Natural Resources Wales' monitoring networks for groundwater level and quality

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Introduction

Natural Resources Wales, which was formed in April 2013, has taken over the functions of the Countryside Council for Wales, Environment Agency Wales and Forestry Commission Wales, as well as some functions of Welsh Government. Its purpose is to ensure that the natural resources of Wales are sustainably maintained, enhanced and used, now and in the future. This includes ensuring that the quality of groundwater, surface water and coastal waters continues to improve.

In Wales, groundwater only contributes around 3% of the total public water supply **(Environment Agency, 2008a)**. However, it is still an important resource in rural areas where records held by local authorities identify at least 21,000 private water supplies, typically comprising shallow wells, boreholes and spring sources. Groundwater also provides baseflow to rivers and groundwater dependent wetlands. Therefore it is important that sufficient data is available to understand, manage, protect, forecast and report on the quality and availability of groundwater.

Since 2000 the Water Framework Directive (2000/60/EC) (WFD) has been the key driver for monitoring groundwater levels and quality. The data that is collected is used to define the status of groundwater in both quantitative and chemical terms as either 'good' or 'poor'. Data is also needed to inform decisions on groundwater protection, abstraction licensing, groundwater modelling and other local investigations.

To comply with European and national legislation and meet the needs of internal and external customers Natural Resources Wales has developed groundwater level and groundwater quality monitoring networks. Groundwater levels are monitored at 140 sites **(Fig.1)** and groundwater quality at 250 sites **(Fig.2)** across Wales. The day to day management of these networks is the responsibility of the Geoscience Team within Natural Resources Wales based in Cardiff.

Groundwater Level Monitoring Network

History

The origins of the groundwater level monitoring network lie with the Water Resources Act 1963 whose primary purpose was to support the management of groundwater abstraction for public water supply. Boreholes were installed into the high yielding Carboniferous Limestone aquifers across south Wales, and Permo-Triassic sandstone aquifers in the Vale of Clwyd and Dee Valley in north east Wales. These aquifers are classed as 'Principal Aquifers' as they can support water supply and/or river base flow on a strategic scale.

Since then the network has expanded to provide data on groundwater levels in other aquifers in Wales, primarily in response to the requirements of European legislation such as the Habitats Directive (92/43/EEC) and Water Framework Directive and internal organisational initiatives such as Catchment Abstraction Management Strategies (CAMS), which are used to assess the availability of water in a particular catchment (**Environment Agency, 2010**).

What is the network?

It comprises a mixture of privately owned and purpose-drilled boreholes. The oldest sites became part of the Regional Water Authorities in 1974, and were subsequently passed to the National Rivers Authority in 1989. These sites became the responsibility of the Environment Agency on its creation in 1996, and passed to Natural Resources Wales on its formation in 2013. Sites consisted of either investigation boreholes installed to explore the resource potential of a particular aquifer or observation boreholes associated with public abstraction boreholes.

Over the past 15 years new sites have consisted of purpose-drilled boreholes (**Fig.3**) on land leased to Natural Resources Wales, or more typically on Local Authority highway verges which provided easier access for drilling and ongoing monitoring. Boreholes were designed to have a finished diameter of between 150-200mm to allow for the installation of a pump for water quality sampling and pump testing to allow aquifer properties to be determined. In some instances the boreholes were completed as a dual-installation consisting of two 50 mm piezometers to allow the monitoring of groundwater

levels either in two geological horizons within the same aquifer or in the bedrock and overlying superficial deposits.

In 1994 the network was expanded into the Devonian Old Red Sandstone of the Lower Wye and Usk Valleys. The sandstones and mudstones in this area, whilst classed as Secondary 'A' Aquifers are heavily abstracted locally for agricultural use, particularly for the spray irrigation of crops. Secondary 'A' Aquifers are permeable strata capable of supporting water supplies at a local rather than strategic scale and can form an important source of baseflow to rivers. Between 1995 and 2000 boreholes were installed into the Carboniferous Limestone and Permo-Triassic sandstone to provide more data to improve the conceptual understanding of these aquifers. Since 2000 monitoring boreholes have been installed into Secondary 'A' and 'B' Aquifers of the Silurian mudstones in the Teifi, Aeron and Ystwyth catchments in order to improve the hydrogeological understanding of these areas for CAMS.

