# FRACTURE FLOW AND PREFERENTIAL GROUNDWATER FLOW PATHS IN HARD ROCKS – ILLUSTRATIONS FROM PRECAMBRIAN AND LOWER PALAEOZOIC STRATA IN WALES

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## ABSTRACT

*Groundwater in the Lower Palaeozoic and Precambrian hard rocks is mainly constrained to limited storage and circulation in an upper weathered and fractured zone. Some deeper circulation via favourable fractures is possible and there may be hydraulic connection with storage in Quaternary gravels and with surface waters. Examples from Wales illustrate some of the features typical of the small aquifer units that occur in these hard rocks and provide some of the methodologies that have been attempted in understanding groundwater recharge, storage and transport on a catchment scale.*

## 1.0 INTRODUCTION

Groundwater is generally abundant in most areas of basement rocks (Lower Palaeozoic and older) despite the perception that these strata are supposed to be dry. Yields are generally small, typically only about 1 to 3 l $s^{-1}$, and baseline quality is good, as the waters are young and weakly mineralised, but vulnerability to pollution is generally high, although the pollution risk may be small in some upland areas. The stratigraphical sequence in Wales extends from the Precambrian through to recent deposits and offers a useful region with which to illustrate some of the more common features of hard rock hydrogeology. The oldest rocks occur in the north of Wales and are mainly metamorphic and igneous Precambrian and Cambrian rocks. Central Wales is dominated by Lower Palaeozoic sediments (Ordovician and Silurian), which occur from the south-west to the north-east of Wales. Soil cover is typically thin, particularly in parts of Snowdonia where exposed bedrock outcrops over large areas. Till and associated glacial deposits are widespread on the lower-lying ground but tend to be absent in many upland areas. Alluvium occurs in many valleys and there are large groundwater dependent peat bogs.

The basement rocks have a low primary porosity and permeability, although many have some secondary fracture permeability and porosity. Depth of weathering tends to be shallow especially on valley sides where glacial erosion has removed weathering products. Groundwater occurs in a shallow weakly permeable aquifer that is capable of maintaining rural domestic and limited agricultural and industrial demand. Characteristic features of these shallow weathered aquifers are summarised in Table 1.

Wales enjoys a maritime climate, typically receiving over 1000 mm per year, seasonally biased towards the winter months. The distribution of rainfall varies, with the highest average annual totals approaching 3000 mm in the mountainous areas of Snowdonia and the Brecon Beacons.

## 2.0 GROUNDWATER OCCURRENCE EXAMPLES

### 2.1 THE PRECAMBRIAN

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 rocks and between 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 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 conventional hydraulic theory may not apply. Nevertheless, the ancient hard rocks do contain groundwater, and it is a resource which is often under-used in Britain although it has been widely developed in areas such as Scandinavia (Banks and Robins, 2002). Yields from springs, wells and boreholes are generally small; aquifer properties are not easy to evaluate.

### 2.1.1 A statistical approach in Anglesey

Statistical analysis of hydraulic data provides the most appropriate means of comparing the performance of different lithostratigraphic zones in a given area. In general this is not carried out in the UK because of insufficient data, but a data set that was collected for the Mona Complex on Anglesey for apparently quite unrelated reasons in the 1970s has allowed such an analysis (Robins and McKenzie, 2005). The well and spring data set 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 lithostratigraphic contact.

**Table 1** Groundwater occurrence in basement rocks (after Robins, 1999)

| Occurrence | Description | Example |
|---|---|---|
| Shallow groundwater circulation | Groundwater are young, weakly mineralised and derive from local recharge area in a catchment scale | Much of upland Wales |
| Perched groundwater | Common where two or more hydraulically independent fracture systems occur, or where granular drift and bedrock are hydraulically separated – tends to issue as wet weather springs | Much of West Wales |
| Confined fracture flow | A fracture fed from a phreatic zone at a relatively high elevation in a catchment | The confining head tends to increase with depth beneath valley bottom (Figure 2) |
| Non-sustainable supplies | Water bearing fracture which is not in good hydraulic contact with a recharge source | Common upland feature |
| Preferred flow paths | Lines of weakness which may parallel major tectonic features and stress release features such as dominant fracture orientation. | Dominant fracture orientation, e.g. Dyfi (Glendining, 1981) |
| Drift aquifer storage | Groundwater in valley gravels contributes to overall storage in fractured bedrock wherever there is hydraulic continuity. | Afon Teifi (Robins et al., 2000) Rheidol (Hiscock & Paci, 2000) |
| Regolith storage | Granular weathering that offers high storage but removed under glacial ice | Not in Wales, but can be seen in Cornwall and the Channel Isles |
| Deep groundwater circulation | Uncommon except where deep fracture systems link recharge and discharge zones. | The saline spa waters at Llandrindod Wells (Edmunds et al., 1998) |
| Springs | Wherever a water bearing fracture intercepts ground surface. | Upland valley sides |

