conglomerates do not crop out and have poor recharge potential.

Triassic Blue Anchor Formation exposed in cliffs at St Mary's Well Bay, south of Penarth. P802431.

The younger Mercia Mudstone Group comprises massive red-brown dolomitic mudstones with gypsum either in veins or retained as nodules. The uppermost part of the sequence, the Blue Anchor Formation comprises grey dolomitic mudstones and siltstones, and the Penarth Group, which is nowhere thicker than 12 m, grades from calcareous marls and marly limestones to sandstone near Bridgend where small potable groundwater supplies have been obtained. Typical yields range up to 8 $l\ s^{-1}$ in the Cardiff area where the water has a bicarbonate concentration of up to 500 $mg\ l^{-1}$.

The Jurassic Blue Lias Formation is essentially an aquitard although seeps can occur where fractures intercept the ground surface at low elevations.

# Hydrogeology of Wales: Quaternary aquifers

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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## Geological setting

A blanket of glacial and postglacial material was deposited during the Late Devensian time over much of the lower-lying parts of Wales. Glaciers flowed radially down from the mountains towards Cardigan Bay in the west and the Welsh Borderland in the east. The Irish Sea Ice flowed southwards into the Vale of Clwyd, south-west across Anglesey and the Lleyn Peninsula into Cardigan Bay, thence south-east and south into Dyfed and into the Afon Teifi valley *above* Cardigan and Lampeter. The deposits are complex wherever the Irish Sea and Welsh ice sheets met, but elsewhere lodgement till was deposited during the advance of the ice and a range of melt-out and flow tills, morainic deposits and outwash sands and gravels were deposited during the retreat. Glaciolacustrine deposits were formed both during the advance and the retreat of the glaciers. Smaller cwm glaciers formed during the final Loch Lomond Stadial, when drumlins, eskers, kames and kettleholes were formed.

In north Wales the Welsh till is blue-grey in colour except in the Vale of Clwyd where it has a reddish hue. It is divided between a lower till, middle glaciofluvial sand and an upper till, the product of the advance and retreat of a single ice sheet. The sequence is generally 20 to 30 m thick, exceptionally up to 95 m thick in parts of the Vale of Clwyd. Only the basal lodgement till is present wherever the drift sequence is thin. The upper till is sandier than the basal till and is a flow till. The Irish Sea till in Anglesey and the Lleyn Peninsula is red, uncompacted and sandy, but there may be a lower compacted blue till derived from the Welsh Ice sheet. In south Wales the valleys in the coalfield are lined with till from the Welsh Ice sheet.

Glaciofluvial sands occur as channel deposits and proglacial outwash fans interbedded within the till in some areas. Glaciolacustrine deposits formed in ice dammed lakes are generally fine grained or have a fine-grained matrix, whereas river terrace deposits comprise sands and gravels deposited in the colder more temperate stages of glaciation. Head deposits also occur as slump deposits on valley sides, and are the most widespread deposit which includes periglacial and postglacial active layer deposits and displaced till.

Alluvium has been widely deposited in the valley bottoms during the Holocene. These deposits are fresh water, estuarine and marine alluvial silts, clays and sands. Coastal dune-lands occur locally and there are also widespread areas of blanket peat inland, mostly in areas of high ground.

# Hydrogeology of Wales: Quaternary aquifers - groundwater occurrences

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
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Groundwater is present in most of the Quaternary and Holocene deposits and is stored and transported in useable quantities in many of the saturated sand and gravel deposits. These deposits receive direct rainfall recharge and may be in hydraulic continuity with rivers which can have identifiable gaining and losing reaches. However, persistent interbedded peat and clay horizons may inhibit the downward migration of recharge. For example, in the Vale of Clwyd in north Wales, the central valley floor is covered in thick weakly permeable till, but gravel deposits formed during the retreat of the ice along the margins of the valley enable direct rainfall recharge to access the underlying Carboniferous Limestone and Triassic sandstones, and put these aquifers into hydraulic continuity with the Afon Clwyd.

Widespread deposits of lodgement till are poorly permeable and tend to inhibit recharge to underlying aquifers. However, where they thin to less than 5 m thickness, postglacial weathering enhances the permeability of the shallow material such that it can transmit infiltrating water to lower horizons.

Alluvial deposits vary in water-bearing properties from weakly permeable silt and clay material to coarser sand and gravel, although the properties of the latter are inhibited wherever a fine-grained matrix is present. For example, the alluvium beneath the Cardiff Bay Barrage has a hydraulic conductivity of $5 \times 10^{-5}$ m $d^{-1}$ and a transmissivity of 250 $m^2$ $d^{-1}$ in the subordinate gravel horizons, equivalent to a hydraulic conductivity of between 40 and 60 m $d^{-1}$ (**Entec, 1996**).

Coastal dune-lands offer distinctive and delicate groundwater dependent ecosystems with wet dune-slacks that tend to become dryer as they mature. These deposits are characterised by a shallow lens of saturated sand fluctuating about the slack bottoms, typically by about 0.5 m above the slack in late winter to 1.5 m below the slack floor in late summer.

Blanket peat and domed peat deposits such as that at the Tregaron Bog in the Afon Teifi catchment (**Plate P802432**) offer high groundwater storage potential but poor transmitting properties. However, where the peat has dried out it cracks so that the permeability significantly increases. As a consequence recovery of desiccated peat rarely occurs. A significant issue is the ingress of pesticides via surface waters into blanket peats which is selectively retarding peat development with a consequent risk of desiccation and loss of storage.

The Tregaron Bog in the upper Afon Teifi valley. P802432.

Resource potential in the granular superficial deposits is generally limited, but exceptionally in the Afon Rheidol, Afon Teifi, Afon Dyfi and Afon Tywi catchments in west Wales, higher yields have been developed for public supply. Lovesgrove Borehole No. 1 [SN 614 808] near Aberystwyth in the Afon Rheidol catchment has a licensed abstraction of 5 Ml $d^{-1}$ from a coarse-grained alluvial formation. There are three production boreholes and a number of observation boreholes in which the transmissivity has been found to range between 290 and 5500 $m^2 d^{-1}$ (**Entec, 2009**). There are numerous other smaller abstractions for public supply in valley bottoms which provide a relatively low-cost means of supplementing supply to the more isolated rural communities. In addition there are a large number of private boreholes, wells and springs that draw on the shallow Quaternary aquifers supplying isolated rural dwellings and farmsteads with potable domestic water, supply for stock watering and washing down. These supplies are critically important to the social and economic well-being of many small rural communities, notably in central and west Wales.

The Quaternary alluvial aquifers may provide additional storage to bedrock aquifers. In many of the valleys in west Wales drillers traditionally case off the sand and gravel cover and complete boreholes as open-hole within the underlying bedrock. This is a convenient construction design for percussion drillers and also some rotary drilling procedures. Abstraction from the completed borehole draws water from bedrock and is limited by its transmissive properties. The storativity is greatly enhanced, however, as the bedrock fractures draw on water in storage in the shallow gravels and sands, and they in turn may draw from the surface water course flowing down the valley (**Robins et al., 2000**). As a consequence borehole yields may be modest, typically 2 to 4 $l\ s^{-1}$, but are sustainable even through long periods of dry weather. These sources are, however, vulnerable to surface pollutants as rainfall recharge can penetrate rapidly to bedrock carrying with it contaminants spilled on the ground such as fuel and agricultural chemicals.

