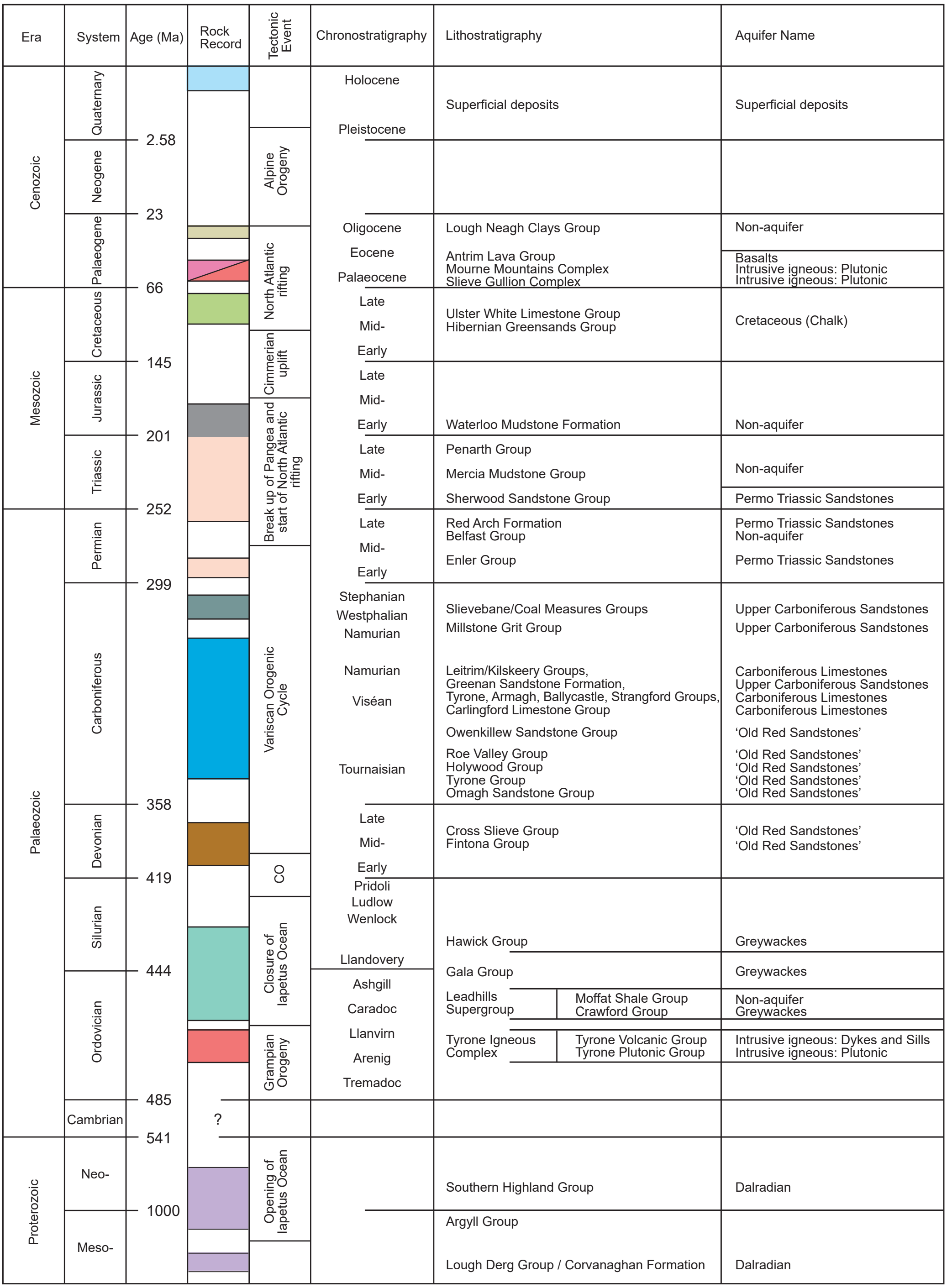
Northern Ireland's Groundwater Environment

Paul Wilson, Brighid Ó Dochartaigh, Mark Cooper and Rebecca Ní Chonchubhair



Era	System	Age (Ma)	Rock Record	Tectonic Event	Chronostratigraphy	Lithostratigraphy	Aquifer Name
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					Tournaisian	Roe Valley Group Holywood Group Tyrone Group Omagh Sandstone Group	'Old Red Sandstones' 'Old Red Sandstones' 'Old Red Sandstones' 'Old Red Sandstones'
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	Silurian	444		Closure of Iapetus Ocean	Pridoli Ludlow Wenlock Llandovery	Hawick Group	Greywackes
						Gala Group	Greywackes
	Ordovician	485		Grampian Orogeny	Ashgill Caradoc	Leadhills Supergroup: Moffat Shale Group Crawford Group	Non-aquifer Greywackes
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	Cambrian	541	?				
Proterozoic	Neo-	1000		Opening of Iapetus Ocean		Southern Highland Group	Dalradian
	Meso-					Argyll Group	
						Lough Derg Group / Corvanaghan Formation	Dalradian

CO - Caledonian Orogeny

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Front Cover Photographs
Top: St. Patrick's Holy Well Spring,
Co. Fermanagh.
Bottom: Hanging Rock cave, Co. Fermanagh

Back Cover Photographs:
Top Left: Carboniferous Limestones aquifers hydrogeological conceptual model
Bottom Left: Cascades Rising, Co. Fermanagh
Middle: Drilling of a groundwater monitoring borehole
Right: Artesian borehole

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Contents

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Summary

Groundwater is an essential, yet usually hidden, natural resource for Northern Ireland. Until the 20th century, groundwater from shallow wells and springs provided the main water supply for many settlements and it continues to quietly provide a continuous supply of baseflow to rivers and streams across Northern Ireland, keeping them flowing and maintaining aquatic ecosystems during dry spells. This vital ecosystem service will become even more important in the future, with climate change predicted to cause more frequent and longer dry periods.

Groundwater has made a significant contribution to the industrial and economic development of Northern Ireland: some settlements developed where they are because of the presence of local groundwater sources that provided them with reliable water supplies. Advancements in drilling technology in the late 18th century allowed deep boreholes to be drilled into bedrock aquifers such as the Sherwood Sandstone Formation in the Lagan Valley, contributing to the industrial boom of late Victorian times. At the start of the 20th century, Belfast was the largest exporter of bottled carbonated water in the world, all of which came from groundwater pumped from the Sherwood Sandstone aquifer.

Northern Ireland's geology is exceptionally diverse for such a small region, with many different types of metamorphic, igneous and sedimentary rocks and superficial deposits, ranging in age from 600 million years to less than 10 000 years (Figures 1 and 2). The groundwater environment of Northern Ireland is controlled in large part by its geology and is also highly varied. Different rock types form distinct aquifers, distinguished by characteristic geological and hydrogeological features that control how groundwater is stored, how it flows and its chemical quality. Across Northern Ireland, there are consistently highly productive aquifers in very different geological environments, including superficial glaciofluvial sand and gravel, Cretaceous chalk, Permian and Triassic sandstones and Carboniferous limestone.

Other rock types, such as Palaeogene basalts, can also provide high-yielding groundwater supplies in some places, but these tend to be the exception and are generally less productive aquifers. The most productive and heavily used aquifers have been relatively well studied, but there is still much about the hydrogeology of Northern Ireland that is not yet fully known because it is still to be explored.

Northern Ireland has a temperate, maritime climate, with annual average rainfall varying from just under 800 mm in low-lying, southern and eastern areas to about 2000 mm in upland, western areas. In all areas, the wettest months are in the winter, between October and January, and the driest months are in the late spring and early summer. Evapotranspiration rates are relatively low, ranging from about 32 to 44 % of annual rainfall (Mills, 2000), so that potential recharge – the infiltration of rainfall to aquifers – is generally high. Groundwater levels in Northern Ireland's aquifers follow a typical overall seasonal pattern of winter rise, when recharge is highest, and summer fall, when recharge is lower. Recent high-frequency groundwater level monitoring has shown some aquifers also receive significant recharge during summer months, after high-intensity rainfall events.

This book presents a regional overview of the current understanding of Northern Ireland's groundwater environment, hydrogeology and groundwater resources. It is based on the latest hydrogeological data and, for each aquifer, provides a quantitative summary of physical properties and groundwater chemistry (derived from statistical analyses of the available data) and a graphical conceptual hydrogeological model. Accompanying this book is a 1:250 000-scale dataset that presents summary physical and chemical properties of each aquifer.