**Table 2** Distribution of springs and wells in the Precambrian Mona Complex, north-east Anglesey (after Robins and McKenzie, 2005)

| Formation | Outcrop area ($km^2$) | Number of wells | Number of springs | Wells $Km^{-2}$ | Springs $km^{-2}$ |
|---|---|---|---|---|---|
| South Stack Group | 18 | 77 | 18 | 4.3 | 1.0 |
| New Harbour Group | 133 | 373 | 92 | 2.8 | 0.7 |
| Holyhead Quartzite Formation | 3 | 3 | 0 | 1.2 | 0.0 |
| Gwna Melange Formation | 61 | 183 | 66 | 3.0 | 1.1 |
| Church Bay Tuffs and Skerries Grits | 13 | 45 | 12 | 3.4 | 0.9 |
| Central Anglesey Shear Zone and Berw Shear Zone | 28 | 58 | 33 | 2.0 | 1.2 |
| Coedana Complex | 38 | 88 | 61 | 2.3 | 1.6 |
| Coedana Granite | 29 | 76 | 37 | 2.6 | 1.3 |

Spring discharges from the basement rocks in north-west Anglesey and Holyhead Island are, for the most part, small, typically less than 2 l $s^{-1}$. Analysis of the density distribution of both springs and wells for each bedrock formation is given in Table 2. The data include those wells and springs that derive 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, therefore, dominantly reflect changes in bedrock properties, the Quaternary properties being areally consistent.

There are 3.7 springs and wells per $km^2$ in north-west Anglesey. 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 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.

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.

## 2.2 THE CAMBRIAN

Groundwater occurrence and circulation in the Cambrian rocks, which are largely sedimentary in origin, is much the same as in the Precambrian. Groundwater is contained largely in the near surface weathered and fractured zone which offers little storage potential with transport confined to dilated joints and fractures. Flow paths are typically short and shallow and of catchment scale. Spring discharges occur where fracture systems intercept the surface and along valley bottoms to provide baseflow to surface waters. Steep topography over much of the Cambrian outcrop provides additional transport of 'groundwater' via soil or scree interflow; consequently Base Flow Indices may be misleading in such terrain. Although there are numerous springs associated with the Cambrian outcrop some are sourced partly from overlying superficial deposits.

### 2.2.1 Flowlogs at Dinorwic

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 measured under non-pumping conditions are shown in Figure 1. These clearly show upward movement of groundwater from the interception of the lowest active fracture in each borehole EP4 and EP9, both situated in the valley bottom. 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 2). By contrast, exploratory boreholes EP5 and EP7 in the same vicinity were static throughout the borehole column.

Boreholes EP4 and EP7 were also flow logged during pumping at 2 l $s^{-1}$. The work showed that all the pumped water in EP4 derives from the uppermost 15 m of the borehole, reflecting the location of active fractures seen in the static log (Figure 1). Borehole EP7, which showed no upward transport of water in the non-pumped state, revealed a production zone between 4 and 10 m below ground level, again indicative of shallow groundwater circulation. Pumping was only maintained for brief periods at Dinorwic and sustainable yields are likely to be considerably less than the recorded 2 l $s^{-1}$.