# Hydrogeology of Wales: Quaternary aquifers - Afon Teifi

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

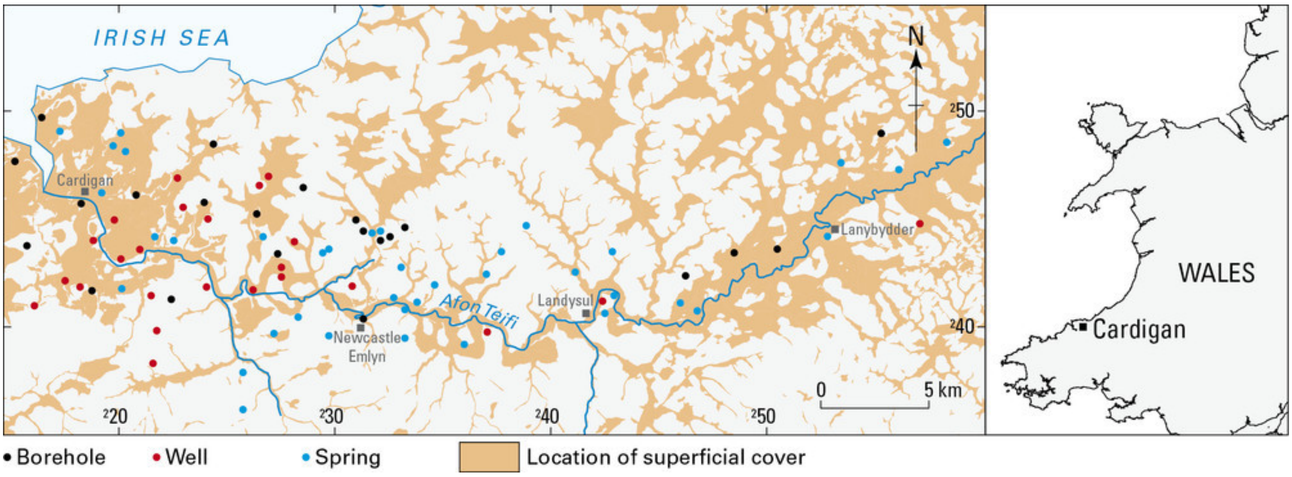
The superficial deposits in the western part of the Afon Teifi catchment, which derive from the Irish Sea Ice Sheet, offer little potential for groundwater abstraction. The deposits are clay rich, and there are a number of springs which issue from bedrock at the perimeter of the drift. The hydrogeological role of the sandier drift deposits, which are known to underlie the clay-rich deposits in some places, is uncertain.

Dŵr Cymru operate a borehole at Olwen, near Lampeter [SN 582 496] which is 26.8 m deep and draws water from fluvioglacial deposits in the valley floor of the Afon Dulas, a tributary of the Afon Teifi. The borehole lithological log indicates that water is supplied from two sand and gravel aquifers, separated by a clay layer which confines the lower gravels. The borehole is licensed to abstract 395 $m^3/d$, and generally takes close to the full licensed amount.

A constant rate pumping test on the Olwen borehole indicated an aquifer transmissivity of 210 $m^2/d$ from the early drawdown data (**Howard Humphreys, 1984**). The specific yield of the aquifer is assumed to be 10 per cent and the saturated aquifer thickness 18 m. These values may not be representative of the whole aquifer due to its heterogenous nature.

The superficial deposits in the Afon Teifi catchment which have some groundwater potential are those which typically contain a high proportion of clast-supported, granular materials preserving a high level of primary porosity, principally sands and gravels. Both nonaquifer and weakly permeable superficial deposits may intervene at depth between these near surface horizons and bedrock. The more permeable deposits, of which sand and/or gravel grade material dominate, include glaciofluvial deposits, undifferentiated melt-out deposits, head deposits and blown sand.

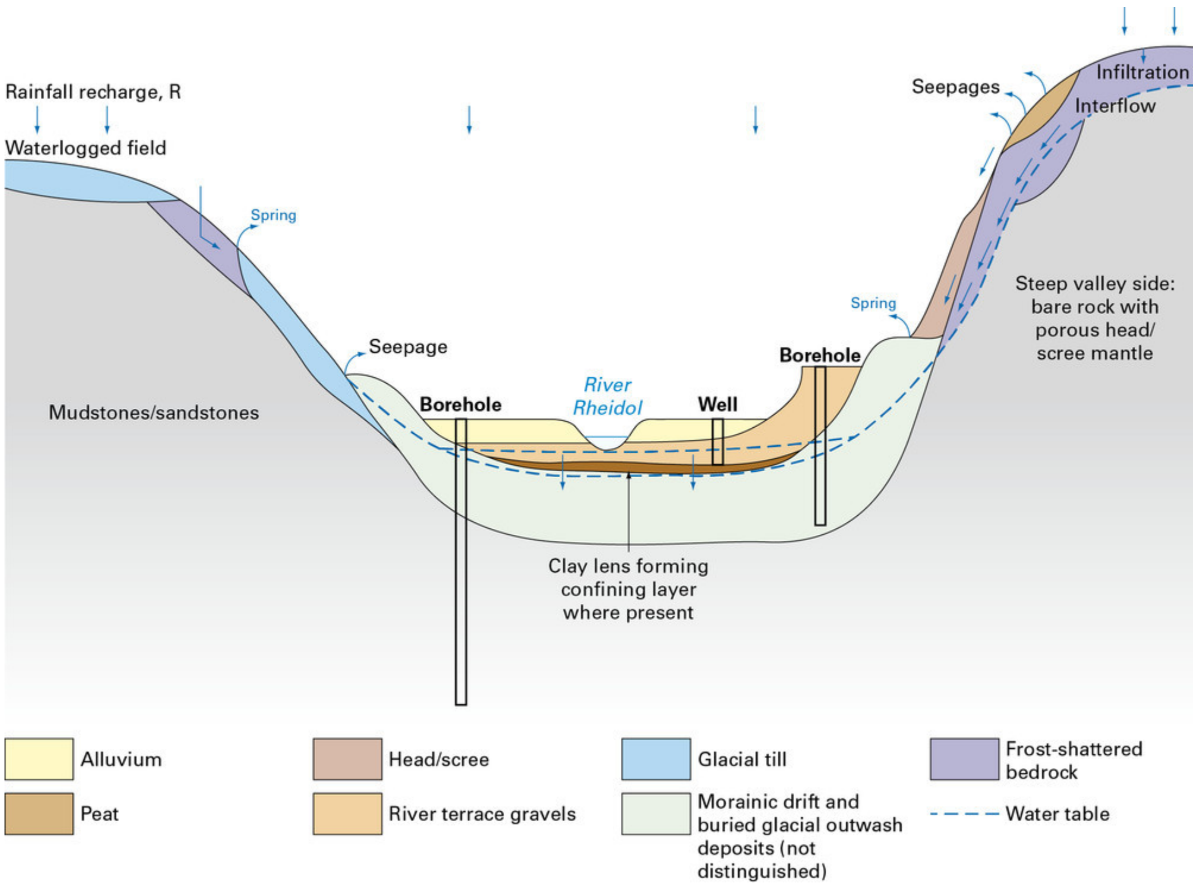
The permeable deposits occur throughout the Afon Teifi catchment and are potentially the most useful of the local minor aquifers. They are particularly widespread and at their thickest in the western reaches of the Teifi catchment notably around Penparc, Ferwig, Gwbert and west of St Dogmaels; and, in the east, within the main Teifi valley between Llanfihangle-ar-arth and Lampeter (**Figure P859280**). Extensive spreads of superficial deposits also occur in the upper reaches of the Ceri valley, around Rhydlewis. Sequences of these aquifer deposits are known locally to exceed 50 m in thickness. However, the superficial materials included in this group are characterised by rapid lateral variations in thickness. Subordinate low permeablility horizons and irregular masses of clay-rich materials are also a feature of some of the minor aquifer deposits. These lower permeability horizons inhibit the local movement and extractability of groundwater at some sites and their occurrence underlines the need for site specific investigations.




Distribution of superficial deposits in Afon Teifi showing borehole well and spring locations (after Robins et al., 2000). P859280.

There are a variety of estuarine alluvial deposits which occupy the tidal reaches of the lower Afon Teifi. These include tidal river, salt marsh, marine shoreface and beach deposits which have a collective potential as brackish groundwater aquifers. The most widespread and thickest developments of these various alluvial aquifers are associated with the modern courses of the Afon Teifi and its largest tributaries including the Afon Cych, Afon Ceri, Afon Tyweli, Nant Cledlyn and Afon Grannell. However, in contrast with other river systems in the region, such as the Afon Rheidol, the alluvial sequences of the Afon Teifi and its tributaries are relatively thin. The highest river terraces may be underlain by several metres of gravel dominated material, but in many areas the present day floodplains of the catchment may be underlain by alluvial deposits more or less equal in thickness to the bank height of the present river or its tributaries. These attenuated alluvial sequences reflect the net prevalence, since late glacial times, of incision over deposition throughout this river system. Moreover, thick sequences of clay-rich, glacial materials with little aquifer potential, including tills and glaciolacustrine deposits, are likely to underlie much of the alluvial belts in the valley, further limiting their potential for large volume groundwater abstraction.