There are still areas of Wales where the number of groundwater monitoring sites are low, particularly in mid-Wales, the Conwy Valley, and Gwynedd. These consist of areas of Silurian, Ordovician and older strata which were historically considered to be 'non-aquifers' but which have now been re-classified as Secondary 'B' Aquifers. Despite their relatively low permeability, storage and yield these aquifers can still be important locally for domestic use where mains water is unavailable. Water yields are dependent on the existence of geological features such as fissures and joints, the extent of permeable horizons and the degree of weathering in the rock strata.

Groundwater resources available in these aquifers are not heavily exploited for public supply, there are no known impacts to river baseflow or groundwater dependent wetlands and it is unlikely that the network will undergo further significant expansion. If groundwater level data is required for a particular project, reliance would be placed on collecting data from third party owned boreholes, wells and springs rather than drilling new boreholes.

Whilst groundwater level monitoring sites are now located across a number of different aquifers in Wales it is worth noting that 67 of the 140 boreholes are installed into the two Principal Aquifers in Wales, the Carboniferous Limestone and Permo-Triassic sandstone.

Requirements for monitoring sites

To understand the way a hydrogeological system works and hence develop a good conceptual understanding, groundwater level data should be available from enough locations within the aquifer. As a minimum this should comprise monitoring boreholes in the recharge, flow path and discharge areas of each aquifer. In practice however, this would create a large and financially unsustainable network. Therefore, a risk based approach to the selection of sites focussed on monitoring aquifers which are exploited for public water supply, have known problems with over-abstraction or where data is needed to respond to future pressures like a changing climate.

After the area of interest within an aquifer had been identified the final borehole locations were selected using a combination of factors, including the

availability of land access agreements, accessibility for the drilling rig, health and safety, and finally financial costs.

Where possible new sites were located away from the influence of any large abstractions or dewatering schemes (such as quarries) so that the level data collected is representative of natural aquifer conditions in that area. Installing boreholes in areas with artesian groundwater conditions was avoided as they can be difficult to monitor accurately. **(Fig.4).**

The depth to which boreholes were installed was dependent on the characteristics of the geological strata and the anticipated depths of water strikes within the aquifer. For boreholes installed into bedrock, the typical depths were 40-50 m, but some of the Carboniferous Limestone boreholes in south Wales and Permo-Triassic sandstone boreholes in north east Wales extend to depths of over 100 m. The deepest Carboniferous Limestone borehole is at Llantwit Major, and is 130 m deep, whilst the deepest Permo-Triassic borehole is at Pont y Cambwll, near Denbigh, and is 150 m deep.

Monitoring frequency and equipment

The majority (~90%) of the monitoring sites in Wales are fitted with pressure transducers and data loggers which allow the collection of high frequency and high quality data. Groundwater levels are typically logged at 30 minute intervals and the data is collected from the boreholes every three months by staff from Natural Resources Wales Hydrometry and Telemetry teams. A hand held water level dipper is used to take a reading during each visit to

ensure that the transducer is still recording data accurately. Any variation of +/-20mm in the recorded water level is an indicator that the pressure transducer may be faulty and should be replaced. For some sites in third party ownership, the design of the boreholes headworks is not suitable for automatic data logging equipment, and these are dipped on a monthly basis using a hand held dipper. In recent years there has been a further emphasis on using telemetered data loggers, particularly at remote sites. These use mobile phone networks to transmit the data directly to Natural Resources Wales offices. This has led to a significant saving in the number of staff required to maintain and collect data from these sites.

Groundwater level data in addition to surface water and rainfall data collected elsewhere by Natural Resources Wales is stored on a central database called 'WISKI' (Water Information Management System Kisters), from where data can be exported for further analysis and interpretation.