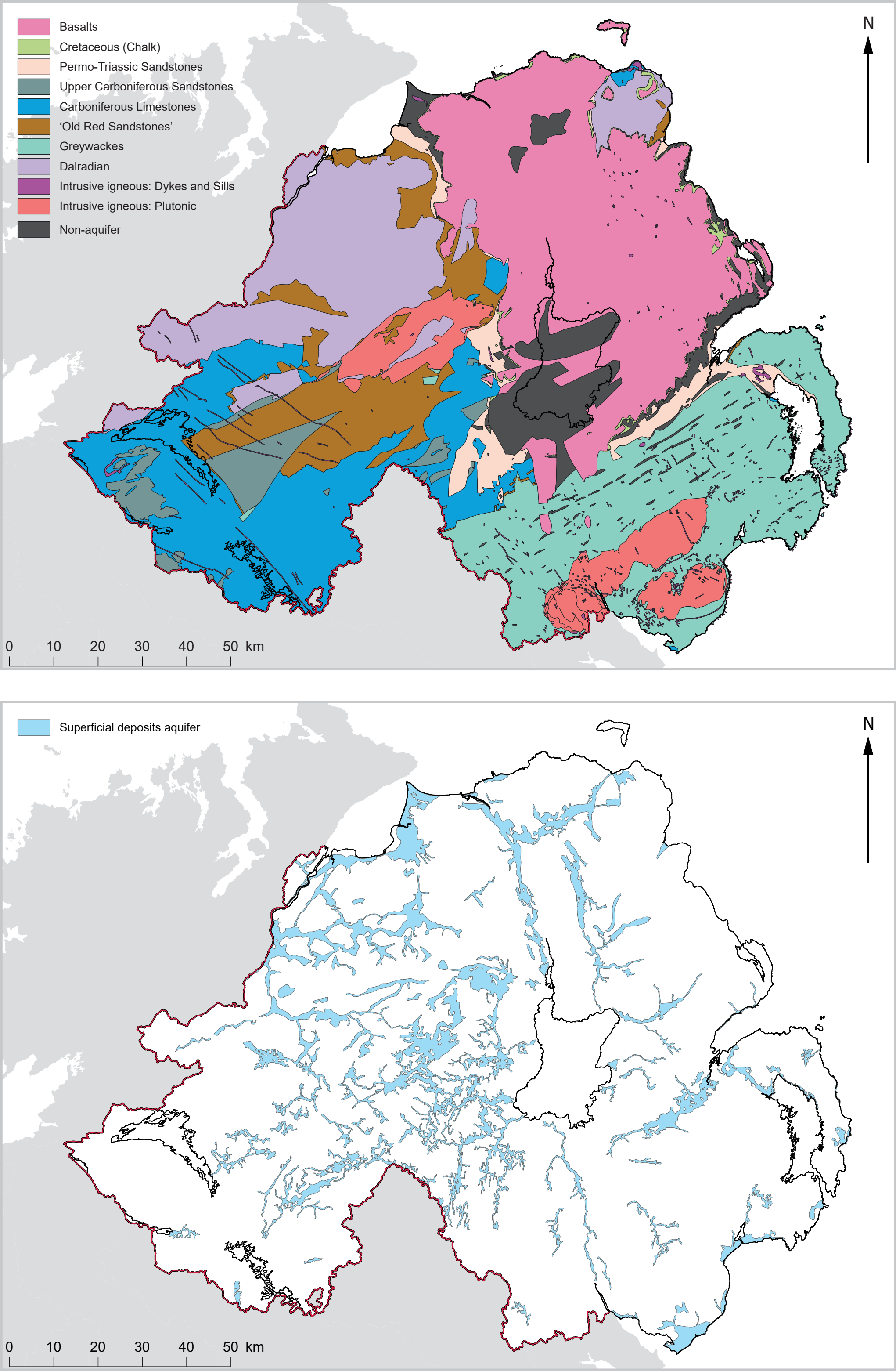
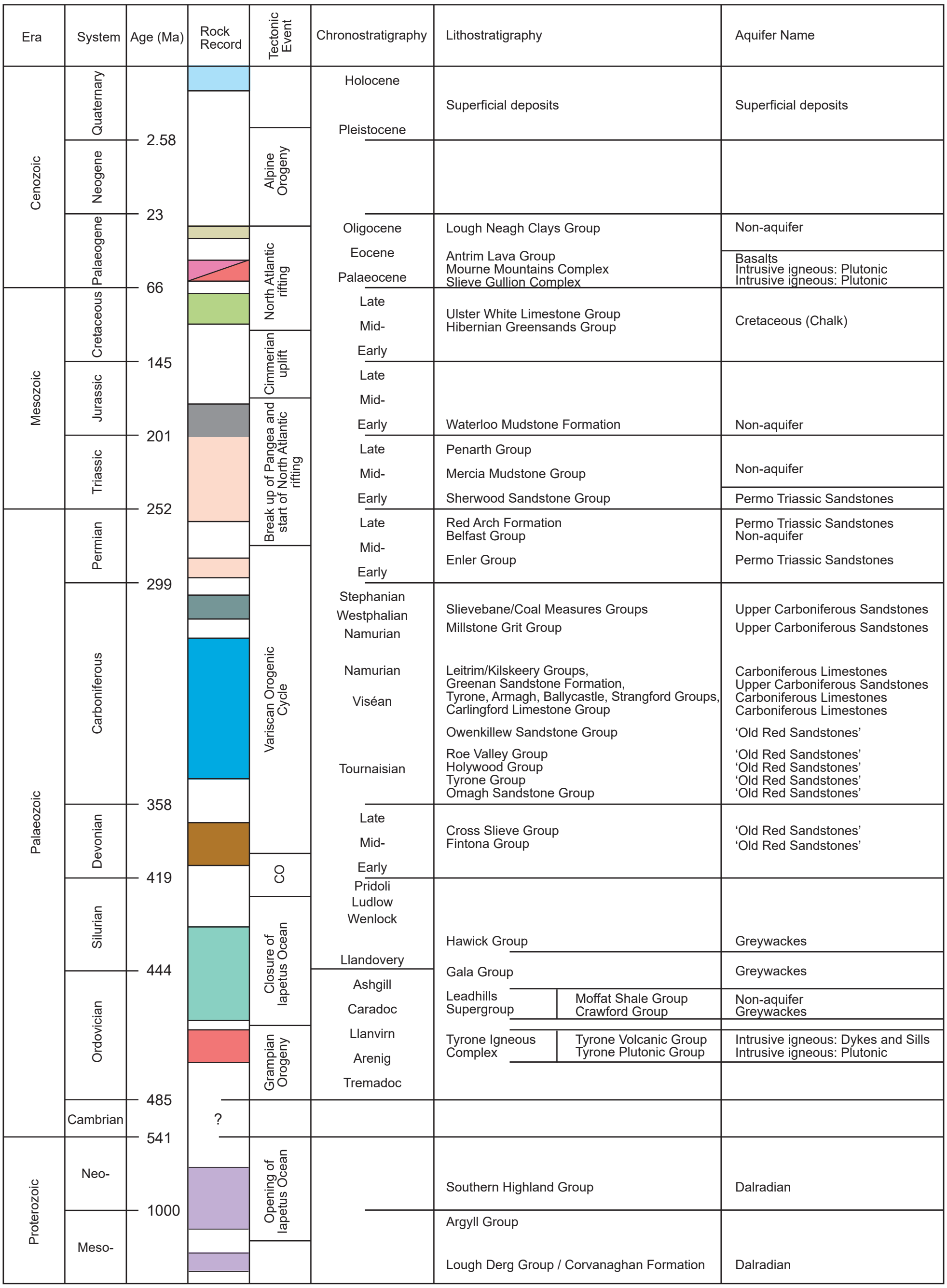


Figure 1. Groundwater environments (aquifers) of Northern Ireland: bedrock (upper map) and superficial deposits (lower map). Contains OGL and CC-BY-4.0 Data



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CO - Caledonian Orogeny

Figure 2. Relationship between aquifers and geological units in Northern Ireland.

1. Introduction

1.1 Using this book

This book presents a regional overview of the current understanding of Northern Ireland's groundwater environment, hydrogeology and groundwater resources. Since the publication of Hydrogeology of Northern Ireland (Robins, 1996), the last overview of Northern Ireland's hydrogeology, there have been many changes in the way that groundwater is regulated, managed, monitored and used in Northern Ireland, driven in particular by the implementation of the European Water Framework Directive (WFD) (2000/60/EC). Advancements in technology, data management and analysis have also opened up new opportunities for hydrogeological studies and, together with regulatory drivers, have led to the collection of new groundwater data.

This book, and the accompanying dataset, provide a basis to:

- help stimulate renewed interest in groundwater as a critical natural resource in Northern Ireland
- support groundwater management and decision making
- provide opportunities to strengthen the groundwater research community

There is great scope for the future development of groundwater resources in Northern Ireland, underpinned by new hydrogeological research, including prospecting for new groundwater and geothermal groundsource energy supplies, and improved hydrogeological risk and environmental impact assessments for new developments. This book also provides a reference guide for the general public who wish to learn more about the groundwater beneath their feet.

The book is split into the following chapters:

- Chapter 1: Introduction, with context and a brief introduction to groundwater in Northern Ireland
- Chapter 2: a summary of the availability of hydrogeological data and information in Northern Ireland
- Chapter 3: detailed descriptions of the hydrogeology of each aquifer in Northern Ireland
- Chapter 4: an overview of how groundwater is managed in Northern Ireland
- Chapter 5: a brief history of the development of groundwater exploration and hydrogeological understanding in Northern Ireland

The main body of the book is Chapter 3, which describes how the aquifers of Northern Ireland have been classified and presents a summary of the current understanding of the geology, hydrogeology and issues of groundwater use, management, and potential for future development for each aquifer. We also present schematic conceptual models of the hydrogeology of each aquifer, which include information on:

- aquifer physical properties
- recharge processes
- storage, flow and discharge processes
- groundwater levels
- natural groundwater chemistry

Hydrogeological conceptual models are a means of summarising and visualising complex aquifer systems. The graphical hydrogeological conceptual models presented here have been drawn to represent the general geological and geomorphological settings of the aquifers across Northern Ireland. They are not representative of the detailed local characteristics of the aquifers.

1.2 Overview of groundwater in Northern Ireland

1.2.1 Introduction to groundwater and hydrogeology

Groundwater exists in aquifers: these are rock layers that have sufficient porosity and permeability to store and transmit groundwater. Different aquifers can have very different physical and chemical hydrogeological characteristics.

In Northern Ireland, aquifers occur almost everywhere beneath our feet. Some are formed of consolidated bedrock, such as sandstone or limestone; others of unconsolidated sediments, such as sand or gravel. The properties of an aquifer are controlled in large part by its geology and the complex and varied geology of Northern Ireland means that our aquifers are highly diverse. They have distinctive physical and geochemical characteristics that control groundwater flow and storage; how productive they are (i.e. how much water can be abstracted from them), and their natural (baseline) groundwater chemistry. Some of the bedrock aquifers are present immediately below the ground surface, with only a relatively thin layer of soil or artificial material overlying them. Others are overlain by thicker unconsolidated sediments (superficial deposits), which may themselves also form aquifers: these may be small and localised, such as river alluvium in valleys; more extensive, such as large outwash plains of glaciofluvial sands and gravels. Some bedrock aquifers are partly covered by thick, low-permeability (non-aquifer) sediments with little groundwater, such as the Lough Neagh Clays Group.

Groundwater – the water in aquifers – originates as rainfall. When rain falls, some of it is evaporated back to the atmosphere; some runs off rapidly into streams and rivers, and some infiltrates the soil (Figure 3). Some of the water infiltrating the soil is absorbed by plant roots and transpired back to the atmosphere and, in areas close to rivers, some of the soil water flows through the soil and discharges quickly into the river. The rest of the water that infiltrates the ground continues to flow downwards through the void spaces (pore spaces or fractures) in the soil and any underlying permeable superficial deposits and rocks – the aquifers – until it reaches a geological layer with such low permeability that it restricts any deeper groundwater flow. This layer is called an aquitard or, if it is completely impermeable, an aquiclude.

