Regional hydrogeological assessment of Wales

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Wales is blessed with abundant surface water and plentiful groundwater, either of which can be an asset and at times also a hazard. Groundwater is important to Wales, not least as the source of baseflow sustaining rivers and streams during periods of low flow. Despite its importance, hydrogeological conditions in Wales are not widely understood while there remain a number of issues yet to be resolved. Occurrence of groundwater in the fractured Lower Palaeozoic bedrock of west and central Wales is boosted by groundwater storage in Quaternary valley fill deposits many of which are in hydraulic contact with surface waters. Groundwater in the Coal Measures has long being considered a threat both underground during mining and nowadays because of acid mine water discharges to surface. Carboniferous Limestone offers classic karst hydrogeology and the Triassic aquifer in the Vale of Clwyd provides a groundwater source valuable for supply and river augmentation. Throughout the Principality, as elsewhere, the industrial and mining heritage coupled with modern day activities has created pollution that will take many years to flush through the groundwater system.

Groundwater in Wales

A basic knowledge and understanding of the occurrence of groundwater, its availability and its quality, within the varied rock types present in Wales, is invaluable for regulators, planners and environmental managers. Groundwater is a critically important Welsh resource, particularly in rural areas. It is readily accessible at least in small volumes, is of a consistent and generally favourable quality, is economic to develop, and is in part abstraction license exempt. It also provides a key baseflow component to river flows. On the negative side it is widely polluted beneath many former mining and industrial areas and the generally shallow unconfined aquifers of Wales are largely vulnerable to contemporary diffuse pollution from farming as well as point source spills from the storage and transport of liquid products.

The prevailing maritime climate assures >1000 mm mean annual rainfall, the wettest period being December and January. Rainfall distribution varies with the highest average annual totals exceeding 3000 mm in Snowdonia and only marginally less over the Brecon Beacons. Approximately 250 Ml/d or about 8% of the total water in public supply derives from groundwater in Wales and up to 95 Ml/d is abstracted for private consumption from 5000 or so sources, including wells, boreholes and springs (Fig.1). Groundwater is an attractive resource for rural communities, as it offers consistent and generally favourable quality, is readily accessible at least in small volumes and is economic to develop.

The geology of Wales is diverse (Fig.2), with a good representation of strata from the Precambrian through to the Quaternary (Howells 2007). The oldest rocks occur in the north of Wales and are mainly metamorphic and igneous Precambrian and Cambrian rocks with low interstitial porosity and permeability and limited fracture permeability and porosity. Central Wales is dominated by Lower Palaeozoic sediments which have a shallow weathered and fractured zone which encourages catchment scale groundwater flow systems, occasionally deeper as in the case of the celebrated spa sources in central Wales. Devonian sandstones, mudstones and conglomerates in the east of Wales and the Welsh borderlands offer slightly better hydraulic characteristics and are widely exploited for small scale supply particularly from spring sources. Upper Palaeozoic sediments including Carboniferous limestones, sandstones and coals, occur within east-west trending belts through southern and northern Wales encompassing the coalfield basins of south and north-east Wales. Groundwater occurrence and transport in these strata are controlled by fracture flow and are largely of catchment scale with only a minor regional flow element. Triassic sandstones and mudstones outcrop in the south-east and north-east of Wales and Jurassic shales and limestones outcrop in the south-east. Triassic strata occurring in the Vale of Clwyd in North Wales, and Carboniferous limestones in South Wales form the better aquifers in Wales. Valley fill glacial and fluvial deposits provide storage to underlying fractured aquifers and are a viable aquifer in their own right.

Much of the groundwater is unconfined with generally short and shallow flow systems and is, therefore, generally well oxygenated and only weakly mineralised with calcium and bicarbonate forming the main ionic components. More mineralised groundwater, depleted in oxygen, occurs in occasional 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 solid geology, residence time and the nature of the Quaternary cover. Water from the Coal Measures is typically poor quality due to the solution of iron and sulphate, the result of many years of mining below the water table. The Triassic strata are typically moderately mineralised and of the Ca-HCO_3 type.

The traditional perception of groundwater availability in Wales is one of insignificant resource potential while being a hazard to the mining communities (e.g. Bassett 1969). Data scarcity is an issue in many areas including the Carboniferous and the hard rock valleys of west Wales (Robins *et al.* 2005). However, the onset of the Water Framework Directive (European Community 2000) has brought new impetus to the understanding of groundwater in Wales as the Directive requires that even the smallest producing aquifers, their physical and chemical status, be reviewed and remedial targets set. There are also several significant innovative groundwater schemes in Wales, including the Clwyd Augmentation/Abstraction scheme (Lambert 1981) and hydrogeological investigations carried out during the development of the Cardiff Bay Barrage (Heathcote *et al.* 2003).

