Hydrogeology of Wales: Carboniferous aquifers - the Carboniferous Limestone aquifer

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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.

Karstic Avon Group strata at Mynydd Llangattog. P802429.

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).

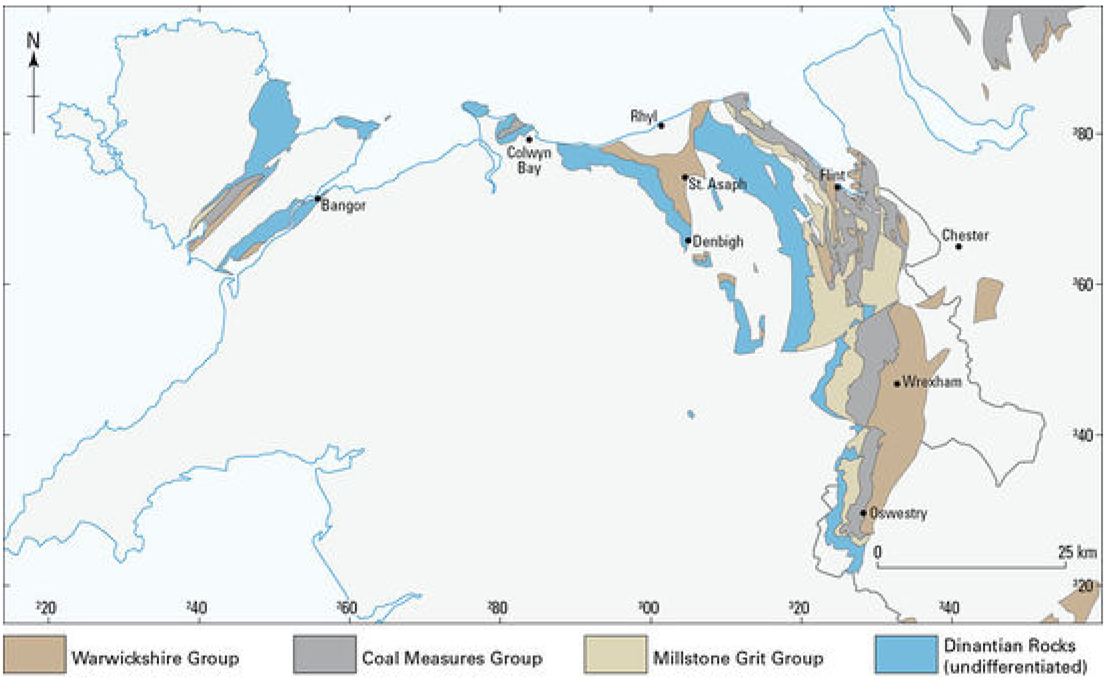
Speleogenesis is the origin and development of caves, the primary process that determines the evolution of karst features. The development of caves through limestone is caused by water circulation with carbon dioxide dissolved within it, producing carbonic acid which permits the dissociation of the calcium carbonate 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

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.

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.

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}.

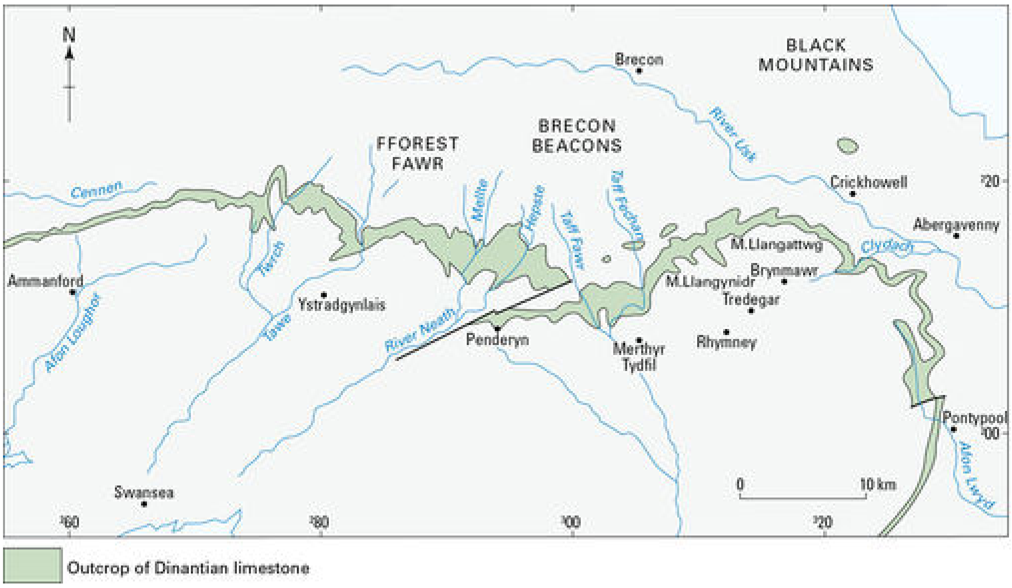
Llangattwg	SO 21	Dye tracing has proved relationship between a series of sinks and risings.
Mynydd Llangynidr	SO 21	The main resurgence is Fynnon Shon Sheffrey [SO 1265 1188]. Dye tracing has proved the relationship between various sinks and risings (**Figure 5.2**).
The Rhymney Valley	SO 01	Dye tracing 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 °C, the only thermal spring in Wales (**Farr and Bottrell, 2013** . Previous measurements reported a variety of temperatures all less than 20 °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**).

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