The various low permeability superficial deposits which occur in Afon Teifi are typically clay-rich materials principally till and glaciolacustrine deposits. The distribution of these weakly permeable deposits has an important bearing on the geometry of associated drift aquifers and on the movement of groundwater into and within adjacent solid and drift aquifers (**Robins et al., 2000**). It is particularly significant as a factor in determining the vulnerability of the catchment bedrock aquifers to pollution. Low permeability drift deposits commonly overlie surface drift aquifers and surface run-off from these materials represents an important means of groundwater recharge for both solid and drift aquifers. **Figure P859281** shows both solid and drift aquifers, and distinguishes those areas in which drift aquifers and low permeability drift deposits occur in close association, within which vertical groundwater movement is restricted.




Schematic section of the central part of the Lower Afon Teifi showing the main flow components (after Robins et al., 2000). P859281.

# Hydrogeology of Wales: Quaternary aquifers - the Upper Lugg catchment

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

The River Lugg flows from the hills to the north-west of Llangunllo, south-east to Presteigne and out of Powys towards Byton in Herefordshire. Gravel deposits floor the valley between Monaulty to the north-west and Byton in the east, below which the valley narrows sharply. The largest area of gravels lies in the broad, level valley floor to the east of Presteigne. The underlying bedrock rises steeply at the edges of the gravels. The bedrock geology is predominantly of Silurian age with isolated faulted inliers and outliers of Proterozoic and Devonian strata respectively.

The main aquifer in the Upper Lugg is the river gravel (**ESI, 2006**). At Pilleth these are over 20 m thick and are highly transmissive (>1000 $m^2d^{-1}$). The gravels are overlain by 2 to 3 m of clay which has a low vertical permeability which allows a shallow, upper ‘perched’ groundwater system to develop in permeable cover above the clay. The water table in this shallow system is controlled by a combination of ditches and field drains in order to improve the quality of the land for agricultural purposes.

At Glan Llugwy Bridge (Monaulty) and the public supply abstraction boreholes at Pilleth [SO 260 678] the gravels are at least 23 m thick and none of the boreholes penetrate bedrock. The aquifer comprises loose, medium- to coarse-grained grey sand and fine to coarse gravel with occasional cobbles. Silt and clay horizons occur below 7 m depth. The gravels are overlain by a continuous 2 to 3.5 m-thick layer of silty, sandy clay (varying in colour between blue/grey and orange/brown). Drillers’ logs for the observation boreholes at Rock Bridge [SO 2914 6558] and Letchmoor Farm [SO 3455 6447] show that the gravels continue with a similar thickness downstream from Pilleth. The driller’s log for the Natural Resources Wales observation borehole at Evenjobb [SO 2615 6179] shows 10 m of drift overlying the Silurian Wenlock Formation; 8 m of which is 'clayey gravel'. Average annual rainfall is just over 1000 mm and effective precipitation is about 530 mm. Details of the licensed abstractions in the Upper Lugg are given in the **Licensed abstractions table**.

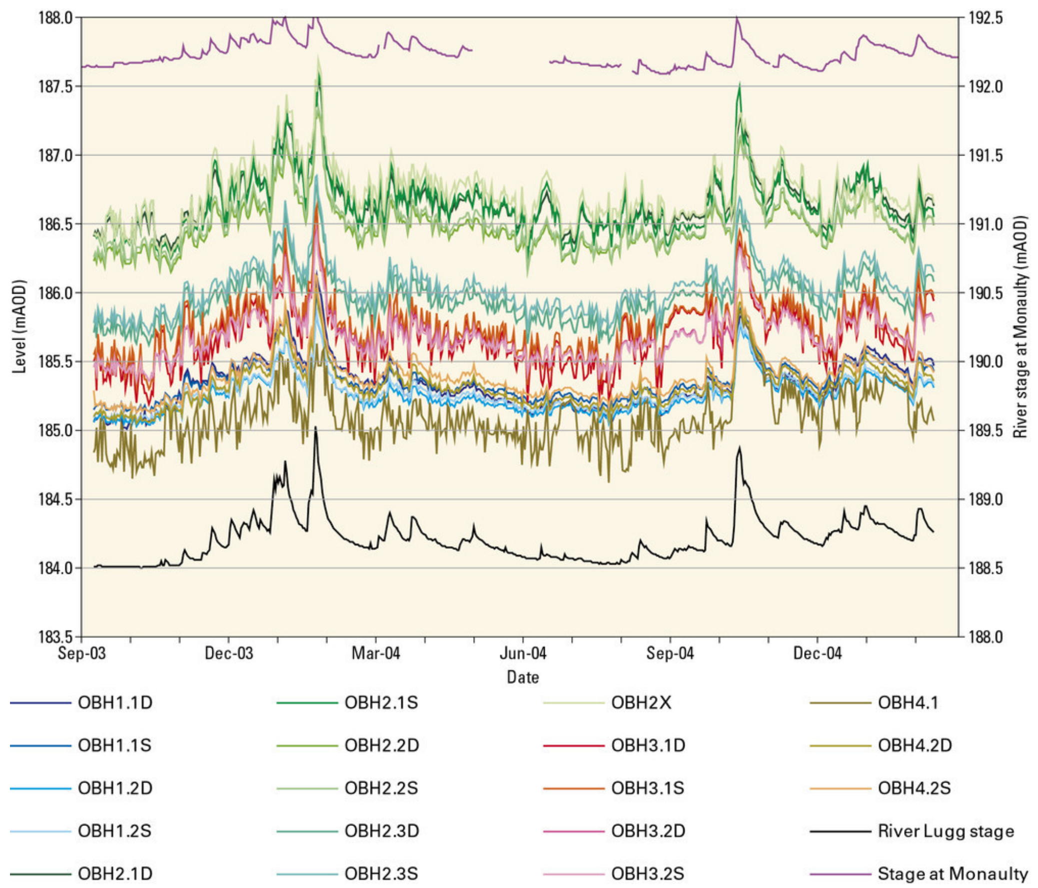
### Details of the licensed abstractions in the Upper Lugg (see Figure 4.2 for locations of key abstractions).

| Licence number | NGR | Annual quantity ($m^3$) | Daily quantity ($m^3$) | Surface (s) or groundwater (g) | Use |
|---|---|---|---|---|---|
| 19/55/8/0030 | SO 316 644 | 41 596 | 114 | g | Industrial services |
| 19/55/8/0030 | SO 316 644 | 72 377 | 198 | g | Industrial services |
| 19/55/8/0134 | SO 170584 | 6636 | 188 | g | General agriculture |
| 19/55/8/0142 | SO 238 633 | 2785 | 8 | g | General agriculture |
| 19/55/8/0179 | SO 253 676 | 1 409 260 | 3819 | g | Public water supply |
| 19/55/8/0046 | SO 192 624 | 141 426 | 386 | g or s | Public water supply |
| 19/55/8/0125 | SO 363 641 | 414 823 | 1137 | g | Public water supply |
| 19/55/8/0193 | SO 269 604 | 9092 | 318 | g or s | Spray irrigation |
| 19/55/8/0210 | SO 225 628 | 7300 | 20 | g or s | Water bottling |