A number of high profile industries have been founded on Welsh groundwater. 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. Nowadays Welsh groundwater is in demand in the form of bottled Natural Mineral Water, and is sold at a price significantly in excess of that of an equivalent volume of petrol or diesel.

This paper provides an overview assessment of the groundwater domains within the stratigraphic column as it is presented in Wales. This assessment provides a platform on which more detailed thematic and domain specific work can stand.

Precambrian and Cambrian

Greenly (1919), in his treatise on the geology of Anglesey, recognised the hydrogeological importance of the contacts between different lithologies in the Precambrian, especially low angle contacts and contacts between dykes and country rock. Remarkably, Greenly also recognised the vulnerability of weathered fracture systems to surface pollutants during field work campaigns he carried out over one hundred years ago.

Groundwater circulation in the Precambrian crystalline rocks is shallow and restricted to short flow paths on a local catchment scale within interconnected fractures. Groundwater storage is modest and spring discharges are often intermittent and responsive to recent rainfall events. Partial cover of till may contain some perched water but generally inhibits rainfall recharge to bedrock. Nevertheless, the Precambrian rocks contain groundwater, and statistical analysis of hydraulic data provides the most appropriate means of comparing the performance of different lithostratigraphic zones in a given area (Banks and Robins 2002). In general this is not carried out in the UK because of insufficient data, but a data set comprising the location, source type and geology of 1775 groundwater sources was collected for the Mona Complex on Anglesey for apparently quite unrelated reasons in the 1970s (Robins and McKenzie, 2005).

The Anglesey data show that spring discharges are, for the most part, typically less than 2 l s^{-1}. Not all of the wells penetrate bedrock, and some shallow wells in till offer prospects of perched water in gritty, moderately permeable horizons, while springs may occur at the contact with bedrock. Blown sand deposits are well drained and unsaturated, and alluvium is generally fine-grained and weakly permeable. The density distribution of the wells tends to concentrate around villages, whereas the distribution of springs is constrained not by social needs but by geology and topography.

There are 3.7 springs and wells per km^2 in north-west Anglesey (Table 1). 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 Mona Complex 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 Mona Complex 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 and the Llandovery which has better than average 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 4.3 wells km^{-2}, but only 1.0 springs km^{-2}, and the New Harbour Group, which has 2.8 wells km^{-2} and 0.7 springs km^{-2}. The presence of distinct foliation in the Gwna Melange Formation and the Church Bay Tuffs and Skerries Grits 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.

Similar hydraulic properties have been reported for the Padarn Ridge to the south of Bangor where young weakly mineralised and chemically immature groundwater reflects short and shallow flowpaths (Welsh Office Agriculture Department 1986) and in the Gwna Melange in Bardsey Island (Webb 2000). 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.

Groundwater occurrence and circulation in the Cambrian sedimentary rocks is much the same as it is in Precambrian. Groundwater is contained largely in the near surface weathered and fractured zone of bedrock which offers little storage potential. Transport is effected via dilated fractures, and flow paths are typically short and shallow and of catchment scale - usually down hill slopes towards valley bottoms. Spring discharges occur where fracture systems intercept the ground surface.

Although there are numerous springs associated with the Cambrian outcrop some are sourced partly, if not entirely, from overlying drift deposits. Detailed engineering investigations were carried out in exploratory boreholes in the Llanberis Slate Formation during the construction of the Dinorwic Pumped Storage Scheme in the 1970s (Robertson 1974). Heat pulse flow logs of two of the boreholes in the valley bottom non-pumping conditions (Fig.3) clearly show upward movement of groundwater from the interception of the lowest active fracture. 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 beneath the floor of the valley and each derived from a higher recharge elevation on the valley side.

Silurian and Ordovician

The diverse lithologies within the Ordovician and Silurian strata in Wales support a range of hydraulic properties. There are many areas in which the strata yield useable quantities of groundwater, for example from the Silurian grits, from which there is usually sufficient groundwater to support domestic and small-scale agricultural uses. Glacial frost shattering has enhanced the near surface permeability of the rock, and tectonic activity has induced discontinuities throughout much of the sequence so that bedding plane fractures, and sub-vertical breaks are commonplace. The boundaries between lithologies and between volcanic facies tend also to be marked by dilated joints sufficient 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 in most areas because effective precipitation is greater than the infiltration capacity of the rock. Flow boundaries may be defined by fracture orientation and distribution of favourable fracture hydraulic conductivity. Dominant fracture orientation may also dictate the preferred groundwater flow direction.