Analysis and reporting

Groundwater level data in Wales is reported in a number of ways. The raw data is provided to external bodies such as the British Geological Survey, Centre for Ecology and Hydrology, Universities and consultants for research purposes and their own environmental assessments.

Groundwater level data is used internally in Natural Resources Wales to inform the CAMS process. Level data helps determine whether a particular surface water catchment or aquifer has water available for new abstractions

taking into account existing users of water, and the need to support baseflow to rivers and protect groundwater dependent wetlands. In addition the level data is used as part of the WFD River Basin Planning (**Environment Agency, 2009a and 2009b)** process to develop the conceptual understanding of the hydrogeology of particular aquifers.

Natural Resources Wales also publishes a 'Water Situation Report' which summarises groundwater levels, rainfall, soil moisture deficit, river flows and reservoir stocks **(Environment Agency, 2011)**. Analysis of this data can help predict the onset of flood events or drought conditions.

During 2013 the Centre for Ecology and Hydrology has been working with a number of organisations, including Natural Resources Wales, to develop a hydrological outlook for rainfall, river flows and groundwater levels, which focuses on the next three months. To forecast groundwater levels the British Geological Survey simulates fluctuation in groundwater levels at 25 locations across the Principal Aquifers of the UK. One of these is a Natural Resources Wales level monitoring borehole installed into Permo-Triassic sandstone in the Vale of Clwyd. This modelled data is then combined with climate forecasts produced by the Met Office to generate a probabilistic groundwater level forecast for each location.

Groundwater Level Case study

The site known as Glyn Y Bedd Farm is a 212m deep borehole, located 6km to the north east of Neath in south Wales. It was installed into the

Carboniferous Coal Measures in 1994 as part of a feasibility study for the remediation of the River Dulais and Neath canal minewater discharges. The target consisted of former deep coal workings in the No 2 Rhondda Seam and the borehole was cased to its full depth, with a slotted section of pipe from 193-199 metres below ground level (mbgl).

Following these investigations it was adopted as a groundwater level monitoring site and since the installation of a pressure transducer and data logger to the borehole in the late 1990s 'spikes' have occasionally been recorded in the data record. Data spikes are not uncommon when using pressure transducers to collect level data and often occur when the transducer is disturbed when data from the associated loggers are downloaded. However, after some investigation it became clear that on at least two occasions these data 'spikes' correlated with 'megathrust' earthquakes. These are exceptionally large earthquakes associated with destructive plate boundaries at subduction zones. Two examples are presented, the Indian Ocean Earthquake of 26 December 2004 (Magnitude 9.3M_W) (**Fig.5**) and the Japanese Tōhoku Earthquake of 11 March 2011 (Magnitude 9.0M_W) (**Fig.6**).

The mechanisms causing changes in level aren't fully understood, but are thought to result from seismic waves causing changes in pore water pressures in the aquifer **(Cooper *et al,* 1965).** Due to the depth of the borehole, there is a significant confining pressure onto the aquifer from the overlying strata which may amplify the response recorded on the data logger.

Alternatively the seismic waves may be distorting signals from the pressure transducer such that there is no actual change in the water level in the borehole. Whilst this doesn't have a practical purpose for the monitoring of water resources in Wales, it is nevertheless an interesting phenomenon that can be detected in some boreholes when using high frequency groundwater level monitoring equipment.

Groundwater Quality Monitoring Network

History

The routine monitoring of groundwater quality in Wales is a relatively new development. Prior to the Water Framework Directive, groundwater quality monitoring was inconsistent and only a relatively small number of sites in Wales had the benefit of long (> 10 years) data records. Because of this, insufficient data was available to fully characterise the hydrochemistry of Welsh aquifers. The Water Framework Directive required a groundwater quality monitoring network to be in place by December 2006. Between 2003 and 2006 field work was undertaken across Wales in which approximately 500 potential sites were visited to determine their suitability for inclusion on the network.