This process of water infiltrating down into aquifers is called ‘recharge’. The amount and speed of recharge depends on the permeability of the soils, sediments or artificial materials at and near the ground surface. Materials with low permeability, such as natural silts or clays, or concrete – restrict infiltration and cause more rainfall to runoff to rivers.

The amount of groundwater that can be held in an aquifer depends on the thickness and storage capacity of that aquifer: that is, how much porosity (void space) there is to store groundwater. Groundwater fills up the void spaces in aquifers until they are full or until the supply of recharge stops; for example, if there is a long, dry spell with no rain. The parts of the aquifer where all the void spaces are full of groundwater are ‘saturated’, with no room for more water to be stored. The uppermost surface of this saturated zone of an unconfined aquifer is the water table, sometimes called groundwater level, piezometric level or potentiometric level.

In Northern Ireland, the water table is usually less than 10 m below the ground surface. It is usually deeper on hills and shallower in valleys and generally forms a subdued mirror of the topography of the ground surface (Figure 3). Once groundwater reaches aquifers, it doesn’t stop moving, but continues to flow ‘downhill’, following the slope of the water table until, in most cases, it comes to a point where the water table intersects the ground surface – maybe as a spring on a hillside, or at a river or lough in a valley (Figure 3). Here, the groundwater discharges naturally back to the ground surface as a spring or as baseflow to surface waters.

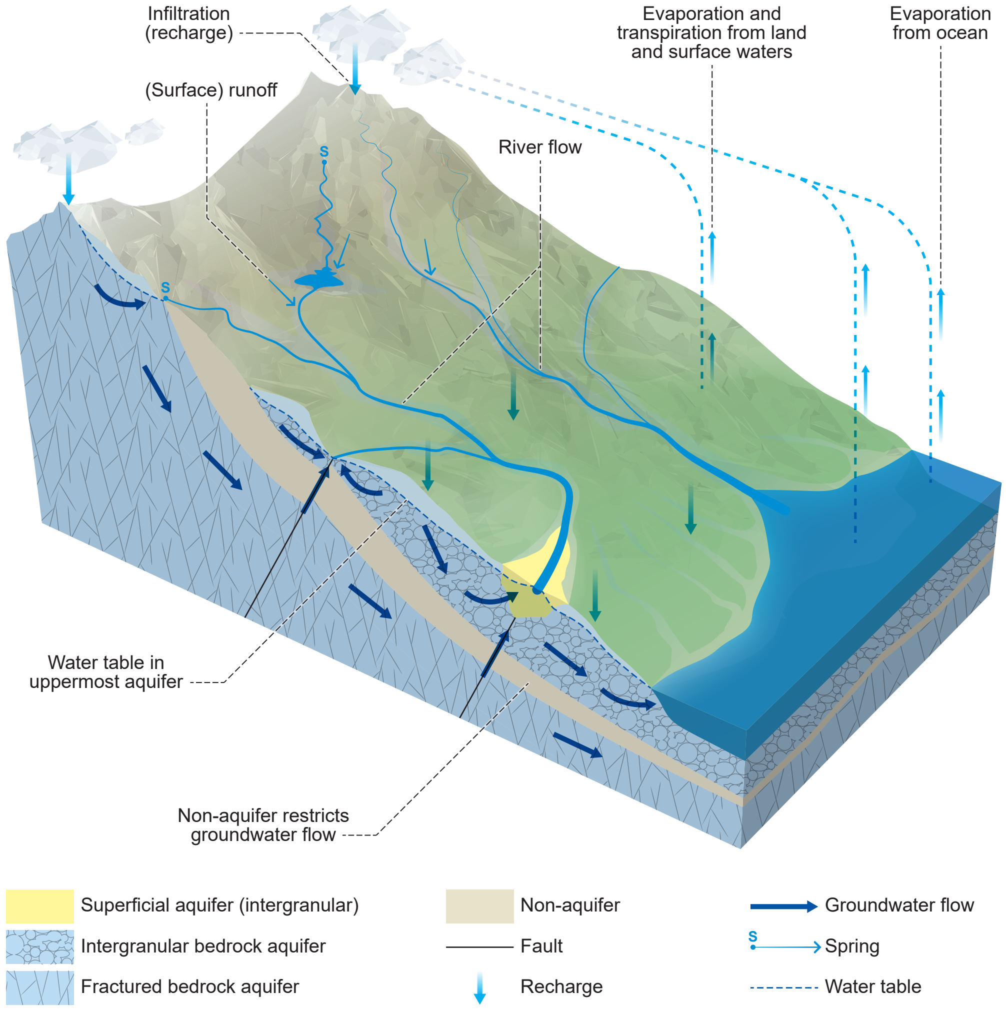


Figure 3. Water cycle: the role of groundwater in the hydrological cycle. BGS © NERC 2022.

Although surface water and groundwater both originate in rainfall, their chemistry can become quite different from each other. The chemistry of Northern Ireland's groundwater varies naturally from one aquifer to another and is influenced by many factors, including:

- lithology
- mineral reactions and redox (oxidation) conditions of the aquifer and any overlying soils and sediments
- hydrogeological properties of the aquifer that control groundwater flow paths and residence times

1.2.2 The role and management of groundwater in Northern Ireland

Groundwater plays an important role in Northern Ireland's environment, society and economy. It provides a reliable source of water for drinking, agriculture, industry (including the agri-food sector) and recreation (Glovers, 1996). Groundwater is often accessible close to where it is required and usually needs less treatment before use than surface water supplies from lakes, rivers or reservoirs.

Groundwater currently only provides a minor component (less than one %) of Northern Ireland's public water supply, but in the 1990s it supplied 102 megalitres per day (ML/d), which was 14 % of public water supply (Robins, 1996). Groundwater also provides most private water supplies in Northern Ireland, including over 99 % of the approximately 170 large private supplies currently registered with the Drinking Water Inspectorate and most of the approximately 3000 single-dwelling domestic sources, the majority of which are shallow wells, with some springs. Most of these are for domestic or individual farm use, but some private groundwater abstractions from boreholes, wells or springs are used to supply water for large agricultural and industrial businesses, hospitals (such as Belfast City and Ulster hospitals), large public buildings (such as the Lyric Theatre in Belfast), and educational establishments (such as Queen's University Belfast).

Groundwater abstractions of 20 cubic metres per day (m^3/d) or greater, for public or private supply, are licensed. Licenses totalling 90 ML/d have been issued in Northern Ireland, although license returns indicate that only 30 % (about 30 ML/d) of this allowance is currently used.

Small water supply abstractions of less than 20 m^3/d are not licensed or measured but the total volume of current groundwater abstraction from small supplies is estimated at about 20 ML/d, based on the number of small, private groundwater supplies recorded and assuming average values for domestic or small farm abstraction. In the past, before widespread mains water supply, groundwater was used much more for private supply. In the 1930s, groundwater-sourced private water supplies are estimated to have provided 33 ML/d (Robins, 1996).

The total volume of actual groundwater abstraction in Northern Ireland today is about 50 ML/d, although active licenses are in place for more than double this. Applying a conservative economic value of £1.04/m^3 (Northern Ireland Water's current commercial rate), the current use of groundwater has a value of approximately £31.2 million annually to the local economy.

Groundwater also plays a critical environmental role, supporting surface-water ecosystems by providing baseflow to rivers, loughs and wetlands throughout the year. Hydrological modelling to predict river flows in ungauged catchments (Young *et al*., 2003) indicates that, on average, groundwater contributes at least 30 % of the annual flow in all rivers in Northern Ireland, even in small upland rivers, rising to over 60 % in some rivers in drier periods (Figure 4). By helping to maintain healthy river ecosystems, including ecologically important wetlands and fragile ecosystems such as our humid dune slacks and fens, groundwater not only supports a healthier and more diverse environment but also indirectly supports tourism, another important part of Northern Ireland's economy.

Another environmental function provided by aquifers is helping to manage surface-water drainage through infiltration-based sustainable drainage schemes (SuDS) and to mitigate flooding in natural settings by accepting and storing excess surface-water flows. In some circumstances, groundwater can also help dilute and break down concentrations of certain contaminants by natural attenuation (degradation), although there is generally a limited capacity for this that, if overwhelmed, will lead to groundwater, and sometimes surface water, contamination.

Groundwater in Northern Ireland is managed by various government departments and agencies. At the time of publication (2023) the Northern Ireland Environment Agency (NIEA), an

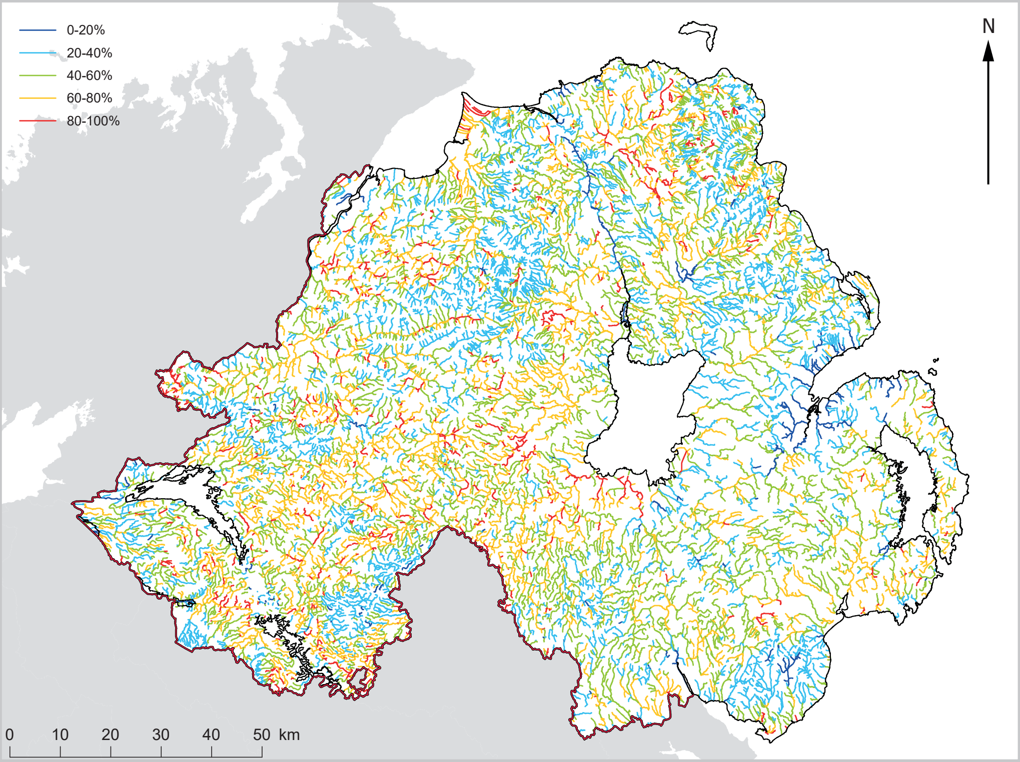


Figure 4. Baseflow indices map of Northern Ireland's rivers. A baseflow index (BFI) of 1 indicates that 100 % of the water in a river is derived from baseflow, which is predominantly from groundwater. This map was produced for the NIEA using the LowFlows Enterprise model (Young *et al.*, 2003). Crown Copyright MOU577.3. Contains OGL and CC-BY-4.0 Data

executive agency within the Department of Agriculture, Environment and Rural Affairs (DAERA), is responsible for the protection and conservation of groundwater. A detailed description of how the NIEA manages and protects groundwater is provided in Chapter 4.1. The Drinking Water Inspectorate is a unit within the NIEA responsible for the regulation of drinking water quality from both public and private water supplies. Northern Ireland Water Limited is the sole provider of public water supply throughout Northern Ireland, including groundwater-sourced public water supplies, and is a Government Owned Company (GoCo), a non-departmental public body sponsored by the Department for Infrastructure.