One of the earliest investigations into groundwater occurrence in the Ordovician and Silurian was a reconnaissance study of the Afon Dulas sub-catchment 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 and 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 sub-vertical to 60^o in dip, the main joints are sub-vertical and orientated between 120^o and 140^o, the faults also are sub-vertical. 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^o joint directions; groundwater flow is also constrained by the structure and jointing. The average annual infiltration to the bedrock was calculated as 316 mm or 19% of the effective rainfall, but this is likely to be an overestimate as it disregards soil and scree interflow, short flowpath discharge through the near valley bottom weathered zone and the capacity of the rock to receive recharge.

Two studies have recently been 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 between Lampeter and Cardigan, whereas Hiscock and Paci (2000) concentrated on the more arenaceous deposits of the Rheidol catchment to the north. Both these investigations highlight the interaction between groundwater in bedrock and in the superficial cover particularly along valley bottoms.

Sustainable yields from bedrock in Afon Teifi are low, although adequate for many private uses. Typical sustainable borehole yields are around 0.3 $l\ s^{-1}$; pumping rates of up to 1 $l\ s^{-1}$ invariably dewater boreholes. 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. Boreholes are generally about 40 m deep. The water table is rarely more than 10 m from the surface, irrespective of the ground elevation, but no clear piezometric surface can be created from water level data for boreholes and spring elevations. This reflects the nature of a fractured aquifer beneath relatively steep surface topography, and the existence of perching. Robins *et al.* (2000) estimated that only about 730 $Ml\ a^{-1}$ groundwater is being used in the overall catchment area, mainly drawn from boreholes into bedrock, some in the valley bottoms also drawing on storage in overlying glaciofluvial deposits, given a comparatively large potential renewable resource of 540 $Ml\ a^{-1}$ per km^2 of aquifer.

The contrasting Rheidol catchment, which enters the sea at Aberystwyth, offers more granular and generally more water bearing bedrock than occurs in Teifi (Table 2). The surface waters are polluted by mine water discharge from former metal mining activities, and the stream is regulated for hydropower. Bedrock comprises Silurian Llandovery Series which includes the Aberystwyth Grits Formation, Borth Mudstones Formation and the Devil's Bridge Formation, which Hiscock and Paci (2000) consider to offer better conditions for groundwater occurrence than the three lowermost formations in the Llandovery Series - the Cwmsymlog, Derwenlas and Cwmere formations. This difference also 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.

The overall porosity of the Series is between 2 and 4%. 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 Grit 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. There are 65 sources providing an estimated 3.6 Ml d^{-1}, 29 of the sources are in bedrock and a further ten in superficial deposits over the contact with bedrock.

Haria and Shand (2004) carried out intensive investigations in the Hafren sub-catchment of the upper Severn near Plynlimon. The transect is some 50 by 10 m in area and is perpendicular to the stream and includes boreholes into weathered bedrock as well as soil piezometers. Time series physical and chemical data highlight the role of groundwater in stream flow generation, and key conclusions include:

- Complex system with discrete flow paths in individual (separately 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 contributes significantly to stream flow.
- Groundwater from the less weathered zone to 10 m depth also contributes to stream flow.
- Some upwelling of 'older' groundwater into the soil zone suggests not all soil water is 'young'.
- The stream is always a gaining stream even at low flow, i.e. gaining from groundwater baseflow.

There is also evidence of some deeper groundwater circulation (Fig.4). The saline waters of the spa sources at Llandrindod Wells and around Builth Wells have been a focus of interest since Roman times. 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 groundwater flow paths exist within this area of Ordovician and Silurian strata (Edmunds *et al.* 1998).

The discharge from all the springs, including the nearby Llangammarch Wells and Llanwrtyd Wells sources, are nowadays collectively <1 l s^{-1}. High salinities indicate a slow passage to considerable depth, there being no evaporite or hydrothermal deposits in the area. Stable isotope and radiocarbon evidence suggest the waters are of Late Pleistocene age. The Br/Cl ratio is enriched in the waters reflecting prolonged water-rock contact with the Lower Palaeozoic marine shales to create a Br-rich composition. 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, and the less mineralised waters at Llangamarch and Llanwrytyd 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. Although no other sources of deep circulation in the Lower Palaeozoic aquifers of Wales have so far been discovered, there is every reason that they may exist.

Devonian

Although the Devonian sequence in south-east Wales and Herefordshire 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. Limestone horizons 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 Devonian strata. To these primary lithological controls are added the effects of poor sorting, frequent presence of micaceous material and induration arising from post-diagenetic compaction and burial. Primary porosity in some horizons of the Old Red Sandstone, for instance, is so low that the rock has long been used for flagstones. Associated cementation, 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. The predominant Old Red Sandstone flow mechanism is via fractures, with much of the storage restricted to joint- and fault-related systems. The effective saturated thickness, for most practical purposes, is only about 40 m, beneath which fracture dilation effectively approaches zero. Steep regional hydraulic gradients of 0.01 to 0.1 reflect poor hydraulic conductivities.