What is the network?

The 250 sampling sites consist of a mixture of boreholes, wells, springs and adits used for public water supply, private domestic supply, industrial use, agricultural purposes, and bottled water operations (**Fig.7**). Forty of these are groundwater level network boreholes that are also used for quality monitoring.

Whereas the level network developed piecemeal over a number of years, the quality network was designed from the outset to be risk-based and cost-effective. This was achieved by choosing monitoring locations in Principal Aquifers, other aquifers vulnerable to pollution and aquifers with a known history of diffuse pollution, such as nitrate or pesticide contamination.

Baseline groundwater quality data was collected to support the chemical classification of all groundwater bodies and identify trends in groundwater quality, both of which are requirements of the Water Framework Directive. Therefore monitoring sites were also needed in the Secondary Aquifers of Wales.

Requirements for monitoring sites

To ensure that the quality data is representative of the wider aquifer conditions monitoring sites were located away from areas of potential point source pollution. It is important that groundwater is sampled before it receives any treatment or storage and where springs and adits are used these are sampled as close to the discharge point as possible. It is also crucial to know from which aquifer horizon water is being abstracted. Therefore only boreholes with known construction details and geological logs were suitable for inclusion in the network.

In contrast to the groundwater level network in Wales, the majority of quality monitoring sites are boreholes owned by private individuals and

organisations, where no formal rights of access have been agreed. This minimised the need for capital investment from the then Environment Agency Wales when developing the network, and as the majority are abstraction boreholes the sites are pumped on a regular basis. This ensures that samples which are representative of chemical conditions in the aquifer are collected for analysis. The absence of formal agreements does mean access could be denied in future, but a good relationship exists between Natural Resources Wales and site landowners, who receive copies of the chemical analysis of their water supply.

Sampling frequency and equipment

Groundwater samples are collected by Natural Resources Wales Sampling and Collection teams approximately every six months. At some sites where more frequent sampling is required or where there are known issues with groundwater quality sampling occurs every three months.

A typical sample requires the collection of 1.5L of water which is then decanted into glass and plastic bottles. These samples are collected by a courier and transported to the Natural Resources Wales laboratory in Llanelli for analysis. Portable meters are used on site to collected field readings for unstable parameters including temperature, pH, electrical conductivity and dissolved oxygen. **(Fig.8)**

Higher frequency measurements (hourly/daily) of temperature, pH, conductivity and dissolved oxygen can also provide valuable data for some

investigations. These include monitoring saline intrusion or where karstic limestone sources show rapidly variable water quality over the course of a year, or more rapidly in the hours following heavy rainfall events. At Taff's Well thermal spring near Cardiff, the only thermal spring in Wales (**Fig.9**), a temperature logger has collected data every hour recording an average temperature of 21.6 ^{o}C **(Farr & Bottrell, 2013)**

Analysis

All groundwater samples are analysed for a standard suite of inorganic chemicals including major and minor ions, nutrients, pH and electrical conductivity. The laboratory in Llanelli also has the ability to analyse for organic chemicals including pesticides, herbicides and solvents and can undertake microbiological analyses when required. Analytical suites are selected to address perceived pressures within the aquifer; these are often related to land use. Over time the analytical suites are tailored specifically to each site allowing monitoring to be driven by local requirements.

Chemical tracers such as chlorofluorocarbon (CFC), sulphur hexafluoride (SF6) and tritium have been used to date groundwater in order to improve the conceptual understanding of several aquifers. Nitrogen and oxygen isotope data has also been used to determine the source of elevated nitrates, often where the receptor is a low nutrient groundwater dependent wetland. Groundwater quality data is used to determine the extent of Nitrate Vulnerable Zones (NVZ) in agricultural areas to allow compliance with the Nitrates Directive (91/676/EEC).