| | | | | | |
|---|---|---|---|---|---|
| | | 2 105 295 | 6198 | | |

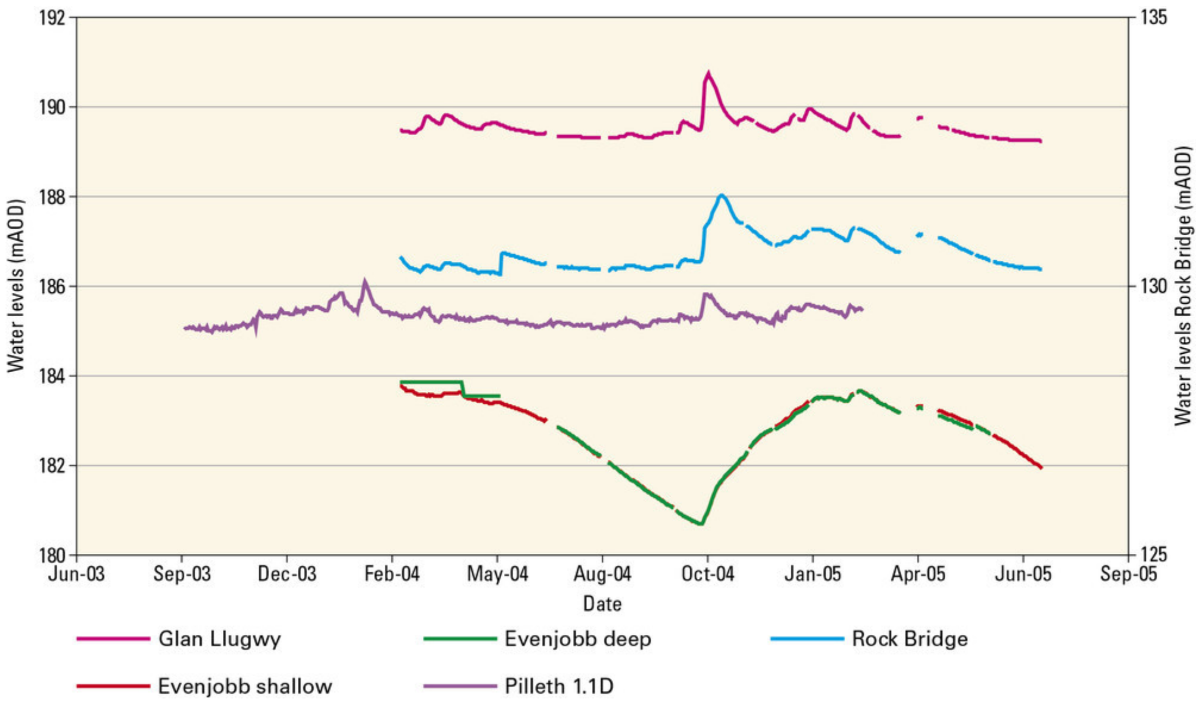
The 19/55/8/0046 abstraction, a source for New Radnor, is currently unused (G. Hyett pers. comm.).

Dŵr Cymru has carried out a programme of testing at Pilleth (**Celtic Water Management, 2005**). The specific capacity data indicate that the transmissivity of the aquifer is >1000 $m^2d^{-1}$. Dŵr Cymru monitors groundwater levels in ten observation boreholes. Eight of these boreholes are completed as multiple monitoring points with an upper and a lower screened section within the main gravel horizons. **Figure P859282** shows that groundwater levels at most of these sites do not generally fluctuate by more than 0.5 m. However, during periods of peak river flows, sharp increases in groundwater level occur, increasing the full range at most of the sites to around 1 to 1.5 m. The behaviour of the hydrographs reflects the nature of the environment of the gravel aquifer, i.e. a low permeability clay cover restricting local recharge and creating confined conditions, but with connection to the River Lugg at the margins of the aquifer allowing sudden changes in river stage to manifest themselves in the observed groundwater levels.



Groundwater levels monitored by Dŵr Cymru in the gravel aquifer near Pilleth (after ESI, 2006). P859282.

Natural Resources Wales monitors groundwater levels in the gravel aquifers in the Upper Lugg catchment at Glan Llugwy, Evenjobb and Rock Bridge. Hydrographs of the available data at these sites are shown on **Figure P859283**. Data from one of the Pilleth observation boreholes is shown for comparison. The Glan Llugwy and Rock Bridge hydrographs show fairly sharp responses to the onset of winter recharge. This reflects an unconfined aquifer in which recharge is relatively unimpeded and in which the one or two metres rise in the position of the water table causes a perceptible change in transmissivity (i.e. one or two metres is a significant proportion of the saturated thickness of the aquifer).

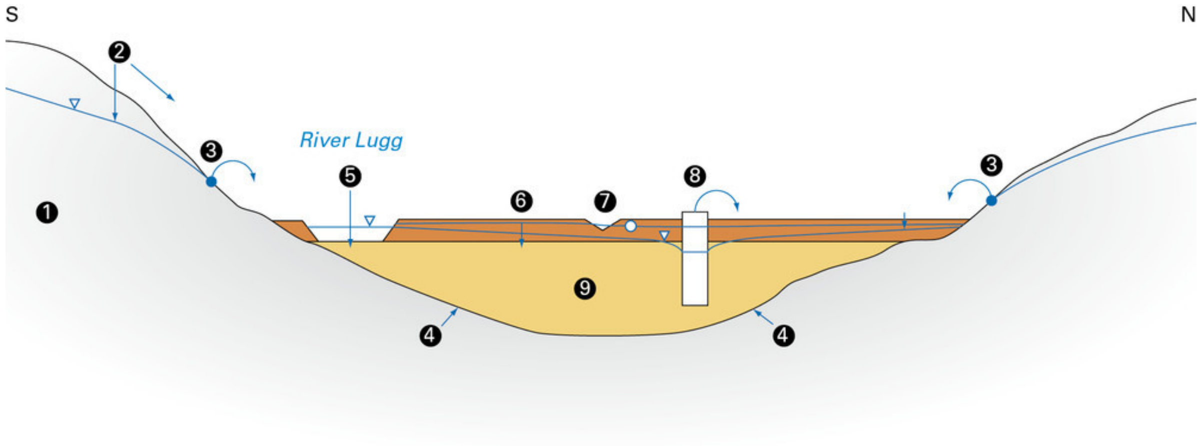



Groundwater levels in Environment Agency observation boreholes in the Upper Lugg catchment (after ESI, 2006). P859283.

Groundwater levels in the gravel aquifer in the vicinity of Pilleth are around 0.5 to 1 m below river stage and, this may contribute to losses in river flow in this reach. However, the gravel aquifer in this area is covered by a clay layer of at least 2 m thickness and a shallow ‘perched’ groundwater system is present above this that is discharging to surface water at the same time. There is a marsh downstream at Combe Moor just south of Byton which represents the main discharge area for groundwater from the gravels, just upstream of the point at which the gravels pinch out at Byton.

Dŵr Cymru was granted a licence to abstract up to 3.812 $Mld^{-1}$ from four boreholes at Pilleth in 1974. The water is used to supply Presteigne (and a significant proportion of this will return to the river at Presteigne STW) and the remainder is exported from the catchment to Knighton.

The gravel aquifers of the Upper Lugg are discrete and it is likely that the hydrogeological setting in each subcatchment is subtly different. Available data only allow the conceptual model of the area around Pilleth Pumping Water Station to be described in detail (**Figure P859284**).




1 Silurian bedrock aquifer dominated by fractures and shallow weathering zone
2 Effective precipitation on hillsides partitioned between recharge and runoff
3 Small springs on valley sides sourced from bedrock — may now be captured by field drains
4 Minor contribution from underlying bedrock strata
5 River in reasonable hydraulic continuity with gravel aquifer. Leakage from river into gravel aquifer
6 Slow downward leakage from shallow 'perched' water table into underlying gravels.
7 Water table in shallow system controlled by drains
8 Abstraction sourced principally from leakage from overlying strata (6) and induced recharge from River Lugg (5)
9 Thick, highly transmissive gravel aquifer overlain by 2 to 3 m of clay. In reasonable hydraulic continuity with river at edge of valley floor

Schematic conceptual model of the hydrogeology of the Upper Lugg catchment (after ESI, 2006). P859284.

The gravel aquifer is confined below this clay layer and shows the subdued response of groundwater levels to the onset of winter recharge. However, the aquifer is responsive to changes in stage in the River Lugg which indicates that the river, which is located at the edge of the valley floor at Pilleth, is likely to be in good hydraulic connection with the gravels.

The groundwater levels in the gravel aquifer are generally below the river stage in the vicinity of Pilleth – presumably as a consequence of groundwater abstraction and, as a result, the river leaks into the gravels. The peak cumulative loss is around 4 $Mld^{-1}$ (most of this occurring as the river first crosses onto these gravels) although there is subsequently a gain of around 1.5 $Mld^{-1}$ further downstream.

The contribution of the bedrock aquifer to the groundwater system in the gravels is uncertain. There is a perception that there is relatively little overland flow on the steep valley sides and this could indicate that much of the effective precipitation on the hills is recharged and subsequently enters the rivers via the gravels. However, the lack of overland flow could, to some extent, be a consequence of land drainage creating storage and intercepting flow.