Transmissivity values derived from pumping tests lie between 10^{-6} to 350 m^2 d^{-1}, with mean of 11 m^2 d^{-1}. The few storativity values that are available indicate semi-confined to unconfined conditions are predominant, the former created largely by confining in individual fracture sets (Jones *et al.* 2000). The Brownstones Formation and the Senni Beds are the best yielding formations in the Devonian and there are some large springs at the base of the St Maughans Sandstone. The groundwater is usually moderately fresh and tends to have a low electrical conductivity reflecting shallow and rapid groundwater circulation mostly within a local catchment scale.

Carboniferous

Carboniferous Limestone

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 Jones *et al.* (2000). 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. Solution channels may have begun to form along fractures as early as the Mesozoic, but the wetter climes of the Palaeozoic produced most of the swallow holes and caverns, with many later infilled with rubble and detritus in the late and post-Glacial periods. Rapid solution of the limestone is limited to the zone of active circulation which is in contact with the atmosphere, i.e. above the water table, or above the level of passages and caverns into which the phreatic water drains. Fossil karst horizons, now submerged beneath the water table, reflect past changes in base level. 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).

Carboniferous Limestone crops out in North Wales 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. It is also present in Anglesey. 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. This has happened to a lesser extent in Anglesey where mudstone horizons have inhibited the downward percolation of naturally acidic rainwater. The limestone has a low intergranular permeability but substantial groundwater flow is possible through enlarged fissures.

Groundwater flows through the Carboniferous Limestone via fractures and available karst features in an north-easterly direction to discharge to the sea via a flow pattern best described as the 'chessboard and staircase pattern'. Swallow holes are common in the main Carboniferous Limestone outcrop to the east of the Vale of Clwyd. 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. Several streams intermittently sink into the Carboniferous Limestone including the Afon Alyn which is dry on average for 170 days a year between Loggerheads and Rhydymyn above Mold (National Rivers Authority 1993). 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. 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 including the Halkyn Tunnel, 8 km in length across Halkyn Mountain, the Government (War) Drainage Scheme – pumping at 300 $l\ s^{-1}$ into the Halkyn Tunnel and the Milwr Sea Tunnel which was designed to lower the water table in the limestone across the Halkyn Mountain area. The minimum yield is about 20 $m^3\ a^{-1}$ representing runoff from the surrounding hills onto the limestone as well as river water lost to local sinks.

In South Wales the Carboniferous Limestone outcrop is comparatively thin both to the north and east of the South Wales Coalfield. Various attempts have been made to establish the water balance over all or part of the limestone outcrops. Work by Aspinwall & Co (1993) focussed on the Vale of Glamorgan and the capture zones of two public supply sources near Bridgend 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. Aldous (1988) delineated flowpaths and likely transport fields for contaminant movement in the aquifer.

Swallow holes occur at outcrop and beneath a thin cover of the basal beds of the Millstone Grit. On the North Crop there are 80 000 dolines, some of which are nothing more than open fractures (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 Shale Group. In wet conditions it punches up through the shale to emerge above Blaen-Rhymney, and much like a Chalk bourne, creates river flow where normally the bed is dry. There are a number of caverns beneath the North Crop especially around the headwaters of the rivers Tawe and Neath.

There are numerous examples of sinks and risings. 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. The Schwyll spring near Bridgend derives from a variety of sinks on the rivers Ogmore, Ewenny, Alun and Methyr Mawr up to 7 km away (Hobbs 2000).

Although fractures and karstification rapidly decreases under the cover of the Millstone Grit, a small proportion of modern groundwater is transported to considerable depths of burial through the limestone to emerge in the coalfield at Taff's Well. The water chemistry suggests a flowpath up to 700m deep via the Carboniferous Limestone (Squirrell and Downing 1969). Dissolved inert gas analysis suggests the water infiltrated the ground some 500m higher in elevation than Taff's Well, most probably along the North Crop (Edmunds 1986).

Water quality in the limestones is typified by slightly alkaline pH up to 7.6, and alkalinity concentrations ranging upwards to 230 mg l^{-1}. The lower values reflect immature waters that have not attained Ca saturation. In North Wales, local mineralization 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 (e.g. the Schwyll Spring) and a marine mixing zone in selected fractures is indicated by enhanced concentrations of Na at some sources.

The Millstone Grit

The Millstone Grit is thickest in North Wales 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.

In South Wales, the Millstone Grit forms a relatively thin horizon at the base of the Coal Measures. The dominant lithology is fine-grained shales and mudstones which tend to act as a barrier between the Carboniferous Limestone and the overlying Coal Measures. Borehole yields are small, typically only a few l s^{-1}, although occasional higher yields have been found where boreholes intersect an open fracture system.