Reporting

In 2009 Environment Agency Wales published a series of 'Groundwater Quality Review Reports' or 'Aquifer Reports' as they are more commonly known for eleven areas in Wales. The reports provide an overview of the hydrogeology and hydrochemistry of an aquifer. An earlier project in partnership with the British Geological Survey led to the publication of a 'Baseline Report Series'. This covers the Devonian Old Red Sandstone aquifer in south east Wales (**Moreau *et al* 2005**), and part of the Ordovician and Silurian meta-sedimentary aquifers in west Wales (**Shand *et al* 2005**).

In 2007 groundwater quality network sites were used in a UK wide study of perfluorooctane sulphonate (PFOS) concentrations in groundwater **(Environment Agency 2007)**. It is extensively used as a fire fighting foam and the study was commissioned to determine baseline conditions in groundwater following concerns after the Buncefield Oil depot disaster in Hertfordshire, England in December 2005, which led to contamination of the Chalk aquifer beneath the site with PFOS.

A requirement of the Water Framework Directive is that groundwater quality data is reported in River Basin Management Plans **(Environment Agency, 2009a and 2009b)**. It will also be used during the ongoing assessment and review of these plans to ensure that the targets set for achieving good chemical status of groundwater bodies are met.

Groundwater Quality Case study

In 2008 the then Environment Agency Wales participated in the first pan-European study of persistent organic pollutants in groundwater which covered 23 countries and 160 sites across Europe **(Loos *et al* 2010)**. Samples were collected during routine groundwater sampling at locations selected to represent areas where organic pollution from anthropogenic sources could occur. The aim was to identify persistent organic pollutants not currently sampled as part of existing Water Framework Directive programmes. Sample sites in Wales were located within urban areas of Cardiff and Bridgend and a 'clean' control source was located at the source of the River Loughor in south west Wales.

Across England and Wales the results identified the presence of pharmaceuticals, antibiotics, pesticides, PFOS and caffeine in groundwater. The most common organics detected in Wales were caffeine, Perfluorooctanoic acid (PFOA), a surfactant that persists indefinitely in the environment, PFOS and carbamazepine, a drug used widely as an anticonvulsant or mood stabiliser. Although all results were lower than the relevant EU drinking water standards the study highlighted the widespread occurrence of some persistent organic pollutants within groundwater.

Summary and conclusions

Without the level and quality monitoring networks it would be impossible for Natural Resources Wales to discharge its legal obligations. The data provided from both networks provides a valuable insight into the current

health of aquifers across Wales and the pressures upon them from human activity.

However, during a time of reduced financial resources there is ongoing pressure to cut costs and justify the extent of any monitoring undertaken. Natural Resources Wales will ensure that the monitoring networks stay efficient, cost-effective, risk-based and that regular site reviews are undertaken. Where sites are no longer suitable either for environmental reasons, inadequate access or health and safety concerns then they will be decommissioned.

The challenge is to maintain high quality level and quality groundwater networks which allow Natural Resources Wales to meet current obligations but also respond to any new legislative drivers and future environmental pressures such as monitoring the impacts of climate change.

Groundwater level and quality case study

Groundwater on the Isle of Anglesey is important not only for private water supplies, but is also critical to the wellbeing of wetlands, including Cors Bodeilio and Cors Erddreiniog **(Schlumberger Water Services, 2010a and Schlumberger Water Services, 2010b)** two alkaline fens of national importance.

These wetlands depend on groundwater from the Carboniferous Limestone bedrock and associated superficial deposits, and require low nutrient waters

containing less than 2 mg/l of nitrate (as N) **(UK Technical Advisory Group, 2012).** Water quality sampling had recorded a number of springs on these two sites having consistently elevated nitrate levels of up to 10 mg/l.

To develop the conceptual understanding of the area Environment Agency Wales undertook groundwater quality and supply survey in 2007 **(Environment Agency, 2008b)** with the aim of identifying and sampling groundwater sources, determining baseline water quality and identifying local pressures from point source and diffuse pollution.