**Figure 1** Flow meter logs at Dinorwic

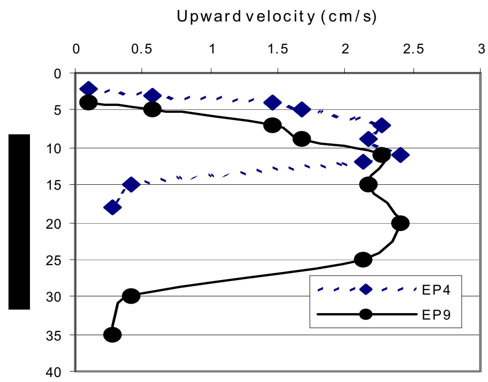
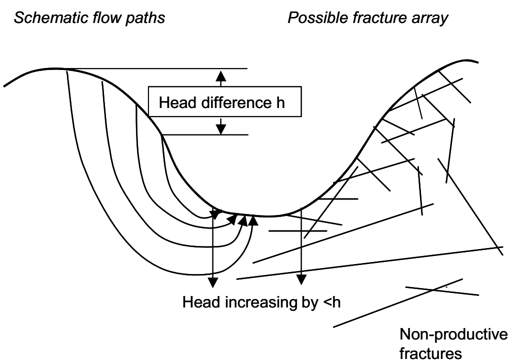



**Figure 2** Schematic valley cross section




2.3 THE ORDOVICIAN AND SILURIAN

The diverse lithologies that are present in the Ordovician and Silurian in Wales exhibit a range of hydraulic properties. This diversity contrasts with southern Scotland and south-east Northern Ireland where the dominant lithologies are greywacke sandstone, siltstone and mudstone, and the strata are described as weakly permeable and capable only of supporting isolated springs and shallow wells (Robins, 1999). In Wales, some of the Ordovician and Silurian strata are also weakly permeable and do not form a useable aquifer, but there are other areas in which the strata are relatively productive.

The degree of glaciation was also significantly less in Wales (except for Snowdonia) than it was in north Britain. Consequently, the removal of the weathered zone by the ice sheets was less effective and the weathered and fractured uppermost layer of rock is partly preserved in Wales. In some areas the effects of glacial frost shattering enhances the near surface permeability of the rock. Tectonic activity has induced discontinuities throughout much of the Welsh sequence and 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. Flow boundaries may be controlled by fracture orientation which dictates the preferred groundwater flow direction. Significant groundwater storage, however, tends to be restricted to the coarser arenaceous deposits. In general, the water table tends to be shallow in most areas.

**2.3.1 Analysis of the upland Afon Dulas sub-catchment**

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. The superficial cover includes head and scree deposits, peat and valley alluvium. The cleavage planes trend north-easterly and are sub-vertical to 60° in dip, the main joints are normally vertical and are orientated between 120° and 140°, 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.

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. Baseflow separation of the catchment runoff 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. The effective rainfall over bedrock was divided between the amount needed to make up the overall baseflow from the catchment plus the runoff (Table 3), i.e. bedrock baseflow was calculated from the total baseflow, derived from baseflow separation estimate, minus the alluvium baseflow. Again it assumed that baseflow equals infiltration in the long term. This shows (Table 3) that the average annual infiltration to the bedrock is 316 mm or 19% of the effective rainfall (against 1685 mm or 100% to the alluvium). 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 accept recharge.

The Glendining (1981) study assigns percentage flow to shallow, intermediate and deep flow paths and uses estimates of hydraulic gradients for each flow path to enable the overall hydraulic conductivity for the rock mass to be calculated. The value is of the order $10^{-3}$ m $d^{-1}$, however, the near surface weathered zone may be of the order 1 m $d^{-1}$.

**Table 3** Effective infiltration (equal to baseflow) divided between alluvium and bedrock in the Afon Dulas catchment (after Glendining, 1981)

| Year | Total flow (mm) | Baseflow (mm) | Effective rainfall (mm) | Alluvium (15 $km^2$) infiltration $m^3 \times 10^6$ | Bedrock infiltration (456 $km^2$) infiltration $m^3 \times 10^6$ | 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 |

### 2.3.2 Groundwater on a catchment scale

Robins et al., (2000) investigated the occurrence of groundwater in the Silurian and Ordovician rocks of the Teifi valley, and 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 shales and slates of Ordovician and Silurian age. Springs are common and issue primarily from discontinuities 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 fractures are in hydraulic contact with overlying superficial deposits which possess intergranular storage, these occur in some valley bottom areas.

Sustainable yields from bedrock are low, although adequate for many private uses. Typical sustainable borehole yields are around 0.3 l $s^{-1}$. 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; exceptions include one borehole which is 140 m deep. Short duration pumping tests indicated transmissivity of the order 5 x $10^{-1}$ $m^2$ $d^{-1}$, but complicated by the presence of boundary conditions and dewatering of shallow fractures during tests.