The Coal Measures

The Coal Measures crop out in North Wales 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. 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.

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

The hydrogeology of the Coal Measures in the South Wales Coalfield was first described by Ineson (1967) and later revisited by Rae (1978). The general hydrogeological character of the Coal Measures Formations are low permeability hydrogeological units composed of carbonaceous mudstones and sandstones with subordinate siltstones and coal seams. The Upper Pennant measures are dominated by sandstone while the Lower and Middle Coal Measure 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 1m 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.

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 deep anthracite field, although rising to the north and the Black Mountains, and a higher area to the east, over the relatively shallow bituminous coals, where topographic divides rise to over 600 m elevation (Fig.5).

There is little vertical flow along faults throughout the Coal Measures sequence, although flow from the shallower sandstones did manage to penetrate some of the deeper mines. The coal mines of South Wales were notoriously wet, requiring 8 tonnes of water to be pumped on average for every tonne of coal recovered. However, Rae (1978) reported that this figure may be misleading as 30% of the South Wales mines pumped at <4 ls^{-1}, a further 40% <20 l s^{-1} and only 15% were very wet mines which required to pump at discharges >50 l s^{-1}.

Water inrushes in collieries in the northern and eastern margins of the coalfield were a problem. 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 critical. Initial flows were typically between 50 and 80 $l\ s^{-1}$, exceptionally 200 $l\ s^{-1}$ but they generally declined rapidly, although a few inrushes stabilised with yields as high as 30 $l\ s^{-1}$, reflecting significant local fracture storage. In the eastern part of the coalfield the thickness below the lowest worked seams and underlying sandstones in the Lower Coal Measures and the Millstone Grit can be as little as 10 m, and floor bursts were not uncommon.

Robins *et al.* (in press) have compared the available piezometry for the coalfield when it was heavily pumped in the 1970s against the contemporary post-mining piezometry and found little difference. This is because the mine pumping only affected a small area around each mine or group of interconnected mines due to the high hydraulic gradients towards the mines, a feature caused by the low overall hydraulic conductivity of the Coal Measures formations. The hydraulic interconnection between mine workings defines a set of discrete ‘ponds’ with much of the shallow eastern coalfield distributed between eight hydraulically isolated systems, i.e. ponds in which abstraction in one mine ultimately affects levels in adjacent mines within the same pond. In the deeper coalfield to the west of the Neath Disturbance the pond effect appears to be lessoned 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, and that the controlling hydraulic barriers within the eastern part of the coalfield are all topographical divides.

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 recharge and runoff from effective precipitation on the Coal Measures to be 988 mm or 2100 $Mm^3\ a^{-1}$ but did not attempt to separate baseflow and runoff. 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 but managed mines	= 25 $Mm^3\ a^{-1}$

Baseflow Indices derived from low flow calculations (CEH/BGS 2003) allow an approximate separation of runoff. Baseflow Indices for the major rivers traversing the coalfield are 0.48, suggesting that some 48% of Rae’s total outflow leaves as baseflow, 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 overall water balance for the area of the coalfield approximates to:

Rainfall	=	Evaporation	+	runoff	+	recharge
1500 mm	=	500 mm	+	520 mm	+	480 mm

Upwelling of groundwater from the Carboniferous Limestone is probable in places but is a small component of the overall regional water balance.

The groundwater in the Coal Measures in South Wales 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, which are common in the English and Scottish coalfields, are notably absent in South Wales. The Upper Coal Measures are typically Ca-HCO_3 type. In the argillaceous horizons Ca and Mn rich groundwaters occur near outcrop with salinity increasing down dip.

Triassic

The Triassic sandstone aquifer in the Vale of Clwyd is situated in a small grabben some 5 km wide. There are Silurian strata to the east, south and west, and Carboniferous Limestone also beneath and to the north of the sandstone. The sandstone is concealed by up to 80 m of glacial till, and some fluvio-glacial gravel material. The main aquifer is in the Ruthin and Denbigh area (Fig.6) in which the central part of the aquifer was originally confined by till with an artesian head of about 6 m (Anon. 1973). Transmissivity was estimated to be between 800 and 2000 m^2 d^{-1} and storativity between 10^{-3} and 10^{-4}. Millstone Grit crops 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}, including Ffynnon Asaph which flows at 4.3 Ml d^{-1} which traditionally supplied the town of Prestatyn (Lambert 1981).

Boreholes at Llanerch, near St Asaph, confirmed 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 river augmentation in order to maintain a prescribed minimum flow for the benefit of fisheries in the River Clwyd. Direct rainfall recharge occurs to the sandstone aquifer via the gravel deposits and from cross-flow derived from the adjacent Carboniferous Limestone aquifer.

