CONCEPTUAL MODELS FOR NORTHERN IRELAND'S CRETACEOUS AND CARBONIFEROUS AQUIFERS

Paul Wilson, *The Geological Survey of Northern Ireland, British Geological Survey, Dundonald House, Upper Newtownards Road, Belfast, BT4 3SB*
Brighid O'Dochartaigh, *British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP*
Mark Cooper, *The Geological Survey of Northern Ireland, British Geological Survey, Dundonald House, Upper Newtownards Road, Belfast, BT4 3SB*

ABSTRACT

Northern Ireland's main limestone aquifers are found in the Carboniferous and Cretaceous sequences. Aquifer conceptual models have been developed for these and the other aquifers in Northern Ireland as a consistent platform from which more detailed conceptual models can be developed for any form of hydrogeological investigation and study. These are based on the most up to date research and data available.

The majority of the Carboniferous and Cretaceous limestones are located in upland terrain. Karst systems have developed within them, receiving sinking streams as their main source of recharge. They are predominantly free-flowing and have exploited pre-existing intersecting faults. Transmissivities are moderate to high but storativity is low in these aquifers. This means that episodic high yields are achievable from karst springs and boreholes, but they may not be sustainable as a supply source during drier periods.

Key words: *Aquifer, Cretaceous, Carboniferous, Northern Ireland, Fermanagh, Antrim, Karst, Chalk, Spring, Conceptual model, Fault, Recharge, Flow, Storage, Discharge, Groundwater*
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INTRODUCTION

Northern Ireland has a broad range of bedrock geology from metamorphic Dalradian to sedimentary Oligocene rocks and everything in between. This means that, unlike the Republic of Ireland, the limestone aquifers are not as dominant. Whereas all the significant limestone aquifers in the Republic of Ireland originate from the Carboniferous period, Northern Ireland has significant limestone aquifers from both the Carboniferous and the Cretaceous periods. These limestone aquifers have created iconic landscapes such as the Marble Arch Caves Global Geopark in Counties Fermanagh and Cavan and the 'White Rocks' that are sheltered beneath a protective blanket of black basalt which accompany your drive along the Antrim Coast Road and the Causeway Coast.

In 2018, a project called 'Northern Ireland's Aquifers' was initiated to undertake a regional characterisation of groundwater aquifers in Northern Ireland. A similar exercise was carried out in the early 1990's by Robins (1996), resulting in what is commonly known as the 'Red Book'. This has been the main reference for all hydrogeology in Northern Ireland in the past 25 years, during which time hydrogeology as a discipline has advanced and the role of groundwater has greatly expanded due in no small part to the EU Water Framework Directive (European Parliament, 2000).

The purpose of this latest project has been to establish a new framework upon which a new period of hydrogeological discovery in Northern Ireland can be based. Central to this is the development of conceptual models that underpin any work that hydrogeologist or engineer undertake. They are a powerful tool in their arsenal, making the complex often easier to understand.

The main outputs from the project are a new attributed hydrogeological map of Northern Ireland and an accompanying reference publication containing conceptual models of all the aquifers of Northern Ireland. The models summarise the best available understanding of the recharge, flow, storage and discharge mechanisms that occur in each aquifer, in the Northern Irish context. These will hopefully be launched at the start of 2021. These are the result of a new Groundwater Data Repository of aquifer property and chemistry values containing data from almost 3000 boreholes and springs gathered from GSNI studies, drillers records and other publically available datasets. An index dataset is available on the GSNI Geoindex with data available upon request. This paper summarises the key characteristics of the Carboniferous Limestone and Cretaceous conceptual aquifer models from this publication.

CARBONIFEROUS

OCCURANCE AND GEOLOGICAL SUMMARY

Carboniferous Limestone rocks in Northern Ireland crop out predominantly in the southwest of the Province in Counties Fermanagh and Tyrone, with smaller outcrops in Counties Londonderry and Armagh, and in the northeast of County Antrim near Ballycastle.