2. Groundwater data

2.1 Northern Ireland Groundwater Data Repository

The Northern Ireland Groundwater Data Repository (NIGDR) is a digital database that brings together groundwater data for Northern Ireland. The NIGDR is held at the GSNI. An online index to the NIGDR is available via the GSNI GeoIndex, showing where and what data are available; more detailed data are available on request by application to GSNI. There is currently no statutory responsibility for groundwater information to be deposited with GSNI for entry to the NIGDR, but any new submissions of groundwater data are welcomed.

The data in the NIGDR include aquifer properties obtained from test pumping, groundwater chemistry analyses and both one-off and time-series groundwater level measurements. The NIGDR holds data gathered from many individual groundwater investigation and development projects, as well as environmental assessment studies that included groundwater measurements previously held separately, such as in project or site reports, and in various formats, often only on paper.

The key data sources from which the NIGDR was populated are:

- NIEA Groundwater Quality Monitoring Network, which in 2021 included 56 monitoring sites (boreholes or springs) (Chapter 4.1.2)
- NIEA Groundwater Level Monitoring Network, which in 2021 included 16 monitoring boreholes (Chapter 4.1.2)
- GSNI borehole database, which holds information on some 24 000 boreholes drilled for various purposes, including water supply and site investigation
- GSNI hydrogeology reports collection, including documents by GSNI and other agencies. These include environmental impact and hydrogeological risk assessment reports, pumping test reports, research papers and academic theses. The locations of sites for which hydrogeology reports are available can be seen on the GSNI GeoIndex. Reports of particular relevance to this overview are:
  - reports on the Lagan Valley Hydrogeology Project, an in-depth hydrogeological investigation of the Permo-Triassic Sandstones Aquifer in the Lagan Valley (Bennett, 1976)
  - reports on Northern Ireland Water studies from the 1960s to the 1980s (Bennett, 1985, 1978a; Benfield, 1971; Benfield and Price, 1971; Foster, 1969a; Manning, 1971a; Price, 1973)
  - a BGS survey of boreholes and wells across Northern Ireland (Robins *et al.*, 1995)
  - reports from the Rural Borewell Scheme (2012–2014), a Northern Ireland Government programme to provide improved private water supplies to isolated domestic properties that were not served by mains water, which involved the drilling and hydrogeological testing of 74 successful groundwater boreholes across Northern Ireland
- approximately 400 geological and hydrogeological logs and reports for newly drilled water boreholes with information collected by drillers and deposited with GSNI
- geological memoirs and technical reports

The development of the NIGDR was a key prerequisite to the updated overview of groundwater and aquifers in Northern Ireland presented in this book and to the accompanying digital aquifer map. To populate the database, relevant information was identified and collated

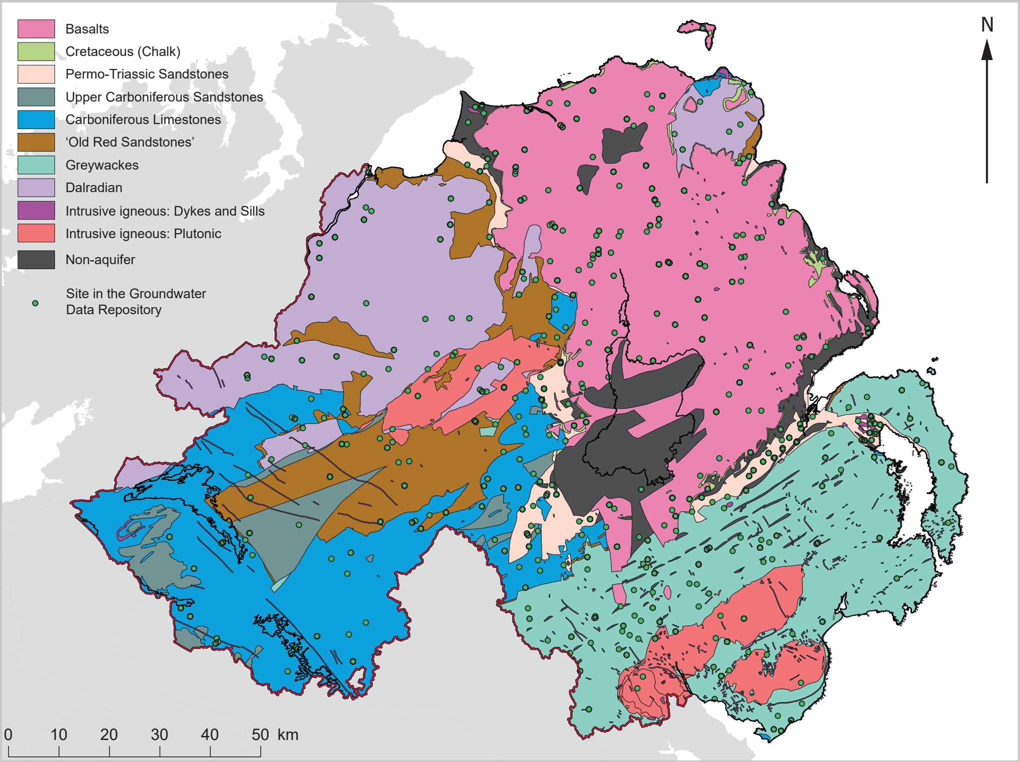


Figure 5. Locations of aquifer property and groundwater chemistry data in the NIGDR. Contains OGL and CC-BY-4.0 Data

from the sources mentioned, data quality was checked and assessed, and raw data were analysed and interpreted where relevant. Consistent quality assurance procedures were developed and applied to assess the reliability of aquifer properties and groundwater chemistry data entered into the NIGDR (Ó Dochartaigh and Wilson, 2021).

2.2 Overview of available groundwater data for Northern Ireland

The NIGDR holds data from over 2500 individual sites; these are either water boreholes or springs. For most of these, only basic information – often only site location, borehole depth (if relevant) and the aquifer from which the source derives abstracts – is available, but for a number of sites there are aquifer properties or groundwater chemistry data or both (Figure 5).

'Aquifer property data' refers to one or more measurement of:

- transmissivity (available for 119 sites)
- storativity (59 sites)
- specific capacity (230 sites)

All of these are derived from:

- borehole test pumping
- hydraulic conductivity (66 sites), largely derived from in situ testing such as slug testing
- porosity (7 sites), from laboratory analysis of rock core
- borehole yield (860 sites), usually from a single record of test or normal operating yield (Table 1)

Where more than one aquifer property data type was available for any one site, such as transmissivity values from two different pumping tests on the same borehole, single preferred aquifer property values were derived for each site and are used here. The methodology for

Parameter	n *	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean (except Porosity*)	75th Percentile	Maximum
Transmissivity (m^2/d)	119	100%	0.08	28.6	124	112	462	6000
Storativity [-]	59	100%	1.36×10^{-06}	0.0001	0.001	0.001	0.008	0.45
Specific capacity (m^2/d)	230	68%	0.026	6.23	28.4	28.6	153	43200
Hydraulic conductivity (horizontal) (m/d)	66	100%	1.74×10^{-07}	0.0009	0.008	0.009	0.50	373038
Porosity (%)	7	100%	5.00	13.0	24.0	20.9*	25.8	40.0
Measured yield (m^3/d)	860	22%	0.24	58.6	158	156	546	5711

* Porosity is an arithmetic mean

Table 1. Summary of available aquifer properties data for all aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	3108	0	280	366	472	577	690
pH	3188	0	6.69	7.17	7.50	7.80	8.14
Dissolved oxygen (mg/L)	150	0	4.90	6.20	7.50	8.70	9.70
Calcium (Ca) (mg/L)	3076	0	23.0	35.6	48.4	64.1	88.8
Magnesium (Mg) (mg/L)	3091	0	5.84	11.0	19.0	26.1	31.0
Sodium (Na) (mg/L)	3131	0	10.2	15.0	19.8	30.9	53.0
Potassium (K) (mg/L)	3080	1	0.46	0.79	1.44	2.37	4.20
Chloride (Cl) (mg/L)	3146	0	12.3	15.8	21.5	31.4	48.7
Sulphate (SO_4) (mg/L)	3130	1	5.59	9.7	15.9	28.0	46.8
Bicarbonate (HCO_3) (mg/L)	2525	0	120	175	233	280	329
Nitrate (as N) (NO_3-N) (mg/L)	3221	220	0.10	0.20	0.50	2.88	6.77
Phosphate (P) (mg/L)	2549	17	0.03	0.30	0.90	1.91	3.17
Aluminium (Al) (µg/L)	1341	188	2.60	8.0	13.0	30.4	98.4
Iron (Fe) (µg/L)	2760	11	7.0	11.0	22.6	145	513
Manganese (Mn) (µg/L)	2493	3	1.50	2.7	8.00	56.0	215

* Number of samples.
† Number below detection limit.