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

Quaternary

The Quaternary deposits of Wales include a variety of tills, both according to their depositional history and their lithology, and a complex array of fluvio-glacial sands and gravels as well as Recent alluvial and lacustrine material. There are also several coastal dunelands (e.g. Fig.7) and there are significant domed peats, such as Tregaron in the upper Teifi catchment in west Wales, which are groundwater dependent. The granular superficial deposits form shallow aquifers in low-lying areas such as valley bottoms. The geometry of these deposits and the juxtaposition of less permeable material is generally complex, but these shallow aquifers act as receivers for overland flow and soil interflow which transport water laterally down the valley sides as well as longitudinally ~~down~~ along the valley bottoms. The deposits may have a complicated interrelationship with surface waters whereby they gain from rivers in some reaches and lo~~o~~se in others.

Resource potential is generally limited, but exceptionally in the Rheidol, Teifi, Dyfi and Tywi catchments in west Wales, higher yields have been developed for public supply, notably the Lovesgove boreholes near Aberystwyth in the Rheidol catchment which yield 3.5 Ml d^{-1} from a formation which has a transmissivity of between 4000 and 6000 $m^2 d^{-1}$. 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 wellbeing of many small rural communities, notably in central and west Wales.

The Quaternary 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 an open hole into bedrock. This is a convenient construction procedure for percussion drillers and also some rotary 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 longer periods of dry weather. These sources are, however, vulnerable to surface pollutants as rainfall recharge can penetrate rapidly to bedrock carrying with it materials spilled on the ground such as fuel and agricultural chemicals.

Issues and the future

A number of groundwater related issues need to be dealt with in Wales in the near- to medium-term future. The ongoing problem of contaminated land and pollution of groundwater from past primary and secondary industries is being tackled head on and will need to continue to be addressed until the quality and quantity status targets, for both groundwater bodies and their respective surface water receptors, are achieved as prescribed by the Water Framework Directive. Acid mine drainage issues were identified at an early stage in South Wales and engineered remediation of many sites has been implemented successfully.

Extreme events and climate change continue to cause concern. Although flood risk is normally associated with surface water flow, groundwater flooding does occur in aquifers in which the water table can rise above the ground surface. This is more particularly a problem in the Chalk of southern England, but was also a key factor in the Oxford city floods in July and August 2007. The widespread flat glacial valley floors characteristic of central and northern Wales which contain fluvial sands and gravels are at risk of flooding due to elevated water tables caused by high volume bank-side storage and intense direct rainfall recharge. Such areas need to be identified in order that structures are not placed at risk. Intense rainfall may also destabilise landforms, man made and others, and drainage systems need to be devised to maintain slopes below their critical threshold.

Future development of the South Wales Coalfield needs to include careful evaluation of the groundwater regime. Prospects for in situ gasification of the deeper coals and of opencast working of the shallower bituminous coals needs to be planned for least impact on both groundwater quality and groundwater baseflow discharge to surface waters.

Groundwater will continue to be an important asset in Wales for public and private supply, albeit of relatively small volume compared to surface water, but nevertheless critically important in terms of its social and economic values. Groundwater systems need to be maintained in order to safeguard groundwater dependent ecosystems and habitat. The role of the regulator, Environment Agency Wales, and of stakeholder agencies such as the Countryside Council for Wales has never been more important. Public awareness of the issues and the proposed solutions is an important component of their work, both through education in schools and through participatory activities and involvement in planning.

The future must also allow a detailed systematic evaluation of the groundwater systems in Wales to be carried out in order to support the planning processes. A number of technical uncertainties remain outstanding, the most significant being an improved understanding of the processes controlling shallow groundwater flow and baseflow discharge in upland hard rock catchments. As yet the low flow or baseflow indices for many upland catchments in Wales are available for analytical uses, but are suspiciously high, and these values need to be resolved before useful and detailed catchment modelling can be carried out.

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TABLE 1 Density of wells and springs in the Precambrian of north-west Anglesey (after Robins & McKenzie 2005)

Formation	**Wells per km^2**	**Springs per km^2**
South Stack Group	4.3	1.0
New Harbour Group	2.8	0.7
Holyhead Quartzite Fm	1.2	0
Gwna Melange Fm	3.0	1.1
Church Bay Tuffs	3.4	0.9
Shear Zones	2.0	1.2
Coedana Complex	2.3	1.6
Coedana Granite	2.6	1.3

TABLE 2 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 (baseflow separation)	753 (baseflow separation)
Runoff	459	667
Baseflow	540	363
Groundwater abstraction	Small	7