The survey revealed that there are few deep abstraction boreholes in the Carboniferous Limestone, and that springs and shallow wells are the dominant sources of local water supplies. To supplement the available monitoring sites four boreholes were installed into the Carboniferous Limestone Aquifer at Llanedwen (80 m deep), Stone Science Museum, Pentraeth (78 m deep) and Llanbedrgoch (22 m deep). Groundwater level and quality data was collected from these sites, and from other water features in the vicinity of both wetlands.

Groundwater flow in a limestone aquifer is mainly via secondary porosity developed in fractures and fissures with limited flow from any intergranular primary porosity. Compared to other parts of Wales the Carboniferous Limestone in Anglesey is not karstic and shale beds within the sequence may impede downwards groundwater movement. Although shallow groundwater

systems dominate there is groundwater flow at depth, especially within the basal Lligwy Sandstone Formation and at its contacts with adjacent strata.

The results of the study were used to develop an improved conceptual model of the Carboniferous Limestone aquifer (**Fig.10**) and its relationship with overlying groundwater dependent wetlands. The data provides a platform for future measures to reduce nitrate pressures on these internationally important wetlands.

Note from the authors

The authors would like to thank Martin Doherty for his comments and advice on the draft version of this paper. All Environment Agency reports referred to are available to download from their website. Raw groundwater level and quality data is available from the customer service centre at Natural Resources Wales and other reports will be available online at www.naturalresourceswales.gov.uk. Data used for non-commercial purposes is provided free of charge. Topographic base maps are reproduced from the OS with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office, Crown copyright. Gareth Farr publishes with the permission of the Executive Director, British Geological Survey (NERC).

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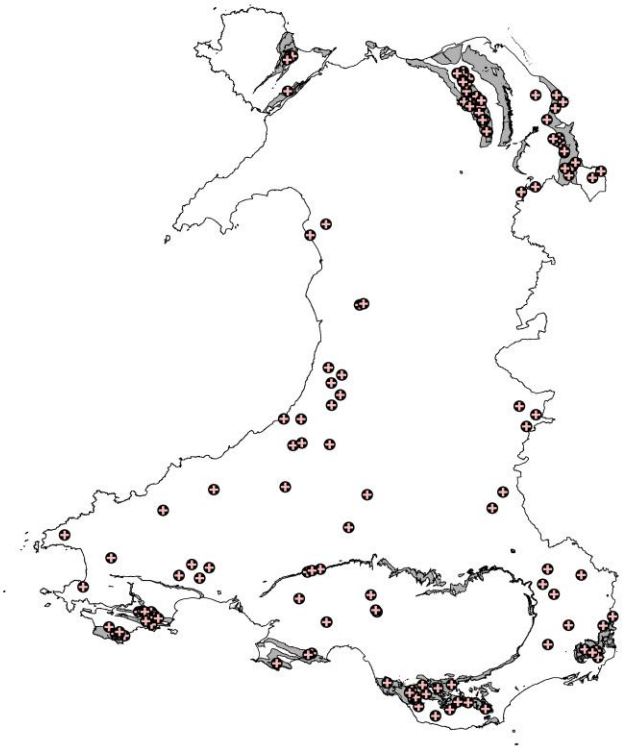
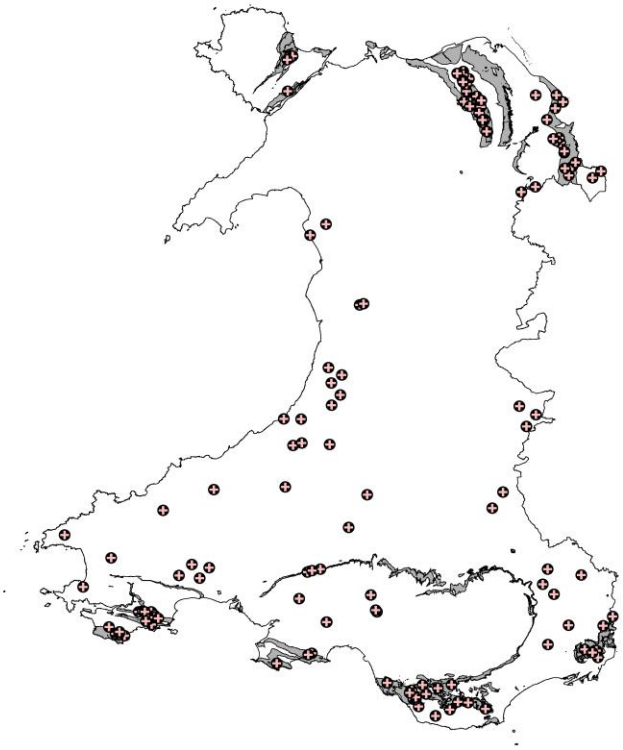