# Hydrogeology of Wales: Quaternary aquifers - Afon Cynffig coastal plain

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

## Margam Moor

Margam Moor is an area of coastal dune-land to the north-west of Afon Cynffig and situated between the Port Talbot steelworks and Porthcawl. The superficial deposits comprise blown sand over thin lacustrine alluvium above marine/estuarine alluvium on till. The blown dune sand forms a strip along the coast and a larger area towards the Afon Cynffig; the lacustrine alluvium is exposed over part of Margam Moor, much of which is floored by marine/estuarine alluvium. Direct rainfall recharge occurs to the blown sand and to an adjacent area of blown sand on which steel slag has been tipped. The sand aquifer gains from the Afon Cynffig throughout the year, as the river stage is higher than the natural water table in the sand. The lacustrine alluvium thins towards the Afon Cynffig allowing ingress of water from the blown sand directly into the marine/estuarine alluvium, although the extent to which it acts as a confining layer to the underlying marine/estuarine alluvium is questionable. The overall groundwater flow direction, however, is predominantly towards Margam Moor, with some groundwater flowing to the coast.

A conceptual flow model has been constructed from the observed groundwater levels and the construction of *potentiometric* levels both for the blown sand and for the marine/estuarine alluvium (C Stratford, personal communication). The conceptual model does not identify relative permeabilities for the blown sand, lacustrine alluvium and marine/estuarine alluvium. Steel works production slag has been dumped on the blown sand between Margam Moor and the Afon Cynffig until quite recently. Current recharge through the slag and into the blown sand is alkaline and mineralised, while the blown sand aquifer discharges to a wet area in the southern flank of Margam Moor. This feeds into a series of 'recharge' ditches which allow the polluted water to ingress into the marine/estuarine alluvium (and partly also the lacustrine alluvium) or at peak flow to discharge towards the north along the ditches. This creates a unique aquatic alkaline habitat in the ditches on the moor which are currently the object of preservation.

## Kenfig National Nature Reserve

Kenfig Pool [SS 797815], to the south-east of Afon Cynffig, is essentially a large flooded dune-slack. It was the subject of detailed investigation when quarry extensions were proposed in a number of Carboniferous Limestone quarries nearby (**Cheney et al., 2000**).

Little evidence was found of a hydraulic connection between the dune sand that supports the Kenfig Pond and bedrock. An earlier study (**Jones, 1993**) showed that the dune sands are underlain by till and glaciofluvial sand and gravel. The till is absent beneath the centre of the dune area to allow a hydraulic connection with the Carboniferous Limestone below and possible upwelling, although groundwater flow modelling by **Cheney et al. (2000)** indicated that this would be unlikely, and dye tracer tests by **Jones (1993)** indicated that the Carboniferous Limestone was not a significant source to the dune aquifer. Some inflow from perched aquifers on higher ground to the east may occur, but direct rainfall recharge to the dune sand and the underlying and adjacent raised-beach aquifer is sufficient to sustain the Kenfig Pool.

# Hydrogeology of Wales: Quaternary aquifers - Whiteford Sands

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

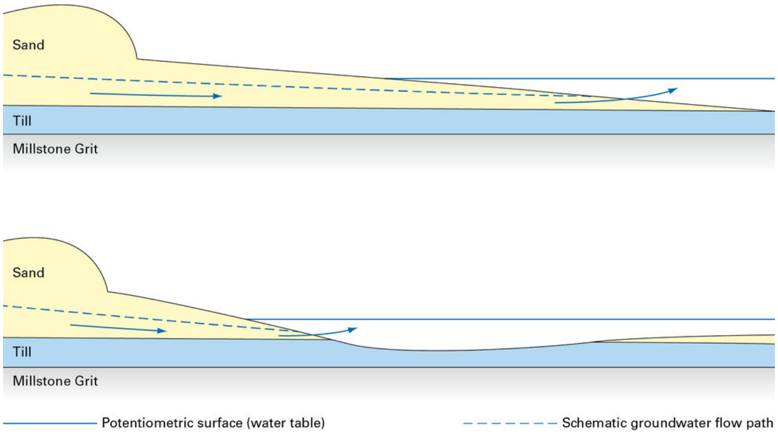
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

Whiteford Sands is a blown sand spit over glacial till (**Plate P802434**). The fore-dunes give way to beach sands and the back of the dunes to the east, to clays and silts of tidal flat deposits. The sand rests on till deposited beneath a Quaternary ice sheet. Steep northerly dipping Carboniferous Limestone strata abut the sand at the landward (southern) edge, although the Millstone Grit succession underlies the majority of the burrows area. It is unlikely that groundwater in the Carboniferous Limestone can ingress the sands due to the steep bedding of the limestone, in which dilated bedding plains will tend to drain to the base of the upstanding outcrop.

Groundwater discharge along the foreshore beneath Whiteford Burrows on the Gower Peninsula. P802434.

The sand acts as a small unconfined aquifer perched over impermeable till. Water contained in the sand derives solely from direct rainfall recharge. The groundwater stored in the sands discharges naturally to the foreshore while a small amount discharges to the salt marshes behind the dunes. There are no external contributions to the water balance although standing water on the shore side of the burrows does enhance evaporative losses from this area.

The groundwater flow regime at Whiteford comprises a groundwater dome created by direct rainfall recharge with discharge to the foreshore. However, it has been heavily impacted by change when storm ingress and erosion of the foreshore took place in 1996 increasing the hydraulic gradient away from the dune front with a corresponding increase in discharge from the dunes (**Stratford et al., 2009**). The consequent lowering of the water table virtually overnight is only now slowly beginning to recover (**Figure P859285**).




Schematic cross section of the central foreshore at Whiteford Sands showing the steepening of the hydraulic gradient away from the dune front following storm damage in 1966. P859285.

# Hydrogeology of Wales: Quaternary aquifers - Newborough Warren

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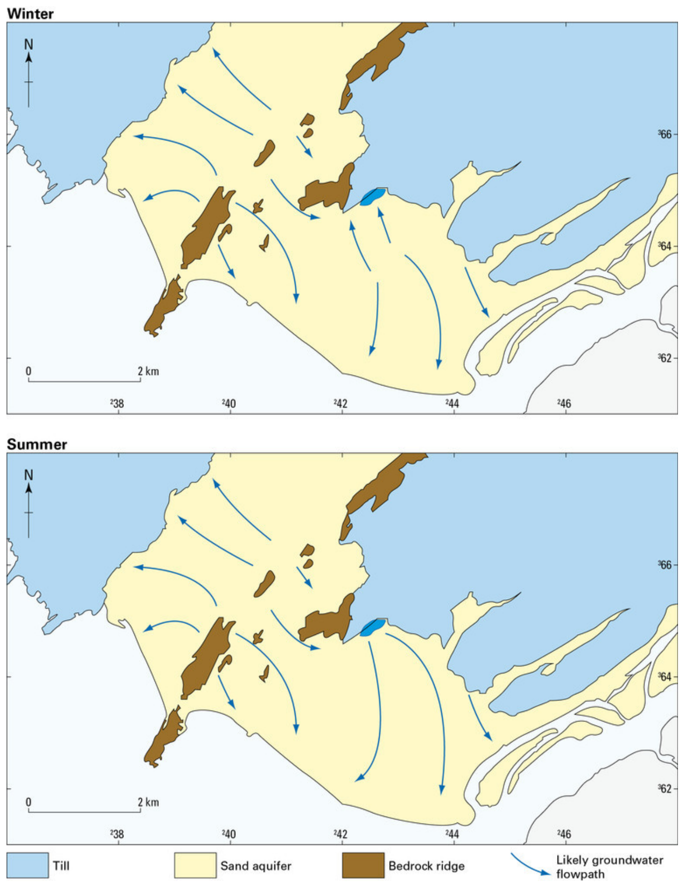
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

Newborough Warren (**Plate P802433**) is located on the south-west coast of Anglesey [SH 423 636] and is part of the Abermenai to Aberffraw Dunes Special Area of Conservation (SAC). Afforestation of 700 ha of the dune system between 1947 and 1965 assisted the stabilisation of a large swathe of the dunes, running 2 km inland from the shoreline. Since this time, the water table in the warren has declined. There is anecdotal evidence that winter standing water is now a rare occurrence in dune-slacks within or adjacent to the forest, though long-term data reveal no significant change in rainfall between the 1950s and 1990s for Anglesey. **Ranwell (1959)** reported extensive winter flooding (including areas within and adjacent to the present forest) during 1950–51, and noted that some areas may remain under water for 3 to 4 months in high-rainfall winters.

Installing an automatic weather station at Newborough Warren, Anglesey. P802433.