FIGURES

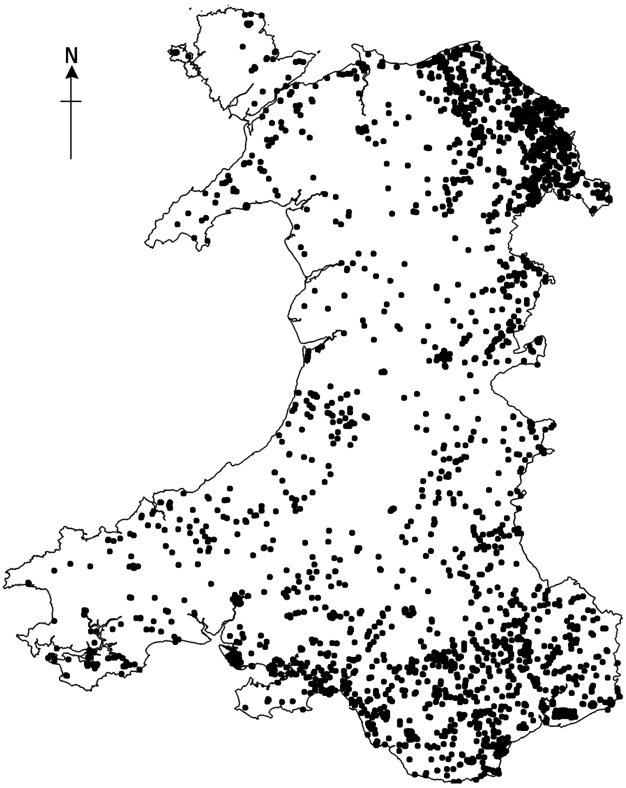

Fig 1 Distribution of water boreholes and springs in Wales from British Geological Survey Wellmaster database

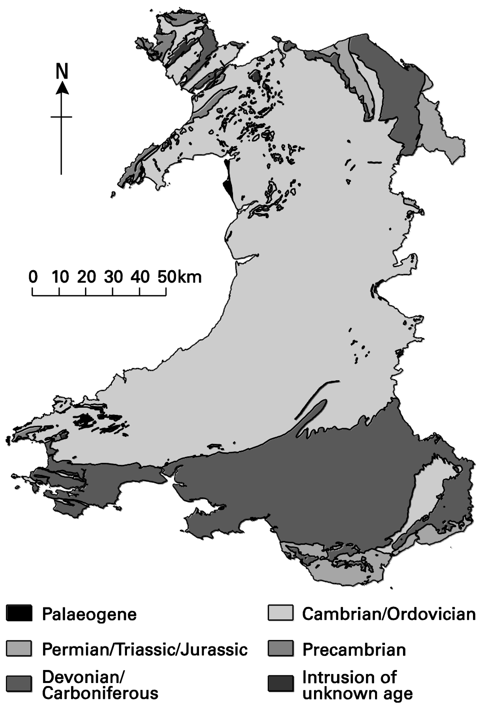

Fig. 2 Outline geology of Wales

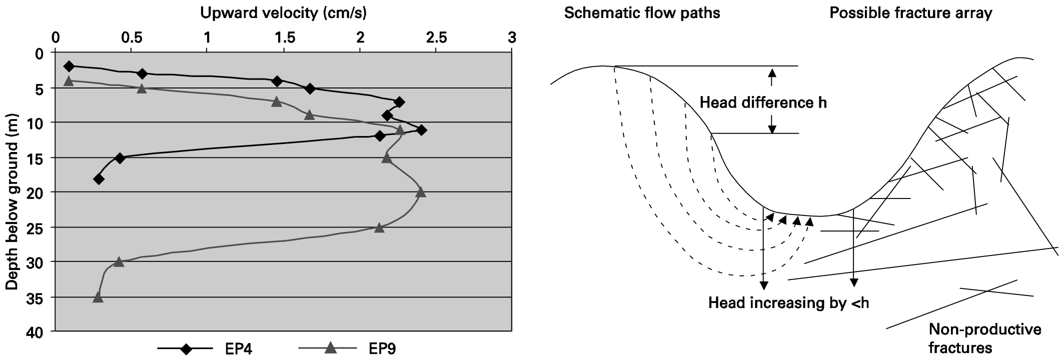

Fig. 3 Heat pulse flow logs in boreholes at Dinorwic with schematic flow regime in fracture shale environment

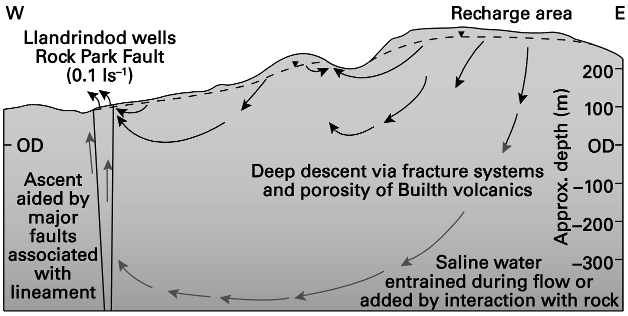

Fig. 4 Probable groundwater flow system beneath Llandrindod Wells (after Edmunds *et al.* 1998)