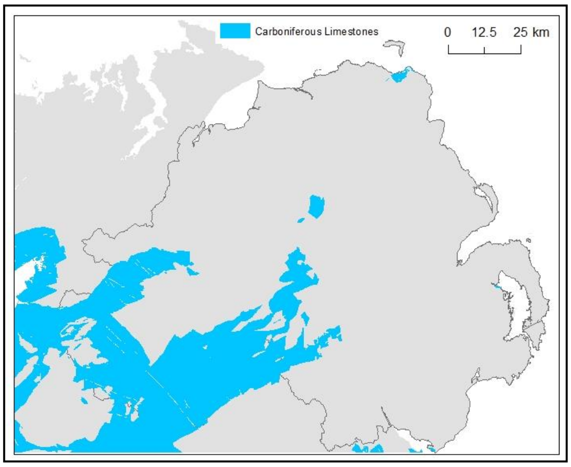

Figure 1: *Carboniferous Limestone Outcrop in the North of Ireland*

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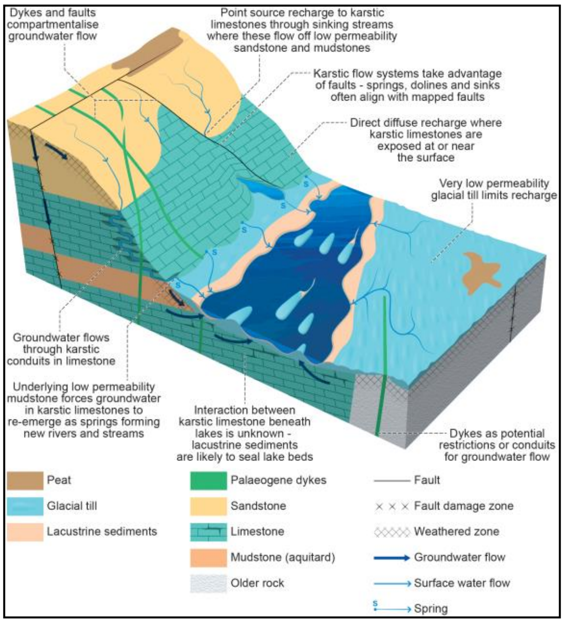


Figure 2: Carboniferous Limestone Conceptual Aquifer Model *(Crown Copyright 2020)*

The Carboniferous Limestone aquifers comprises a sequence of karstic limestones with mudstones, of Lower Carboniferous age. There are three named formations: the Leitrim, Armagh and Tyrone groups. The rocks were formed in a marine deltaic environment with cycles of limestone, mudstone and sandstone deposition. The limestones are characteristically karstified, in some formations particularly so, including the Dartry Limestone Formation, the Knockmore Limestone Member and the Glencar Limestone Formation. These crop out mostly in County Fermanagh on higher ground, such as beneath the Cuilcagh and Belmore Mountains. The older Ballyshannon Limestone Formation is also karstified but is separated in the sequence from the karstic rocks higher in the sequence by the Benbulben Shale Formation, Mullaghmore Sandstone Formation and the Bundoran Shale Formation. Beneath this, the Clogher Valley Formation may also be partly karstified. In general, most of the limestone units are both underlain and overlain by mudstone units.

RECHARGE

The main recharge mechanism to the aquifer system is from river water infiltrating through karstic sinkholes. The rivers may flow over low permeability mudstones that overlie the limestones, with little infiltration, before flowing onto limestone outcrops and into karstic sink holes. Direct rainfall recharge to the karstic limestone aquifer also occurs where rock is exposed at surface. The high infiltration capacity of the karstic limestone means that in these areas, recharge is similar to total effective rainfall.

FLOW

After sinking underground, groundwater flows through the limestone aquifer in the network of fractures and karstic conduits. Intergranular porosity and permeability are negligible. Carboniferous limestone is classed as a high productivity aquifer. Flow rates are highly variable, dependent not only on the size, interconnectedness and degree of complexity of the karstic system, but also on flow conditions (faster flows during higher flow conditions such as storm events). Typical flow rates measured in tracer tests are around 2–3 km/day (Brown, 2005)

Intrusive igneous dykes are a unique feature to the north of Ireland. The exact role they play in groundwater flow is not well understood but it is expected that they act as barriers to groundwater flow, compartmentalising aquifers, and, in this situation, altering karst development. However, positive tracer tests have been performed between sinks and springs separated by dykes. One such test was conducted from Pigeon Pot to Shannon Cave, between which Cuilcagh dyke intersects the sequence of Carboniferous rocks. It is thought that post intrusion faulting may provide a preferential pathway for groundwater flow through dykes.