Table 2. Summary of selected chemistry data for all aquifers in Northern Ireland. These data were drawn from 415 groundwater sources (Table 3, Figure 5). The number of sources in each aquifer is shown in Table 3.

deriving a single preferred value is described in Ó Dochartaigh and Wilson (2021). Borehole yield and specific capacity are included in the NIGDR because they provide useful quantitative data on aquifer properties, especially where there are few other data, and both show a significant correlation with transmissivity in similar aquifers in Scotland (Graham *et al.*, 2009).

'Groundwater chemistry data' refers to one or more values for conductivity (specific electrical conductance), pH or major ion parameters. In most cases, this includes all of these for

Aquifer	Number of groundwater sources with chemistry data
Superficial deposits	15
Basalts	119
Cretaceous (Chalk)	2
Permo-Triassic Sandstones	47
Upper Carboniferous Sandstones	5
Carboniferous Limestones	53
‘Old Red Sandstones’	34
Greywackes	79
Dalradian	40
Intrusive igneous: Dykes and Sills	7
Intrusive igneous: Plutonic	14
Total	415

Table 3. Number of groundwater sources with groundwater chemistry data in each aquifer in Northern Ireland.

each available analysis; less commonly, it includes the trace ions iron, manganese or aluminium, as well as dissolved oxygen content (Table 2). Chemistry data are available for 437 sites. For just under half (229) of these sites, only one chemistry analysis is available and, for the remainder, there is more than one analysis, done on samples collected at different times. Many of these sites with multiple analyses are part of the NIEA Groundwater Monitoring Network (Chapter 4.1.2).

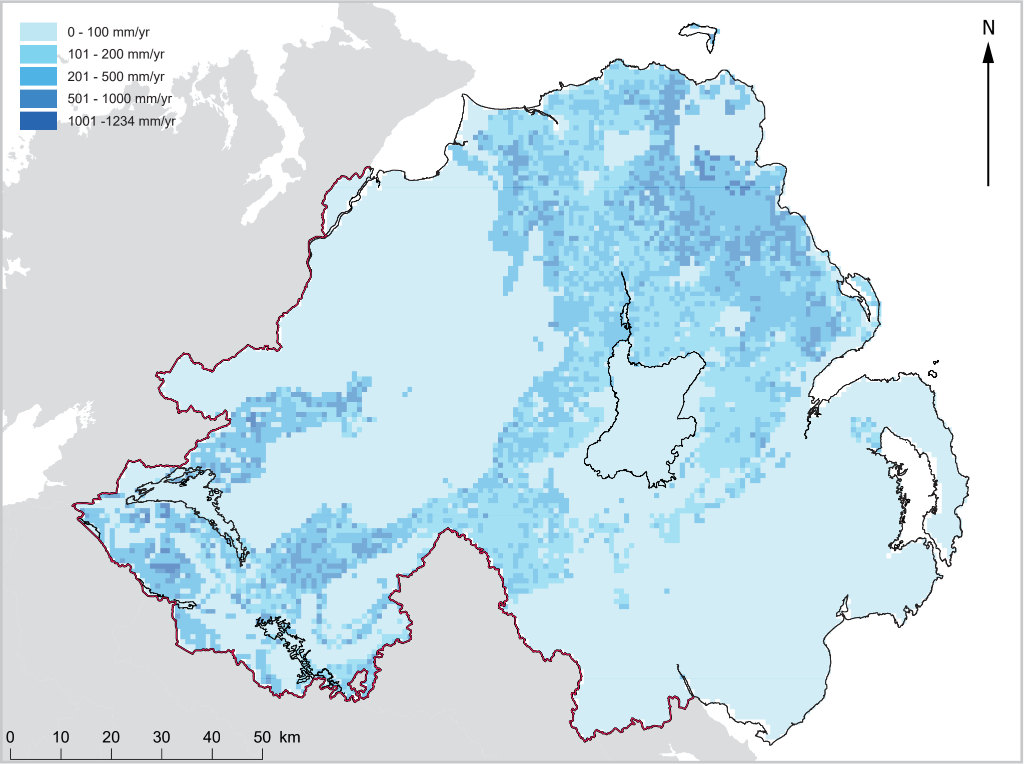


Figure 6. Estimated recharge to aquifers in Northern Ireland (Neary, 2012). Contains OGL and CC-BY-4.0 Data

2.2.1 Northern Ireland groundwater recharge map

A map of estimated recharge developed by GSNI (Figure 6) has been used by the NIEA in catchment water balance assessments as part of ongoing water management activities and for assessing new applications for abstraction licenses, although the map is not publicly available. The development of the map is described in Gibson (2010) and Neary (2012) and a summary of the methodology is given in Appendix 2.

3. Aquifers and hydrogeology of Northern Ireland

3.1 Introduction

This section provides an overview of the main aquifers in Northern Ireland. Eleven distinct aquifers have been classified (Figures 1 and 2; Table 3) comprising ten separate bedrock aquifers, based on the dominant lithologies, alongside a single category for unconsolidated, superficial deposit aquifers. The eleven named aquifers are:

- Superficial deposits
- Basalts
- Cretaceous (Chalk)
- Permo-Triassic Sandstones
- Upper Carboniferous Sandstones
- Carboniferous Limestones
- 'Old Red Sandstones'
- Greywackes
- Dalradian
- Intrusive igneous: Dykes and Sills
- Intrusive igneous: Plutonic

Each aquifer represents specific geological formations of different rock types and ages, which are summarised in Table 3 and listed in detail in the relevant section (Chapters 3.5 to 3.12). These aquifer names are often colloquial terms and, despite using what could be regarded as outdated geological terminology, these are used regularly by hydrogeologists and others involved in groundwater management. Each aquifer is described separately in these sections, with information on:

- aquifer geology
- typical overlying soils and any other overlying unconsolidated sediments
- physical aquifer properties
- groundwater recharge, flow and discharge patterns
- groundwater chemistry

There is also information on groundwater use, history of exploration, management and potential for each aquifer. The spatial extent of the aquifers is shown in Figure 1 and an overview of aquifer characteristics is presented in Table 4. A statistical comparison of key physical properties (transmissivity; storativity; borehole yield) for each aquifer is presented in Figure 5 and graphs comparing key groundwater chemistry parameters for each aquifer are presented in Figures 6 and 7.

3.2 How are the aquifers defined?

Almost all of Northern Ireland is underlain by one of the eleven distinct aquifers described in this book (Figure 1). Only a small area is underlain by rocks that are categorised as 'non-aquifers' – rocks that have such low permeability and storage capacity that they cannot generally provide useful groundwater supplies or significant environmental flows.

Aquifers are largely defined by differences in geological age and lithology. Both of these must be considered, since some rocks of similar geological ages have very different lithologies and therefore different hydrogeological characteristics. Aquifer boundaries for Northern Ireland were delineated using GSNI's published 1:250 000-scale, two-dimensional digital bedrock and superficial deposits geology data which are published as paper 1:250 000-scale maps of superficial (GSNI, 1991) and bedrock (GSNI, 1997) geology. These show the lateral extent and boundaries of the uppermost formations in the geological sequence: for superficial deposits, this is the ground surface; for bedrock, it is either the ground surface (if bedrock is exposed at the ground surface) or rockhead (the upper boundary of the uppermost bedrock formation, if bedrock is overlain by superficial deposits).

Two-dimensional maps do not show how the geology changes with depth and, at present, detailed three-dimensional geological models are not available for Northern Ireland. However, aquifer characteristics at depth can be assessed using borehole records and local studies. The three-dimensional conceptual models presented in this book help to visualise the three-dimensional nature of aquifers and are a reminder that hydrogeological maps must be interpreted with a depth component in mind. They have been drawn to represent the more common geomorphological settings where such aquifers are found in Northern Ireland and are therefore not location specific, but rather a guide to enable site-specific conceptual models to be developed.

McConvey (2005) developed a classification system for Northern Ireland's aquifers for the delineation of groundwater bodies as part of Water Framework Directive (2000/60/EC) assessment. The system is based on aquifer productivity potential and the mechanism of groundwater flow (intergranular; fracture; karst) and is incorporated in the aquifer descriptions presented here (Table 3 and relevant chapters). The aquifer classes are described in Appendix 1.

3.3 Specific hydrogeological concepts for Northern Ireland

3.3.1 Fractured aquifers

In most bedrock aquifers in Northern Ireland, groundwater is stored and transported predominantly, or only, in fractures within the rock (Figure 3). In these aquifers, there is little or no intergranular (matrix) porosity or permeability and therefore intergranular flow is minimal, or at most forms only a minor component of groundwater flow. The hydrogeology of fracture-dominated aquifers is highly variable; historically it has received less attention than often more productive intergranular or karstic aquifers and so is often less well understood, despite fractured aquifers being locally and even regionally important (Ofterdinger *et al.*, 2019).

The conceptual model of metamorphic and igneous ('hard rock') fractured aquifers in Ireland described by Comte *et al.* (2012) is also relevant to many of the fractured bedrock aquifers in Northern Ireland, in particular the Greywackes, Plutonic and Dalradian aquifers. This builds on a standard, three-layered model of such aquifers long-used in the Republic of Ireland (Moe *et al.*, 2010). The models define zones of distinctly different groundwater flow patterns with depth in fractured aquifers, controlled by the degree of weathering and fracturing.

The shallowest zone, which may be less than 5 m thick, is highly weathered bedrock, often with some, usually low, intergranular permeability and storage as well as fracture permeability, sometimes called the transition zone. Below this is a shallow bedrock zone of largely unweathered but variably fractured bedrock. The transmissivity and storage capacity of this zone depend on the number, size and interconnectedness of the fractures, but it can store and transmit significant volumes of groundwater. Below this is a deep bedrock zone of massive, unweathered and largely unfractured bedrock, with little transmissivity and storage capacity and little groundwater.

The thickness of these zones varies depending on the bedrock geology, structural history, overlying deposits and geomorphology, but the base of effective groundwater flow in the fractured bedrock zone is rarely more than about 100 m depth.

3.3.2 Hydrogeological impact of dykes on other aquifers

Dykes and sills are classed here as a minor aquifer in their own right and are described in Chapter 3.12. Dykes are also unique among other rock types in Northern Ireland in having a significant effect on the hydrogeology of other, more extensive, aquifers, impacting groundwater flow dynamics in these aquifers in complex ways. This is described in Chapter 3.12.4.