The water level is rarely more than 10 m from the surface, irrespective of the ground elevation. 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, where perching is common. A best estimate of the quantity of groundwater abstracted from the catchment (based on data collected by the Environmental Health Departments (Table 4) suggests that less than 2 Ml $d^{-1}$ groundwater is being used in the catchment area.

**Table 4** Groundwater consumption in the Teifi catchment (principally from bedrock) excluding the Alwen public supply source which draws from superficial gravels

| | 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 (622 Ml $a^{-1}$) |

Runoff and potential evaporation exceed precipitation, but runoff (river flow) includes groundwater baseflow (infiltration). As the Base Flow Index is 0.54 and the long term average annual runoff near the base of the catchment is 999 mm (CEH/BGS, 2000), about 540 mm derives from groundwater discharge, the majority of this from valley bottom alluvial deposits. This represents a renewable resource of 540 Ml $a^{-1}$ per square kilometre of aquifer, a large value by comparison to the estimated 622 Ml $a^{-1}$ withdrawn from all the boreholes, wells and spring discharges throughout the whole catchment.

Using a transmissivity value of 0.6 $m^2$ $d^{-1}$ (from pumping test analysis), 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 Darcy's Law indicates that the overall throughflow along the length of the valley is 25 $m^3$ $d^{-1}$ or only 9 Ml $a^{-1}$. This is a small amount compared to the total estimated baseflow (540 Ml per square kilometre of aquifer) and it shows that the majority of the baseflow component of river flow derives from local recharge and discharge via flow paths perpendicular to the valley sides, 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 baseflow indices.

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 more 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, and stream regulation for hydropower. The bedrock comprises Silurian grits and shales, of which the uppermost formations 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 Silurian formations coupled with occurrence of sandstones in the upper part of the sequence.

The overall porosity is between 2 and 4%. The depth of weathering is up to 20 m, and brick lined pits have been effectively used to capture springs and divert shallow groundwater flow to gravity fed systems for domestic usage, although 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.

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 ten are in superficial deposits in contact with bedrock. The estimated water balance for the catchment using an evapotranspiration value based on baseflow separation and a Base Flow Index of 0.51 is shown in Table 5.

**Table 5** 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 |

### 2.3.3 Deep circulation to the Central Wales Spas

There is evidence of some deep groundwater circulation in Central Wales. The saline waters of the spa sources in the Llandrindod and Builth Wells area of Central Wales have been a focus of interest since Roman times. The Builth Inlier is characterised by weakly permeable metasedimentary and volcanic rocks with a deeper than normal fracture system associated with the north-westerly trending Tywi 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 the Ordovician and Silurian strata (Edmunds et al., 1998).

The discharge from all the springs including sources at nearby Llangamarch and Llanwrytyd 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.

### 2.3.4 Hydrochemical indicators in the Wye Valley

Investigation of local scale transport process in the Upper Severn catchment at Plynlimon provides further insight into the hydraulics of upland hard rock catchments. This work specifically tackles the issue concerning the role of groundwater in sustaining baseflow and its important contribution to storm flow as demonstrated by isotopic indicators analysed for groundwater and surface water during dry and during rainfall events. 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), and isotopic evidence shows that the stream waters lie on a mixing line between groundwaters and rainfall.

Haria and Shand (2004) have carried out intensive investigations in a 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. The time series physical and chemical data highlight the role of groundwater in stream flow generation. Key conclusions are that the upper 1.5 m saturated weathered zone contributes significantly to baseflow with the less weathered zone to 10 m depth also active. It is a complex system with discrete flow paths in individual (confined) fractures which mix at the valley bottom. Although discharge responds rapidly to rainfall some older upwelling water is included in the baseflow.

## 3.0 CONCLUSIONS

Groundwater occurrence in shallow fractured aquifers of Wales is characterised by catchment scale aquifer units, short and shallow flow paths dictated by fracture availability and direction, and complex inter-relationships with superficial strata and surface waters. Recharge to these aquifer units is not easy to determine. The groundwater resource potential is modest, but groundwater provides a useful social asset to many rural communities in Wales, and baseflow sustains upland stream low flows.

## 4.0 ACKNOWLEDGEMENT

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