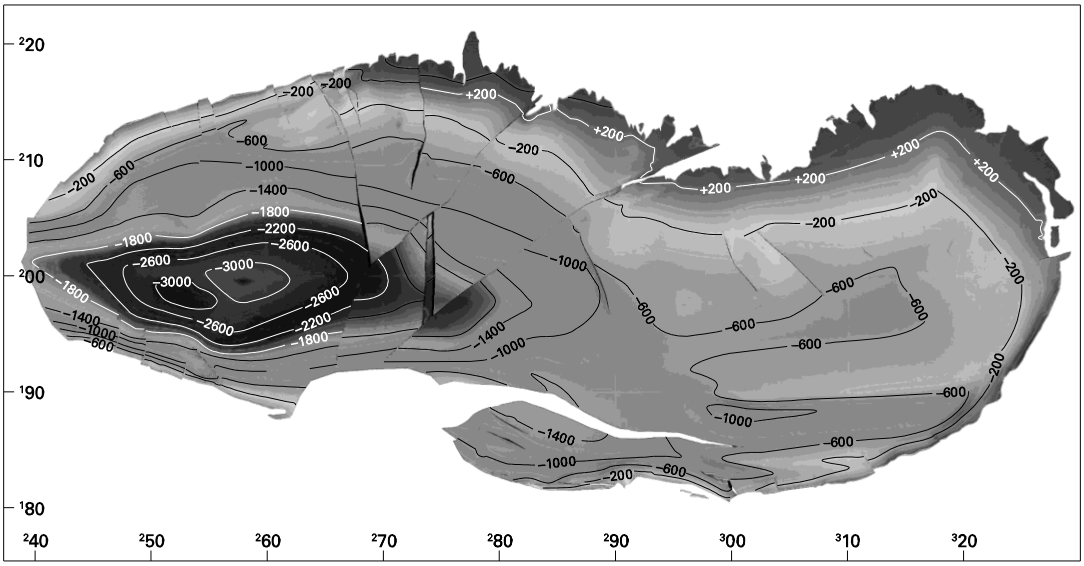

Fig 5. Output from 3-D model of the South Wales Coalfield showing the outline structure and the thinner bituminous coal deposits to the east and the thicker anthracite coals to the west

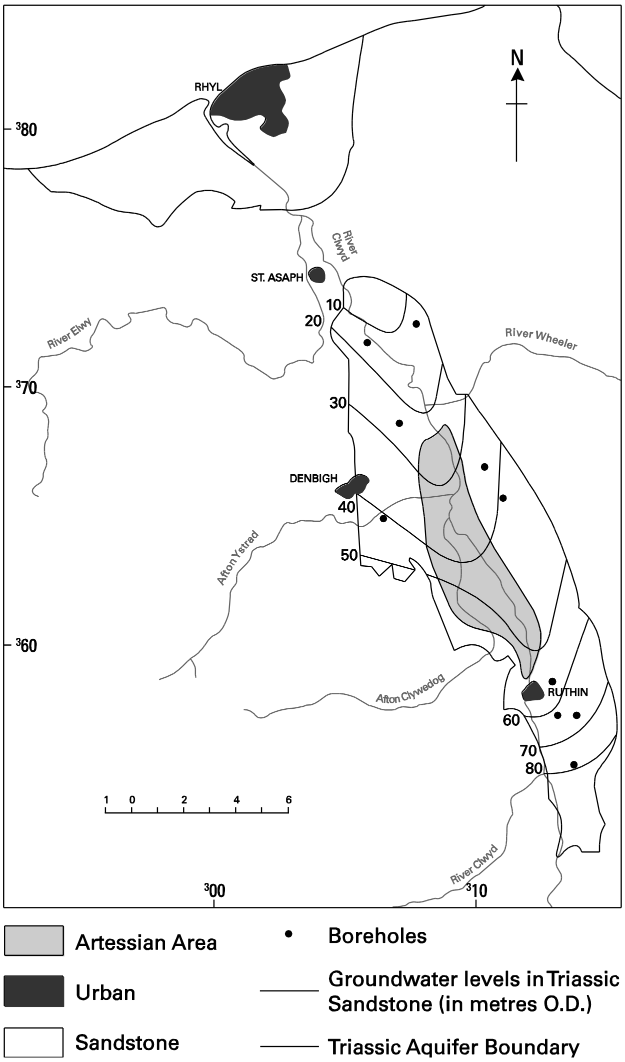

Fig. 6 The Triassic aquifer in the Vale of Clwyd

Fig 7. Groundwater baseflow from blown sand over till on the banks of the tidal Afon Braint, Newborough Warren, Anglesey