3.3.3 Hydrogeological impacts of faults

All of Northern Ireland's bedrock is affected by faults. These can occur as single fractures, but more often are zones of multiple fractures between opposing blocks of rock. Faults and fault zones allow blocks of rock to move relative to each other, usually very slowly in the form of millimetres of rock creep over thousands of years.

Some of the largest geological faults in the UK are in Northern Ireland, including, for example, the Tow Valley, Clogher Valley and Newry faults, which are shown on the bedrock geology map at 1:1 250 000 scale (BGS, 2017). Fault zones associated with these larger faults can be tens to hundreds of metres wide and hundreds of kilometres long.

For every large fault there are countless smaller faults at a range of scales, from regional to quarry to outcrop and even microscopic proportions. Most smaller faults are not shown in detail or at all on geological maps: faults occur in all bedrock types across Northern Ireland, even where they are not mapped.

Faults can have a significant influence on the hydrogeology of the aquifers. They can impact groundwater flow dynamics in two main ways: as preferential flow paths for groundwater or by restricting groundwater flow. Some faults and fault zones are open fractures, increasing the permeability and storage capacity of the aquifer. This effect can be more marked in low-storage aquifers. These open-fracture faults can also be conduits for preferential groundwater flow.

The size, orientation and interconnectivity of faults and the intensity of faulting in an aquifer will influence the length and pattern of preferential flow paths along fault zones. Faults that intersect the ground surface or rockhead below permeable superficial deposits can act as preferential recharge pathways.

In many cases, faults form low-permeability zones and act to restrict groundwater flow, particularly lateral flow, in an aquifer. In some cases, this occurs where faults contain 'fault gouge'. Fault gouge is dominated by fine-grained sediment, formed by grinding and milling within the fault. It has low permeability and acts to restrict groundwater flow. If fault gouge is encountered in a borehole it can make drilling and borehole completion difficult and, if the gouge cannot be screened out of a completed borehole, fine-grained sediment may move into the borehole, causing siltation that can leave the borehole unusable.

Other faults are infilled with secondary minerals such as calcite or zeolite, which can reduce permeability so much that, in some cases, the faults become effectively impermeable. If groundwater flow is restricted enough, an aquifer can be compartmentalised into hydraulically isolated, fault-bounded blocks

There are big gaps in our knowledge of the age and orientation of faults (Worthington and Walsh, 2011; Cooper at al., 2012; Anderson *et al.*, 2018) and further research is needed to fully characterise them and their impacts on aquifers.

3.4 Comparative summary of aquifers

A comparative summary of the hydrogeological characteristics of the superficial and bedrock aquifers in Northern Ireland is provided in Table 4. Statistical comparisons of selected physical properties of each aquifer (transmissivity; storativity; yield) are presented in Figure 7. Statistical comparisons of selected chemical parameters for each aquifer are presented in Figure 8 (conductivity (SEC) and bicarbonate) and Figure 9 (pH and iron). The major ion chemistry of each aquifer is summarised in trilinear (Piper) diagrams in Figure 10.

Aquifer	Key lithostratigraphical units	Geological period	Aquifer type	Typical aquifer productivity/ groundwater supply potential
Superficial deposits	Glaciofluvial; alluvial; raised beach deposits	Quaternary	Intergranular	High
Basalts	Antrim Lava Group: Upper Basalt, Lower Basalt and Interbasaltic formations	Palaeogene	Fracture	Moderate
Cretaceous (Chalk)	Ulster White Limestone Group (Chalk); Hibernian Greensands Group	Cretaceous	Fracture (Chalk); Intergranular (Greensands)	High
Permo-Triassic Sandstones	Sherwood Sandstone and Enler groups; Red Arch Formation	Triassic, Permian	Intergranular and fracture	High
Upper Carboniferous Sandstones	Coal Measures and Millstone Grit groups	Carboniferous	Fracture	Moderate
Carboniferous Limestones	Leitrim / Kilsheery, Tyrone, Armagh, Ballycastle and Strangford groups	Carboniferous	Fracture & karst	High
'Old Red Sandstones'	Roe Valley, Holywood and Omagh Sandstone groups; Cross Slieve and Fintona groups	Devonian – early Carboniferous	Fracture	Moderate
Greywackes	Hawick, Gala and Crawford groups; Leadhills Supergroup	Silurian – Ordovician	Fracture	Low
Dalradian	Argyll and Southern Highland groups	Dalradian	Fracture	Low
Intrusive igneous: Dykes and Sills		Silurian – Ordovician and Palaeogene	Fracture	Low
Intrusive igneous: Plutonic	Tyrone Igneous, Newry Igneous, Slieve Gullion complexes; Mourne Granites	Ordovician, Devonian and Palaeogene	Fracture	Low

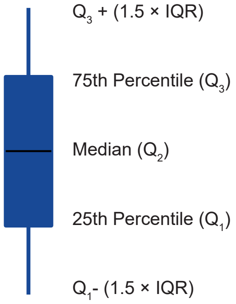
* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.
† The terms highly, moderately and weakly, and high, moderate and low, are used here in comparison to other aquifers in Northern Ireland.

Table 4. Summary of aquifer characteristics. For more detail see individual aquifer descriptions in Chapters 3.5 to 3.12.

	Aquifer class*	Typical groundwater flow path length (m)	Typical groundwater flow depth (m)	Groundwater flow rate	Dominant baseline groundwater chemistry[†]
	Sh(i)	10s to 100s	1–50	Slow	Moderately mineralised, moderate pH, bicarbonate – dominated, no dominant cation
	Bm(f)	10s to 100s (possibly 1000s in deeper zones)	1–100 (possibly deeper)	Medium	Moderately mineralised, high pH, calcium bicarbonate or sodium or potassium bicarbonate type
	Bh(f/k) (Chalk); Bh(f-k) (Green-sands)	100s	1–100	Chalk: fast in east; medium in west Greensands: probably medium	Weakly mineralised, high pH, calcium bicarbonate type
	Bh(l-f)	1000s	1–250	Slow	Highly mineralised, high pH, bicarbonate dominated with no dominant cation (minority calcium dominated)
	Bm(f)	10s to 100s (shallow zone)	100s to 1000s (deep zone) 10s to 100s (shallow zone)	Medium	Highly mineralised, high pH, bicarbonate dominated, no dominant cation
	Bh(f-k) (karstic limestones), Bm(f) (sandstones), Bl(f) (mudstones)	100s to 1000s	1–100	Fast	Highly mineralised, moderate pH, calcium bicarbonate type (minor sulphate)
	Bm(f), some Bl(f)	10s to 100s	1–50	Medium	Moderately mineralised, moderate pH, either no dominant cation or a slight dominance by calcium. Two distinct anionic groups: one dominated by bicarbonate and the other with no dominant anion
	Bl(f)	10s to 100s	1–50	Medium	Moderately mineralised, moderate pH, bicarbonate dominated or no dominant anion; no dominant cation (minority calcium)
	Bl(f)	10s to 100s	1–50	Medium	Moderately mineralised, low pH, calcium bicarbonate or no dominant anion or cation
	Bl(f)	10s to 100s	1–50	Medium	Weakly mineralised, moderate pH, bicarbonate dominated, no dominant cation
	Bl(f)	10s to 100s	1–50	Medium	Weakly mineralised, low pH, usually bicarbonate dominated with no dominant cation

Box plots

The box plots in Figures 7 to 9 provide a statistical summary of the aquifer properties and groundwater chemistry data. Each box shows the quartile range of the data: the lower edge of the box corresponds to the 25th percentile (Q1) and the upper edge to the 75th percentile (Q3); the central line in the box corresponds to the median. The interquartile range (IQR) is the difference between the 25th and 75th percentiles. The upper line extends upwards to 1.5 × IQR above the 75th percentile (or to the data point immediately below this value, if there is no data point at this value): Q3 + (1.5 × IQR). The lower line extends downwards to 1.5 × IQR below the 25th percentile (or to the data point immediately above this value, if there is no data point at this value): Q1 – (1.5 × IQR). The upper and lower lines can therefore be uneven in length.