STORAGE

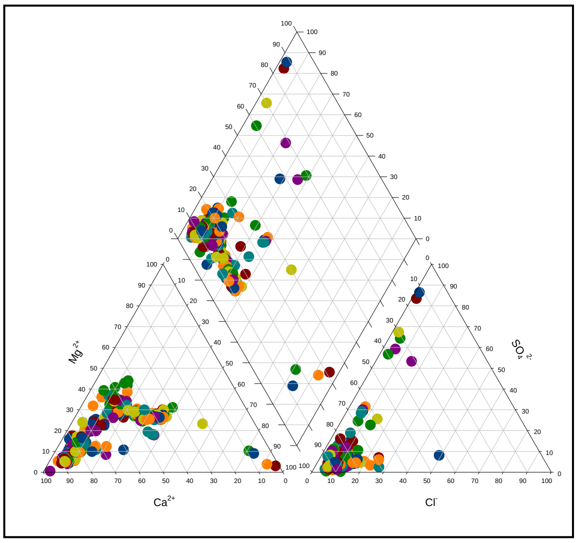
This is predominantly a function of the degree of karstification. The more karstified the limestones are, the more groundwater storage is available. However, in the more open karst systems, as can be entered at Marble Arch Caves, the available storage is not fully utilised, with streams flowing along the base of caves and conduits. In the more upland settings, such as in County Fermanagh, the steep hydraulic gradients increases the rates of flow. Therefore, typically groundwater storage is low in these limestones.

DISCHARGE

Groundwater discharge from the karstic limestone is normally as discrete springs, often at the base of individual limestone units immediately above low permeability mudstone units. Spring-fed rivers then flow over the underlying mudstones. Minor discharge also occurs from the aquifer directly into stream beds. The more well-known examples include the resurgence at Marble Arch, Hanging Rock spring and St. Patrick’s Holywell near Belcoo.

Some of the lakes in County Fermanagh, such as Lough Erne and Lough Macnean, are underlain by these limestones. It is unknown if there is any significant discharge from the limestones to the lakes. It is likely that the Glacio-lacustrine deposits found around these lakes limit the degree to which the lakes and the limestones that interact.

CHEMISTRY



Groundwater in the Carboniferous Limestones is typically highly mineralised (median conductivity 577 µS/cm) and has a moderate pH (median 7.39) compared to other aquifers in Northern Ireland. Groundwaters are mainly calcium-bicarbonate type, with a minority of samples dominated by sulphate instead of bicarbonate (Figure 3). Rapid migration of contaminants as overland flow, into sinking streams and through open conduits make this aquifer extremely vulnerable to pollution. In the normal upland setting, likely sources will be from grazing animals and peat cutting.

Figure 3: Piper (tri-linear) diagram illustrating the distribution of major ion compositions of Carboniferous Limestone aquifers in Northern Ireland

AQUIFER PROPERTIES

A summary of the aquifer properties contained within the Northern Ireland Groundwater Data Repository, developed as part of the NIA project are shown in

Table 1. Transmissivity measurements from pumping tests are some of the highest values observed for bedrock aquifers in Northern Ireland, with a median of 174 m^2/d. Only four storativity measurements have been made. These all reflect an aquifer with limited groundwater storage, as described above. Measured yield is not a precise term but it does indicate how productive boreholes drilled in to these rocks can be. The median value recorded was 327 m^3/d. This shows that these rocks have the potential to yield moderate to high yields but this may not be sustainable due to low groundwater storage. These aquifers are not currently used for public water supply and only a small number of private supplies. However, these demonstrate the potential to provide large supplies but may be more vulnerable to fluctuations in water quality.

Table 1: *Carboniferous limestone aquifer property summary data*

Parameter	n	Minimum	Median	Maximum
Transmissivity (m^2/d)	9	10	174	2200
Storativity	4	9×10^{-5}	1×10^{-4}	4×10^{-4}
Specific capacity ($m^2/d/m$)	15	0.64	42	1177
Measured yield (m^3/d)	110	12	327	3382

CRETACEOUS

OCCURANCE AND GEOLOGICAL SUMMARY

Rocks of Cretaceous age in Northern Ireland comprise the Ulster White Limestone Group – also known as the Chalk – and the Hibernian Greensands Group. The Cretaceous sequence has a very limited outcrop, which is modified by Tertiary faulting that also makes the aquifer discontinuous.