The conceptual groundwater flow model for the dune area (**Figure P859286**) includes a rock ridge running from south-west to north-east through the dunes, that creates a groundwater divide (**Stratford et al. (2007)**. The piezometric surface is draped over the rock ridge, with groundwater flowing off its flanks into the sand. The watershed lying to the south of a small pond is not a static fixture and is perceived to be in that position only under wet (winter) conditions, and to migrate northwards towards the pond during dryer (summer) conditions (**Davy et al., 2010**). In this way the pond feeds the groundwater system in summer but gains from groundwater in the winter. This is caused by the pond acting as a near fixed head whereas the dune water table elevation fluctuates above and below that head. In addition, the foreshore around the warren must be considered a part of the groundwater flow system. Groundwater discharge above low water mark across the surface of the till is the active drainage area for the system.




Conceptual seasonal patterns of groundwater flow at Newborough Warren–upper winter, lower summer (blue–till; yellow–sand aquifer; brown bedrock ridge; blue arrows indicate likely groundwater flowpaths). P859286.

Anecdotal evidence indicates that the water level in the pond varied over the last 60 years as the retaining structure has been modified although accurate levels have not been recorded. Grazing patterns have also changed the vegetation on the open dune-land, and consequent recharge potential, following the dramatic decline in rabbit population in the 1950s due to myxomatosis and since 1986, the reintroduction of sheep, cattle, ponies and rabbits cropping the grass.

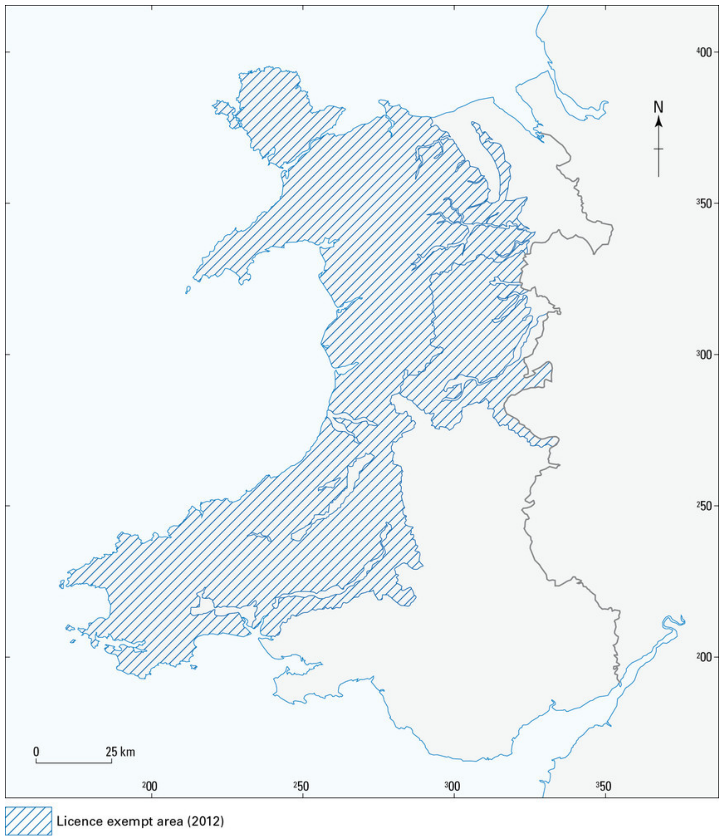
The dune-slacks at Newborough Warren regularly flooded during the winter in the period prior to planting the northern sector of the dunes, but since the mid 1950s flooding is increasingly rare. The perception that the trees are drawing the water table down beneath the afforested dunes is difficult to prove, given the other variables that may have influenced the water table during the same period (**Stratford et al., 2007**). Although some of the trees are now reaching maturity and their water demand is probably starting to reduce, in places new stands have been planted as trees have been felled and most old stands have been thinned, so changing the overall water demand. Regrowth, development of understorey and increased canopy roughness as age classes diverge, promise increasing water demand in the future. Assessment of all these variables in the light of experience derived from other coastal dunes suggests that the trees are likely to contribute to the observed groundwater level changes beneath the dune-slacks during winter months. However, it is unlikely that removal of all or part of the woodland would cause a reversion to the pre-afforestation land cover and ecosystems due to other changes in the dynamics of the dunes. The complex interaction between groundwater and vegetation at Newborough highlights the difficulty of managing groundwater-dependent ecosystems and habitats.

# Hydrogeology of Wales: Management and regulation of groundwater

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
Author(s): N S Robins and J Davies, British Geological Survey
Contributor(s): D A Jones, Natural Resources Wales and G Farr, British Geological Survey

## Background

Groundwater sources have been important drinking-water supplies to communities across Wales for many centuries. The location of settlements with easy access to groundwater resources is no coincidence and historic springs can be seen at the centre of towns and villages.



The abstraction licence exempt are (as at 2012). P859287.

Prior to the implementation of the *Water Resource Act, 1963* groundwater and surface water sources were typically managed by local water boards and district councils, which totalled over twenty in Wales in the early 20th century. This localised approach did allow co-ordination of resources even on a catchment scale. The *Water Resources Act, 1963* recognised the importance of water resource planning and also introduced the abstraction licensing system. Water resources in Wales were managed by the Wye, Usk, Glamorgan, South-west Wales, Gwynedd, Dee and Clwyd and Severn river authorities. Due to the low-yielding nature of the aquifers across west, mid and north-west Wales these areas were subsequently designated in the late 1960s via Statutory Instrument, as exempt from groundwater abstraction licensing (**Figure P859287**).

The subsequent *Water Act, 1973* abolished the Water Resource Board and river authorities and combined their functions into regional water authorities, defined by catchment boundaries and responsible for the supply of drinking water, sewerage, water quality and pollution prevention. Regulation of groundwater in Wales was the responsibility of the Welsh National Water Development Authority (renamed Welsh Water Authority in 1977) and the Severn Trent Water Authority.

The *Water Act, 1989* enacted the privatisation of the regional water authorities, creating water supply and sewage treatment utility companies. Their regulatory functions passed to a new organisation, the National Rivers Authority, the detailed functions of which were set out in the *Water Resource Act, 1991*. The Welsh Water Authority became Dŵr Cymru Welsh Water and is the principal supplier of drinking water and sewerage. Severn Trent provides the same function in the Severn Valley corridor in mid-Wales, with Dee Valley Water providing drinking water within the River Dee corridor in north-east Wales.

The*Environment Act, 1995*resulted in the formation of a statutory body, Environment Agency Wales, responsible for the management and protection of groundwater in Wales. On the 1st April 2013 a new regulatory body called Natural Resources Wales for formed combining the roles of Environment Agency Wales, Countryside Council for Wales and the Forestry Commission Wales.

# Hydrogeology of Wales: Management and regulation of groundwater - groundwater abstraction

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**

Author(s): N S Robins and J Davies, British Geological Survey
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Groundwater currently contributes around 3 per cent of the total public water supply (**Environment Agency, 2008**). This corresponds (Environment Agency Wales abstraction data for 2009) to an actual abstraction volume of around 11 000 Mla$^{1}$.

Dŵr Cymru Welsh Water is the largest abstractor with 22 active groundwater abstractions, and a further 15 standby sources which are used in times of drought or emergency. These are a mixture of boreholes, springs and wells. In total it is licensed to abstract around 45 000 Mla$^{-1}$, but also has abstractions in the licence-exempt areas of Wales. Individual abstraction volumes range from a few tens of cubic metres per day from small spring sources to 8000 Mla$^{-1}$ abstraction from the Carboniferous Limestone aquifer near Bridgend. Dee Valley Water is licensed to abstract 270 Mla$^{-1}$ of groundwater from a borehole installed into Carboniferous sandstone near Wrexham. Severn Trent is licensed to abstract 6000 Mla$^{-1}$ for public supply from river gravels near Newtown.

A further 16 000 Mla$^{-1}$ is abstracted for industry, irrigation, agriculture, and food production.

Records held by environmental health departments indicate there are at least 21 000 private water supplies in Wales. Private water supplies, any supply which is not provided by a water undertaker or a licensed water supplier, are abundant partly due to the historic abstraction licence-exempt areas. The additional exemption from licensing in the *Water Act, 2003* for abstraction > 20 $m^3d^{-1}$ has further increased the number of private supplies as several thousand abstraction licences were de-regulated.

The *Private Water Supply (Wales) Regulations, 2010* places a duty on local authorities to keep a register of these sources and regulate that the water is fit for human consumption.