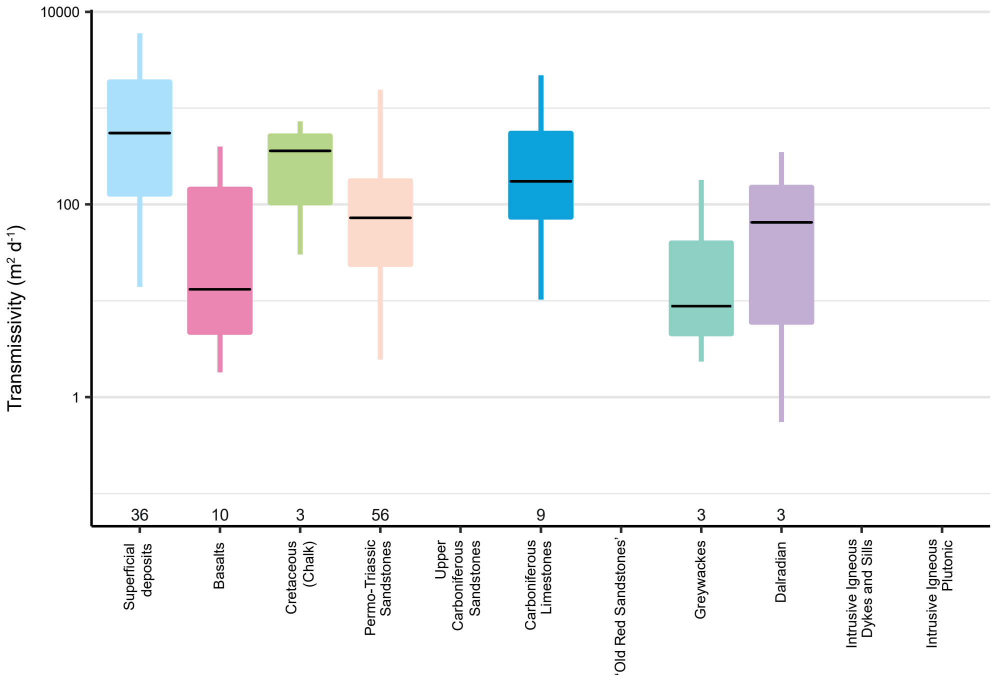
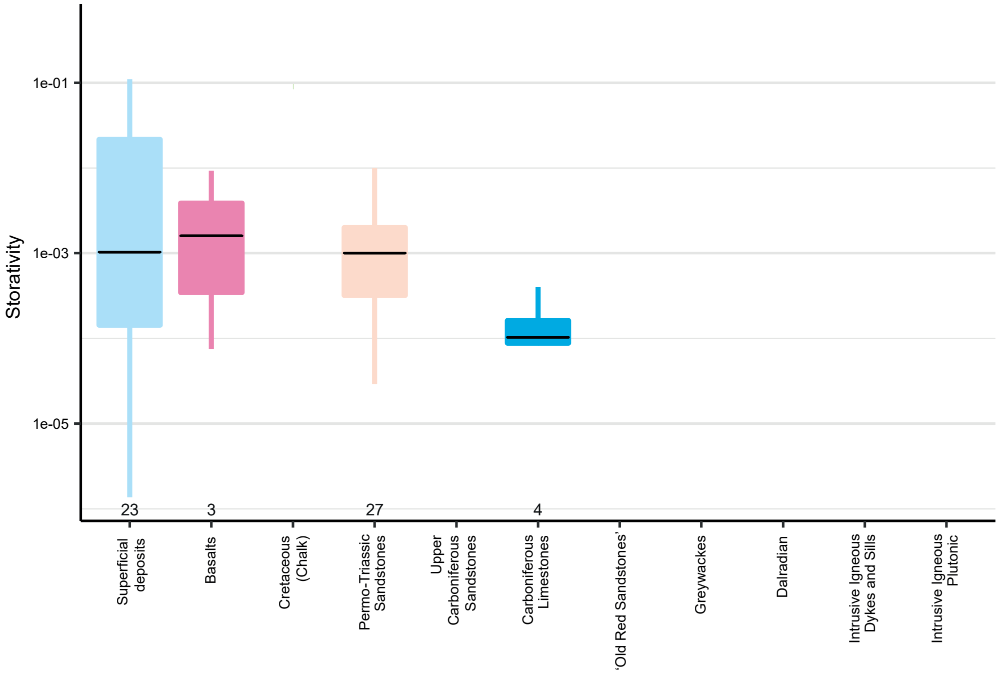
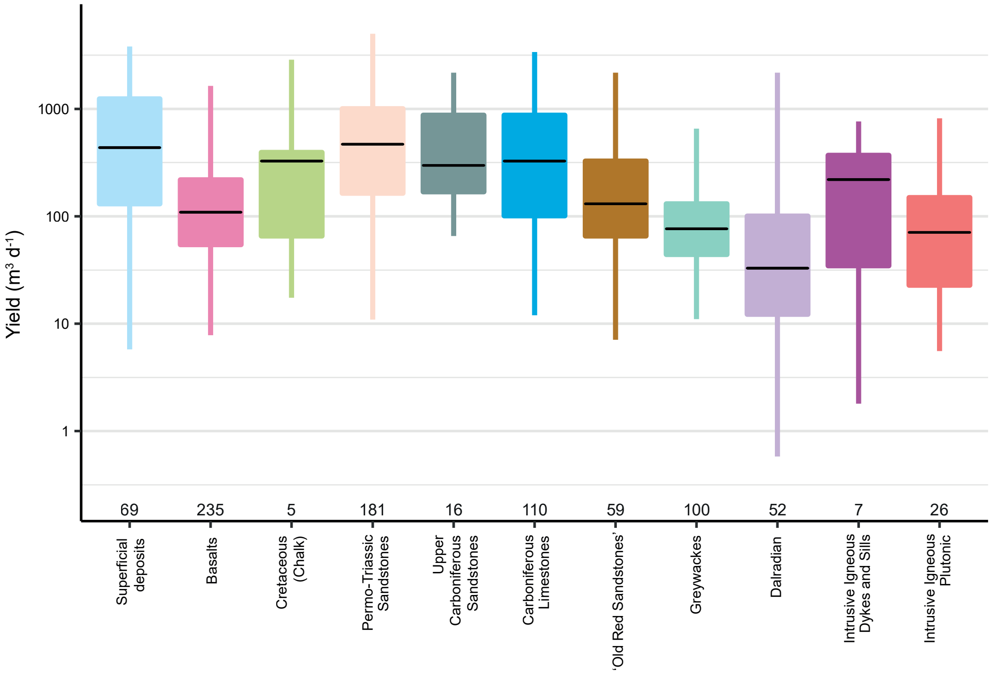


Figure 7. Box plots showing a statistical summary of transmissivity (above), storativity (opposite page, top) and yield (opposite page, bottom) in aquifers in Northern Ireland. Number of values (n) for each aquifer shown.


Storativity
1e-01
1e-03
1e-05
23
3
27
4
Superficial deposits
Basalts
Cretaceous (Chalk)
Permo-Triassic Sandstones
Upper Carboniferous Sandstones
Carboniferous Limestones
'Old Red Sandstones'
Greywackes
Dalradian
Intrusive Igneous Dykes and Sills
Intrusive Igneous Plutonic


Yield (m³ d⁻¹)
1000
100
10
1
69
235
5
181
16
110
59
100
52
7
26
Superficial deposits
Basalts
Cretaceous (Chalk)
Permo-Triassic Sandstones
Upper Carboniferous Sandstones
Carboniferous Limestones
'Old Red Sandstones'
Greywackes
Dalradian
Intrusive Igneous Dykes and Sills
Intrusive Igneous Plutonic

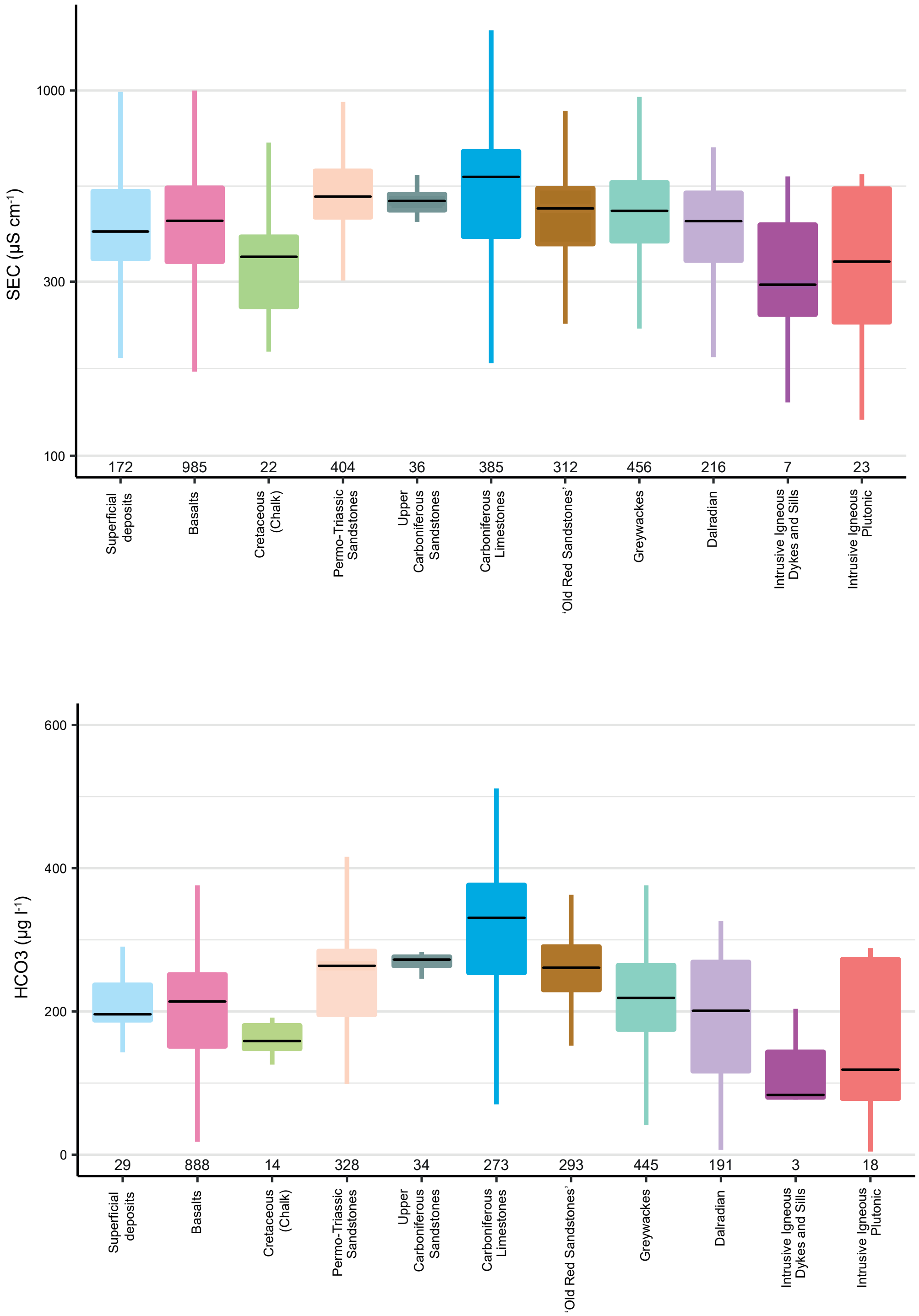


Figure 8. Box plots showing a statistical summary of groundwater conductivity (SEC) (top) and bicarbonate (bottom) in groundwater aquifers in Northern Ireland.