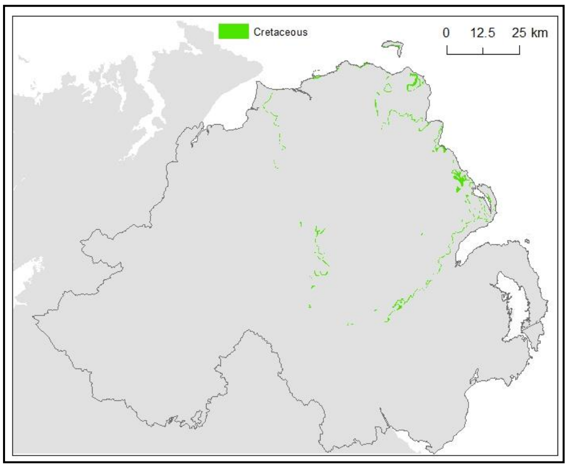


Figure 4: *Cretaceous Limestone Outcrop in the North of Ireland*

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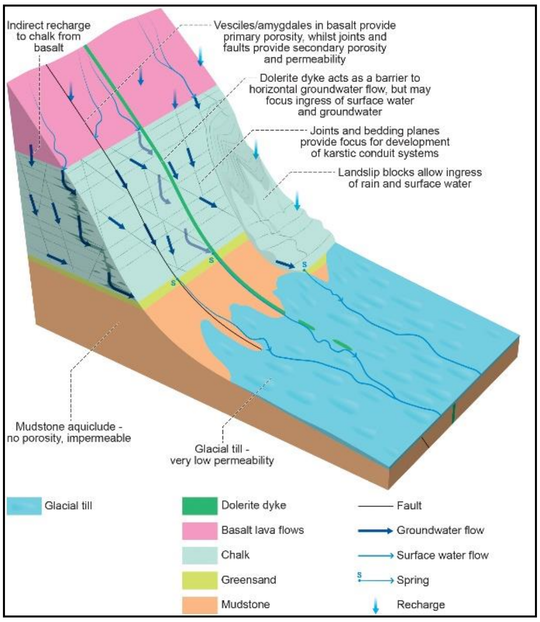


Figure 5: Cretaceous Limestone Conceptual Aquifer Model *(Crown Copyright 2020)*

The Ulster White Limestone Group is the equivalent of the English Chalk. Its total outcrop area is only 80 km^2, around the periphery of the Palaeocene Basalts (Antrim Plateau Lavas), which it underlies in the northeast of the Province. It is typically ~50 m thick, but in some places can be more than 150 m thick (Fowler et al., 1961, Fletcher, 1977). It is typically thickly bedded (0.3 to 1.0 m) with a wide joint spacing (5 to 10 m). It is a hard limestone, significantly harder than most of the English Chalk, due to extensive secondary calcite cementation in pore spaces (Maliva and Dickson, 1997) and can be karstic, forming large openings and conduits due to dissolution of calcium carbonate in the rock (Barnes, 2000).

The Hibernian Greensands Group underlies the Ulster White Limestone Group along the south and eastern edges of the Antrim Plateau between Lisburn and Glenarm, and in a small area east of Limavady. It is thin, with a maximum thickness ~ 30 m. It comprises a variable sequence including glauconitic sands, sandstones, marls and mudstones. It is underlain by Jurassic or Triassic mudstones.

RECHARGE

The Chalk is recharged mainly by infiltration of river water through sinkholes in river beds in the active karstic outcrop zone. These rivers can be seen flowing over the Basalts aquifer outcrop before reaching the Chalk outcrop, where water infiltrates (‘sinks’) through individual large karstic sinkholes or several smaller sinkholes over the course of a short length of river bed.

Where the Chalk is covered by Basalts, some recharge is also thought to occur by groundwater draining down from the overlying lavas. Studies of a number of Chalk springs, such as Toberterin near Stewartstown in County Tyrone, have shown, using water chemistry studies and flow gauging, that the discharging groundwater is predominantly recharge from the basalts (Barnes, 1999).

FLOW

Groundwater flow in the Chalk is dominated by fractures, with a significant karstic flow component. Intergranular porosity and permeability are negligible. The Chalk is classed as a high productivity aquifer.

The main active karst zone within the Chalk occurs in its outcrop area – not where it is buried beneath the Basalts – and the highest permeability values are also thought to be in this zone, although there is little measured data (Robins et al., 2011). Karst development has been promoted by groundwater flow, so that it is greatest in areas where recharge potential is highest and there is the most active groundwater flow. Some of the karst is thought to be palaeokarst, developed before the overlying Basalts were erupted (Robins et al., 2011). Major sinkholes and springs occur along the Antrim coast, indicating significant active karst conduit systems.

Controls on the depth of active groundwater flow in the Chalk vary. At outcrop, its limited thickness is the main control; in the confined zone, where it is covered by Basalts, poorer fracture development may restrict flow to the upper part of the Chalk. Groundwater flow paths in the Chalk beneath the outcrop are likely to be generally short (100s metres), and partly controlled by topography, but preferential flows through fractures and karst features, where they are present, have a significant local influence. There is some potential for limited regional flow down-dip in the confined Chalk. Major fault zones may also influence groundwater flow in some areas. In the east, flows appear to be faster (e.g. 500 to 1000 m/day) and flow paths shorter, with a ‘flashier’ groundwater response, with slower responses in the west (Barnes, 1999). Barnes suggested that this indicated rapid flow of young (recently recharged) groundwater in the east; and discharge from the base of the Basalts in the west.