# Hydrogeology of Wales: Management and regulation of groundwater - need for management

**This page is part of a category of pages that provides an updated review of the occurrence of groundwater throughout Wales.**
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Those aquifers which are exploited for public water supply, industry, power generation and agriculture need careful management to ensure that supplies are able to cope with any future increases in demand and are resilient to a changing climate.

Whilst many other aquifers in Wales are not heavily exploited, they are used for private supply and management of them is also required. Furthermore, groundwater base flow to rivers and streams and support to some wetlands needs to be safeguarded. Groundwater-dependant terrestrial ecosystems are important habitats. There are around 350 known groundwater-dependant ecosystems in Wales, mainly comprising groundwater-fed wetlands such as fens and bogs but also include sites such as the Pant-y-Llyn turlough and cave systems such as Ogof Ffynnon Ddu.

Groundwater is easily polluted and can be difficult and expensive to remediate therefore management of discharges or other activities which can cause pollution is essential. Several of the Carboniferous Limestone aquifer sources have been abandoned for public water supply due to their particular vulnerability to pollution.

The *Water Act, 2003* was implemented to streamline abstraction licensing, with greater focus on water conservation and protection of the water environment. Some activities which were previously exempt from licensing, such as mine and quarry dewatering and trickle irrigation, now need a licence, and the historic groundwater licence-exempt areas were planned to be removed – a process that has yet to begin.

European legislation has also had a significant impact on the protection and management of groundwater, the most significant of which has been the Groundwater and Groundwater 'Daughter' directives, the Habitats Directive and the Water Framework Directive.

Between 2001 and 2008 the Environment Agency also developed Catchment Abstraction Management Strategies (CAMS) to promote groundwater and surface water resource management. These consider recharge, the water requirements of the environment, including groundwater base flow to support flow in rivers, and the amount of water licensed for abstraction. They enable areas of water availability for future licensing and areas which are already overlicensed to be highlighted. However, they only cover areas designated as *principal aquifers* (see Groundwater pollution) and catchments in *secondary aquifers* which have a large number of groundwater abstractions, e.g. the Old Red Sandstone in the Wye catchment.

The CAMS process designated only two catchments in Wales as 'no water available' or 'overlicensed' for groundwater abstraction: the Carboniferous Limestone aquifer in south Pembrokeshire and the Permo-Triassic sandstones in the lower Dee valley. A difficulty in identifying and quantifying groundwater abstraction pressures in Wales is the presence of the groundwater licence-exempt areas where the number and volume of abstractions is not known. Pressures which do exist may be acute locally, but are unlikely to have widespread implications.

Groundwater is used to augment flows in the River Clwyd in north Wales, to mitigate the impact from an adjacent large public water supply abstraction (see Vale of Clwyd [1]). This abstraction from the Sherwood Sandstone south of St Asaph has minimal impact on the river during winter months, but during the summer increased demand for water from seasonal holidaymakers along the north Wales coast, coupled with naturally lower river flows may cause derogation. The augmentation scheme, the only one in Wales, was implemented by the Welsh Water Authority in

1977 at a cost of £580 000. It is designed to augment flow and ensure no reduction in the natural river flow downstream of the abstraction. This is achieved by releasing groundwater from several augmentation boreholes into the River Clwyd higher up the catchment. These boreholes take advantage of the natural artesian conditions which exist in the area due to the thickness of low permeability superficial deposits confining the sandstone bedrock aquifer. The scheme operates when river flow immediately upstream of the public abstraction drops below 147 000 $m^3d^{-1}$. At this point the abstraction must then be compensated by an equal augmentation discharge from the boreholes.

## References

[1] http://nercbgskwxmediawiki/mediawiki/index.php?title=HoW_-_Vale_of_Clwyd&action=edit&redlink=1

# Hydrogeology of Wales: Management and regulation of groundwater - groundwater pollution

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Diffuse pollution is a significant source of groundwater pollution, and it is estimated that 35 per cent of groundwater bodies in Wales are at risk of failing Water Framework Directive objectives because of it (**Environment Agency, 2009**). Nitrate is the most common diffuse pollutant in Wales, but pollution is also caused by phosphates, pesticide and herbicides. Pollution is predominately a result of agricultural activities including land spreading, fertiliser application and poor land and stock management practices. Heavy industry, mining, sewerage networks and atmospheric deposition also contribute to the nitrate problem.

Diffuse and point source pollution in Wales is also caused by historic land contamination and waste disposal operations (landfills). Due to the lack of mains sewerage and mains gas connection in rural Wales, discharges from poorly maintained private sewerage systems, and leaks from domestic heating oil tanks are also common sources of point source groundwater pollution.

It is estimated that 24 200 ha of land in Wales could be contaminated (**Environment Agency, 2009**). The industrial legacy of contaminated land, particularly in parts of south Wales, is both extensive and costly to remediate. Much work has been focused on the Swansea, Neath and Port Talbot areas (**Waters et al., 2005**) investigating the transport of pollutants along discrete geological horizons. One specific problem is the discharge of polluted water into rivers from glacial gravels along valley sides. In the Tawe valley the potentiometric surface cuts through made ground including ash and slags from former metalliferous ore smelting activities generating polluted base flow. Remedial action has required the removal of considerable volumes of made ground for contained disposal.

Wales also has over 100 closed landfills, many in redundant quarries, and were designed as ‘dilute and disperse’ sites without any lining. Waste generation in Wales continues to have a high proportion of mineral wastes and residues (see **Industrial and commercial waste table** ).

## Industrial and commercial waste produced in Wales (tonnes x $10^3$) – data compiled by Environment Agency Wales

| Waste type | Industry | Commerce | Total | % of total for all England and Wales |
|---|---|---|---|---|
| Inert | 129 | 9 | 138 | 5.8 |
| Paper and card | 150 | 106 | 256 | 4.9 |
| Food | 105 | 18 | 123 | 4.8 |
| General industrial and commercial | 572 | 853 | 1425 | 5.0 |
| Other general and biodegradable | 370 | 80 | 450 | 5.1 |
| Metals | 393 | 22 | 415 | 8.7 |
| Contaminated general | 198 | 33 | 231 | 5.8 |
| Mineral wastes and residues | 2654 | 1 | 2655 | 20.7* |
| Chemical and other | 418 | 19 | 437 | 7.4 |
| Total | 4989 | 1141 | 6130 | 8.2 |

*This percentage reflects the high level of activity in the minerals sector in Wales.

At the end of 2007 there were 34 permitted landfill sites 254 transfer stations, 65 treatment facilities, 148 metal recycling facilities and 5 waste incinerators. During 2007 these sites managed a total of over 7.2 million tonnes (see http://www.environmentagency.gov.uk/research/library/data/98033.aspx [1]):

- 3.2 million tonnes of waste were landfilled
- 2.3 million tonnes of waste were transferred
- 1.2 million tonnes of waste were treated
- 500 000 tonnes of waste were handled through metal recycling facilities
- 36 000 tonnes of waste were incinerated.

At the end of 2007 there were:

- 41 $Mm^3$ of available landfill capacity, 73 per cent of this was available at commercial nonhazardous sites
- 200 000 $m^3$ was available at private hazardous waste only sites
- 7.8 years of landfill capacity at commercial nonhazardous waste sites in Wales, at current input rates.

During 2007 in Wales almost 300 000 tonnes of hazardous waste was produced with:

- less than 1 per cent landfilled at restricted user sites
- 10 per cent transferred
- 25 per cent treated
- 61 per cent recycled, recovered or re-used
- 2 per cent sent for incineration with energy recovery and a further one per cent incinerated without energy recovery.

All licensed landfill operators are required to ensure that aqueous pollution does not leave their facilities. To this end a great deal of effort is maintained in monitoring sentinel boreholes strategically sited around such facilities.

Wales has a long history of mining activity which has left a legacy of contamination to soils, groundwater and surface water. The Coal Authority are responsible for managing polluting discharges from abandoned coal mines and have installed 11 treatment plants in south Wales.

In 2002 Environment Agency Wales developed the *Metal Mines Strategy for Wales* to provide a framework for tackling pollution left by the legacy of non-coal mines. Due to the significant number of abandoned sites the strategy aimed to identify the fifty highest priority sites for further investigation, assessment and remediation. The majority of these are concentrated in Ceredigion, west Wales and include the Fron Goch, Cwmystwyth, and Cwm Rheidiol lead and zinc mines.