Figure 1 Extent of Groundwater Level Network in Wales.



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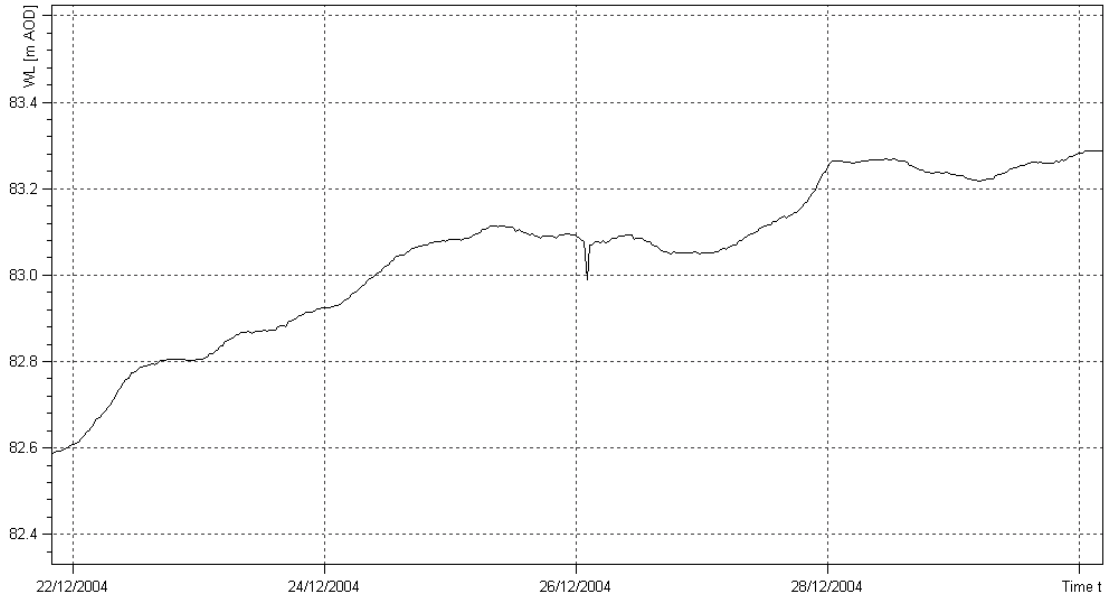
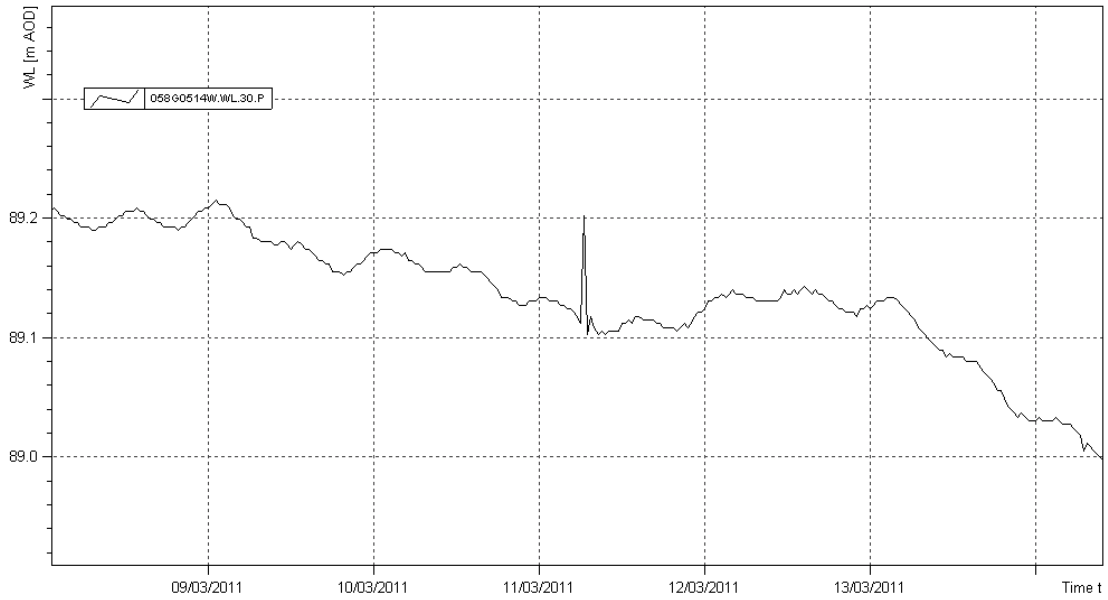