As with Carboniferous limestones, intrusive igneous dykes cut through the Cretaceous sequence. They act as barriers to groundwater flow, compartmentalising aquifers (Comte et al., 2017). This can alter what may be the normal conceptualised flow path for groundwater and need to be considered as a significant influence on the development of any conceptual groundwater model.

The Chalk and the underlying thin Hibernian Greensands are classed together as a single aquifer group, despite having very different hydrogeological properties, because the available evidence indicates they are hydraulically connected (Foster et al., 1969).

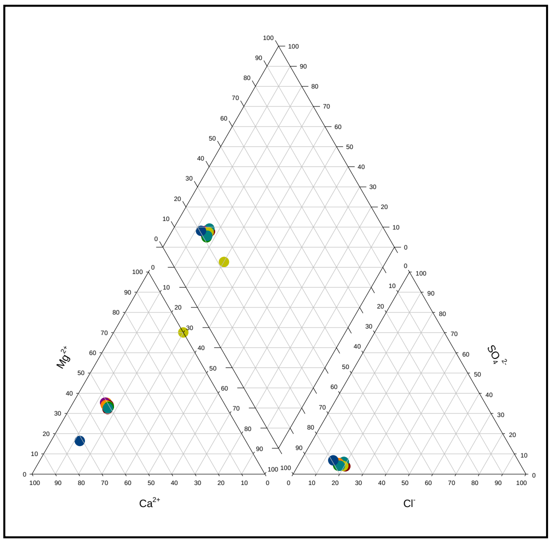
STORAGE

In dry weather, when river flows are low, the Chalk aquifer can accept all recharge from sinking river flow, and Chalk rivers often have dry beds for a few hundred metres before groundwater discharges to the surface again. However, during high flow conditions, the Chalk storage capacity can be exceeded so that the aquifer cannot accept more recharge; groundwater levels rise to the ground surface, including in sinkholes, which become points of groundwater discharge from the aquifer, feeding the previously dry river beds so that they start to flow again.

DISCHARGE

Most groundwater discharge from the Chalk is from springs, of which there are many. These typically discharge from the base of the Chalk or the base of the underlying Greensands, which is underlain by lower permeability older rocks, such as Jurassic and Triassic mudstones. One of the largest known of these springs is Carey River Spring, which is the main discharge point for water draining from Loughareema (the Vanishing Lake) in north-east Antrim. This has a normal flow rate of at least 30 l/s when the lake is empty, and a largest measured flow of over 200 l/s when the lake is full.

CHEMISTRY



There is relatively little groundwater chemistry data for the Cretaceous aquifer. The available data indicate that groundwater is typically relatively weakly mineralised (median conductivity 349 µS/cm) and has a neutral pH (median 7.51) compared to other aquifers in the Province (Figure 6). The groundwater is typically of calcium bicarbonate type (Figure 7).

Figure 6: Piper (tri-linear) diagrams illustrating the distribution of major ion compositions of Cretaceous Limestone aquifers in Northern Ireland

AQUIFER PROPERTIES

A summary of the limited aquifer properties contained within the Northern Ireland Groundwater Data Repository are shown in
Table 2. Of the three transmissivity values available, the median was 360 m^2/d. The median measured yield is 327 m^3/d, exactly the same as the Carboniferous limestones.

Due to Chalk outcrop normally only being accessible to drill along the steep-sided cliffs around the Antrim Plateau, drilling a reliable production borehole can be difficult. It is not uncommon for groundwater to be struck at the base of the Chalk and for it not to rise within the borehole, indicating it to be free-flowing. This therefore requires a sump to be drilled in to the underlying mudstones from which groundwater can be pumped. In the 1970's a feasibility study was carried out to consider the prospects from an adit drilled in to the chalk cliffs as a water supply source for parts of North Belfast, however this was not progressed due to the limited storage within the Chalk aquifer (Bennett, 1978).

Parameter	n	Minimum	Median	Maximum	Single value
Transmissivity (m^2/d)	3	30	360	731	
Storativity	1				0.09
Specific capacity ($m^3/d/m$)	2	21		875	
Measured yield (m^3/d)	5	17	327	2880	

Table 2: *Cretaceous limestone aquifer property summary data*

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