In the mid 1990s some 60 km of river were adversely affected by 90 ferruginous sources from disused coal mines in north and south Wales. Thirty-three mine water and spoil drainage sites in south Wales were described by **Rees et al. (2002)** in which the time since first emergence ranged up to 40 years, and total iron concentration ranged up to 256 mg $l^{-1}$, although most were typically less than 10 mg $l^{-1}$. Most discharges were only slightly acidic with pH values ranging from 5.2 to as high as 7.9. The main hazard from the discharges is iron generated by the oxidation of iron sulphides, but the discharges are better classified according to pH and source (see **Chemical properties of mine and spoil discharges table** ). Most of the Welsh coalfield discharges are from flooded and free draining workings.

## Chemical properties of types of mine and spoil discharges (after Rees et al., 2002)

| Source | pH | Net alkalinity $CaCO_3$ (mg $l^{-1}$) | Type |
|---|---|---|---|
| Flooded workings | <5–8 | 0 to >500 | $Ca\text{-}Mg\text{-}SO_4/HCO_3$ |
| Spoil tip | <5 | -2500 to 0 | $Ca\text{-}Mg\text{-}SO_4$ |
| Free-draining workings | 5–7 | +80 to +180 | $Ca\text{-}Mg\text{-}SO_4$ |
| Flooded and free-draining workings | >5 <8 | -350 to +200 | $Ca\text{-}Mg\text{-}SO_4$ |
| Pumped mine discharge | 6.5–7.5 | +500 to +1000 | $Na\text{-}HCO_3/SO_4$ |

With the closure of coal pits culminating in north Wales when Point of Ayr closed in 1997, and in south Wales when Tower Colliery ceased to work in January 2008, there has been recovery of water levels and free drainage to subhorizontal day adits and other low elevation discharge points. Pits that have since reopened have not impacted this recovery. Tower continues to recover, while two drift mines were reopened in the Vale of Neath. Elsewhere many of the discharges have been ameliorated with chemical dosing and reed bed treatment to ensure least contamination of the surface-water environment. There is a proposal to develop a new mine at Margam and investigations are ongoing into in situ degasification.

The Point of Ayr colliery in north Wales never made much water and prognoses indicated that it would take 80 years to flood. As a consequence the mine was flooded with sea water and an element of flushing allowed with each tide. In south Wales solutions were less easy and at Pelenna, for example, three large wetland schemes were needed to capture and treat all major mine water discharges into the Pelenna catchment (**Younger et al., 2004**). Other major remediation schemes in south Wales include Ynysarwed in the Neath Valley, Taff Merthyr ( **Plates P802438, P802436 and P802435**) in the Taff Bargoed River valley, Six Bells in the Ebbw Fach valley, and Morlais, some 7 km east of Llanelli.

Taff Merthyr Colliery prior to closure in 1992. P802438.

Ferruginous mine water discharged from Taff Merthyr Colliery shaft after closure. P802436.

Mine water from Taff Merthyr after treatment emerging from the reed bed treatment area. P802435.

Metal mine abandonment is also of concern. The longstanding legacy in the Afon Rheidol above Aberystwyth has been investigated (**Younger et al., 2004**) and proposals for remediation of some sources prepared. Mynydd Parys on Anglesey (**Plate P802437**) has received extensive work which focused on the two main discharges, one to the north and one to the south, to produce one discharge point into a single treatment facility before allowing the discharge access to the sea. At Gwynfynydd in Afon Mawddach, the last active gold mine in Wales, which only closed in 1999, tests showed that the mine discharge both during working and since abandonment had little impact on the Mawddach.

The abandoned Parys Mountain copper mine seen in 2004, Anglesey. P802437.

## References

[1] http://www.environmentagency.gov.uk/research/library/data/98033.aspx

# Hydrogeology of Wales: Management and regulation of groundwater - management tools and future issues

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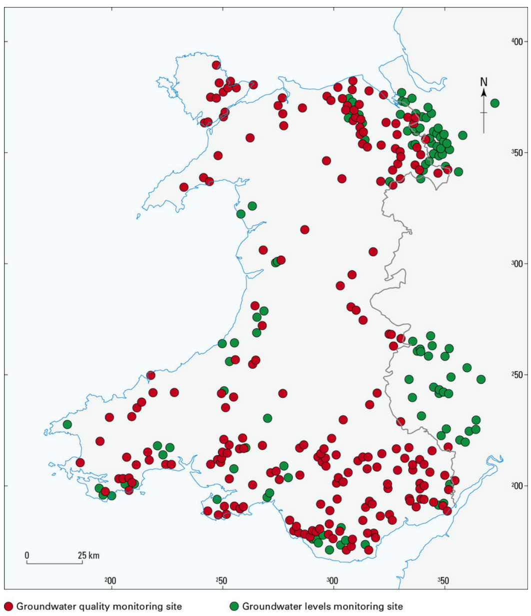
To complement the abstraction licensing and permitting regimes that control activities which can pollute and derogate groundwater, the regulators have developed a number of assessment tools. These allow a risk based approach focussing on aquifers which are exploited for public water supply, have known problems with over-abstraction, have been identified at 'poor' status under the Water Framework Directive or where information is needed to respond to future pressures such as climate change. Some of the key tools include:

River Basin Management Plans – to identify measures to achieve Water Framework Directive requirements for all water bodies. These water bodies have been compiled into specific river basin districts (RBD), three of which cover Wales: Dee, Severn and Western Wales.

Aquifer designations - either Principal or Secondary Aquifers. These reflect the importance of the aquifer as both a resource and its role in supporting surface water flow and wetland ecosystems. Principal aquifers in Wales consist of bedrock aquifers which can supply water on a strategic scale. The principal aquifers are the Carboniferous Limestone aquifers across south Wales and area of north Wales, and the Permo-Triassic Sandstone in north east Wales (**Figure P859288**). Secondary Aquifers include a wide range of rock types or drift deposits with an equally wide range of water permeability and storage.




Location of the present-day groundwater level and quality monitoring networks. P859289.

Source Protection Zones - to protect abstractions used for public water supply and other forms of distribution to the public, such as mineral and bottled water plants, breweries or commercial food and drink production. These zones show the areas of groundwater within which there is particular sensitivity to pollution risks due to the proximity of a potable source. There are currently 76 Source Protection Zones in Wales, ranging from small catchments around water bottling sources to large zones covering areas of heavily fractured and karstic Carboniferous Limestone used for public supply, where pollutant travel times to the source are likely to be rapid. Whereas protection zones around smaller sources can be delineated with analytical or numerical modeling techniques, in areas of karstic, non-Darcian flow they are best defined by tracer testing and field examination.

Nitrate Vulnerable Zones - delineated in areas of agricultural nitrate pollution to meet the requirement of the EU Nitrate Directive (91/676/EEC). Where groundwater quality data demonstrates increasing nitrate trends above the trigger of 11.3 mg-N $l^{-1}$, the drinking water standard, further investigation, for example of land management practices, is applied to refine the catchment areas. The zones are reviewed every 4 years and currently cover around 4% of the land area (cf. 70% in England) and are currently delineated only in parts of the Vale of Clwyd and Dee and Wye Valleys.

Map of Principal and Secondary aquifers in Wales. P859288.

Groundwater level and quality monitoring networks - to comply with European and National legislation and meet internal and external needs from groundwater level and groundwater quality monitoring networks. Groundwater levels are monitored at 140 sites and groundwater quality at 250 sites across Wales (**Jones and Farr, 2015**) (**Figure P859289**).

Population growth coupled with a changing climate is likely to increase the demand for water, and water companies may have to reinstate historic groundwater abstractions or investigate new groundwater sources which will requirement active management. Land uses and land management practices may also alter in response to changing climate which may impact infiltration or increase the risks of groundwater pollution.

Over the last decade the Water Framework Directive has been the driver for much positive work on groundwater, including the development of statutory monitoring networks, delineation of groundwater bodies and identifying where groundwater quality and resources are being impacted. This has built on the pollution prevention and remediation work promoted by the 1980 Groundwater Directive which was aimed largely at controlling discharges of certain (hazardous) substances to groundwater. The immediate future of groundwater management in Wales is likely to focus on addressing the impacts of diffuse pollution and abandoned metal mines.

Work is ongoing in Wales to prioritise which of the Groundwater dependant terrestrial ecosystems are most vulnerable to diffuse pollution or abstraction pressure, and to develop a programme to investigate specific impacts and develop remedial measures.

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