Figure 5 Groundwater level record of Indian Ocean Earthquake 26 Dec 2004



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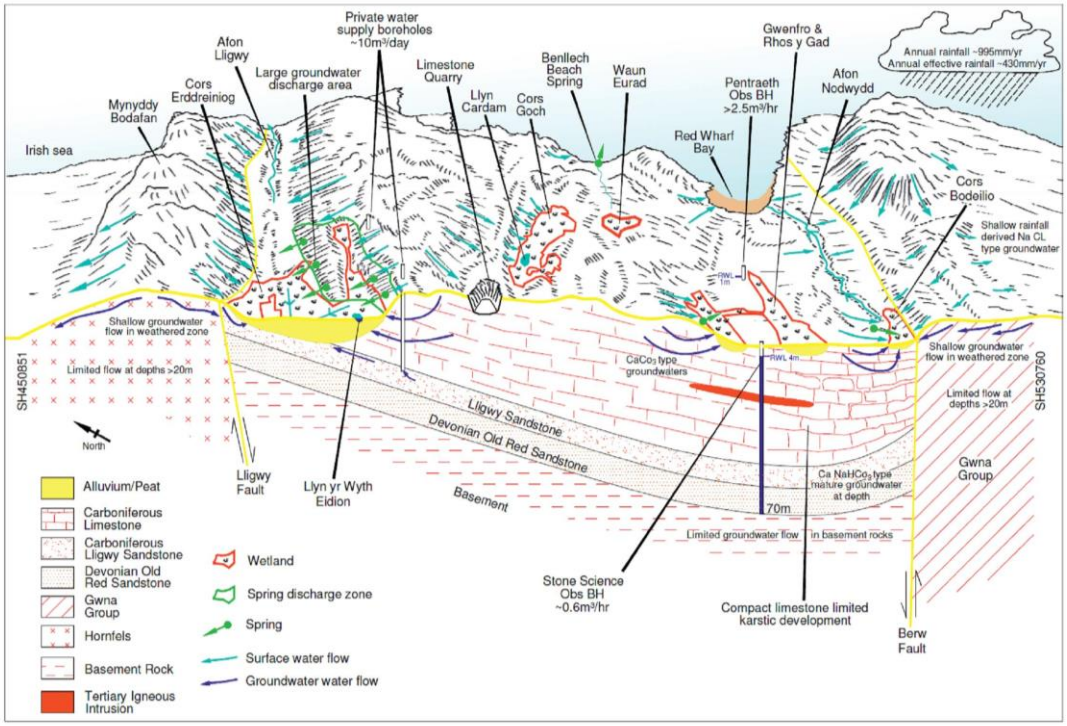

Figure 10 Conceptual model of the Anglesey Carboniferous Limestone (from Beamish and Farr, 2013