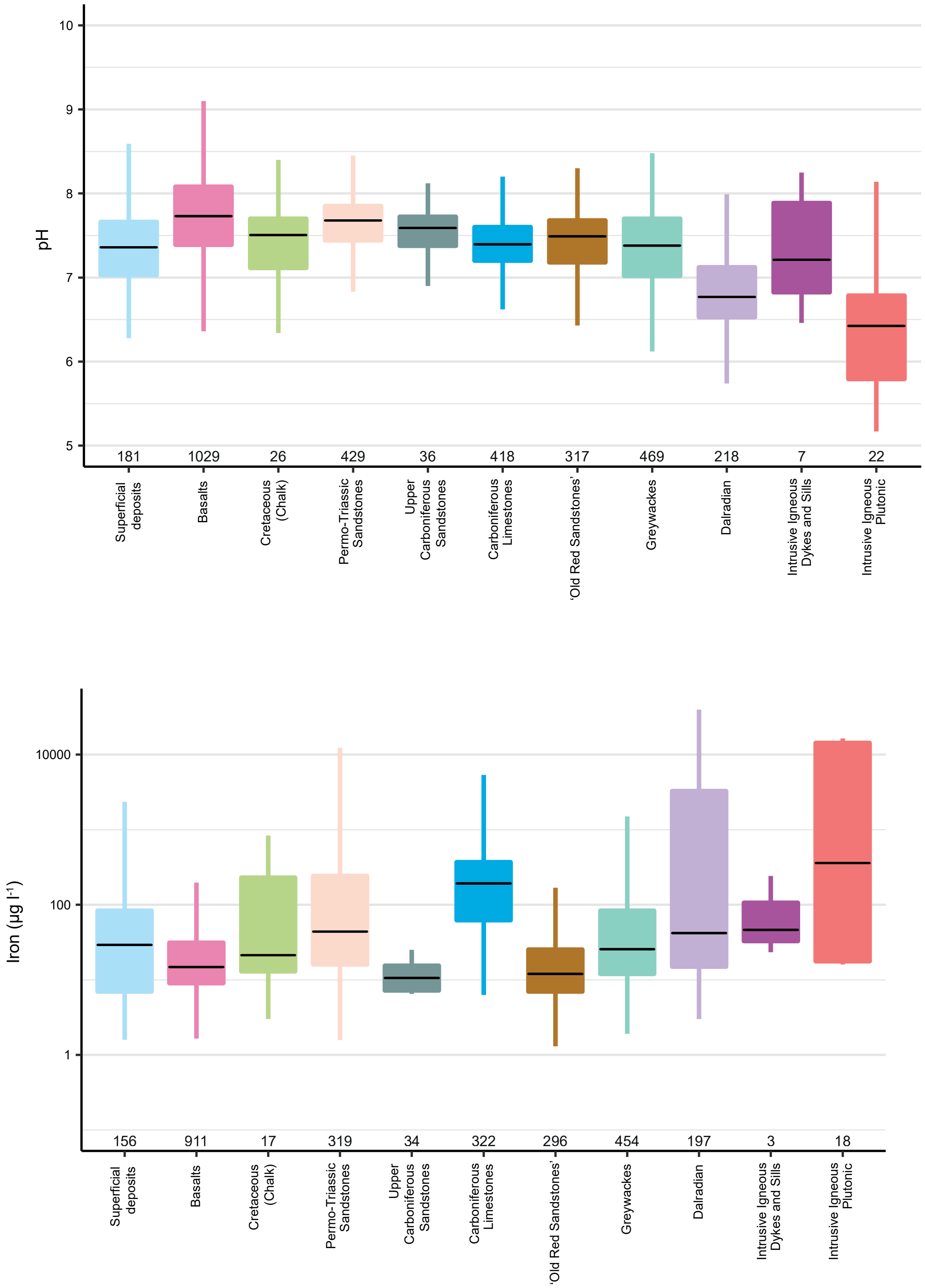
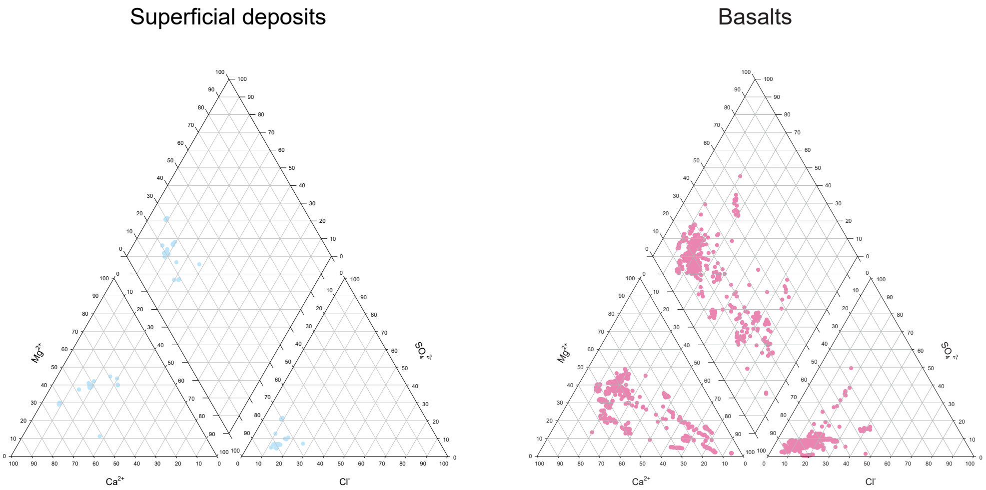
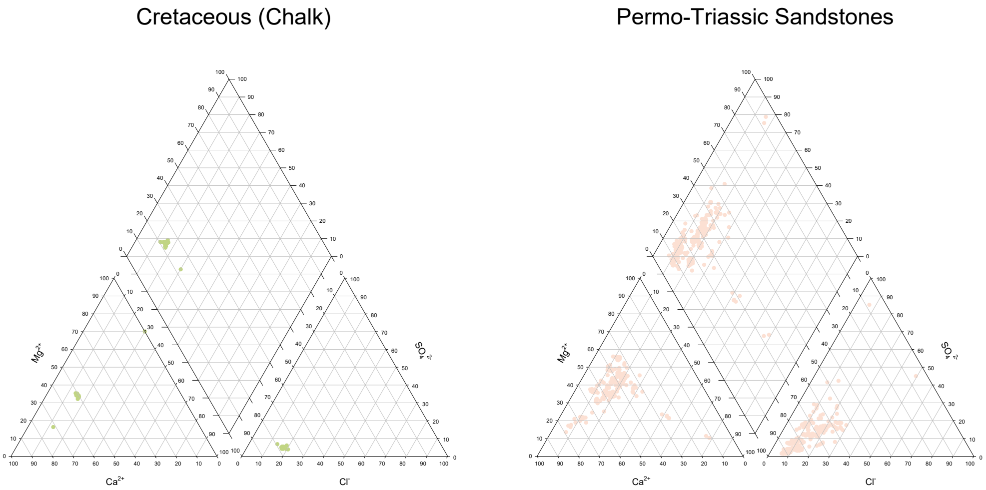


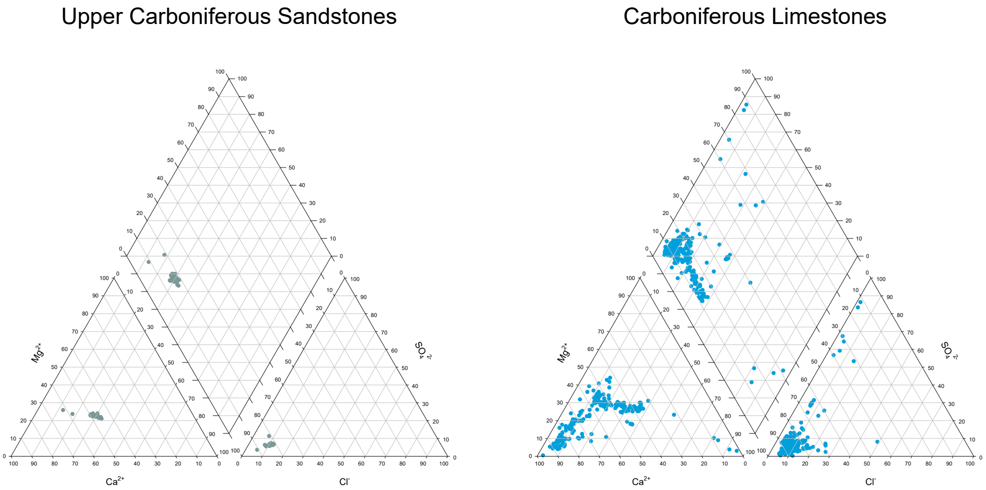
Figure 9. Box plots showing a statistical summary of pH (top) and iron (bottom) in groundwater in aquifers in Northern Ireland.


Superficial deposits

Basalts

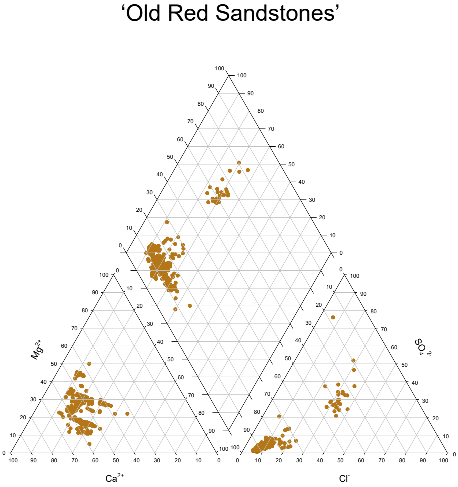

Cretaceous (Chalk)

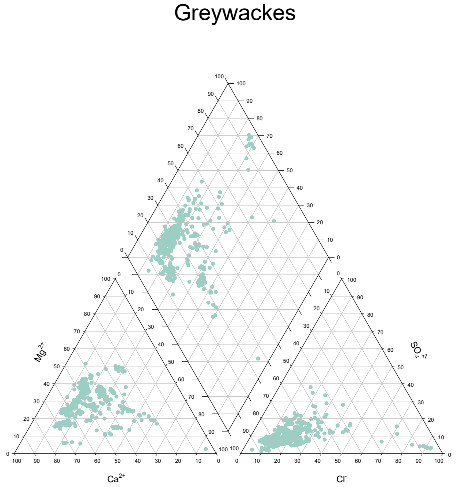
Permo-Triassic Sandstones

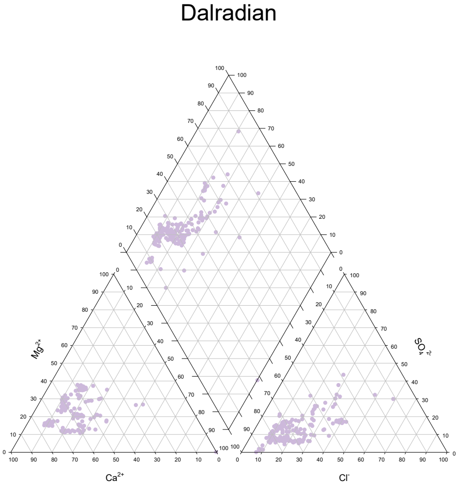

Upper Carboniferous Sandstones

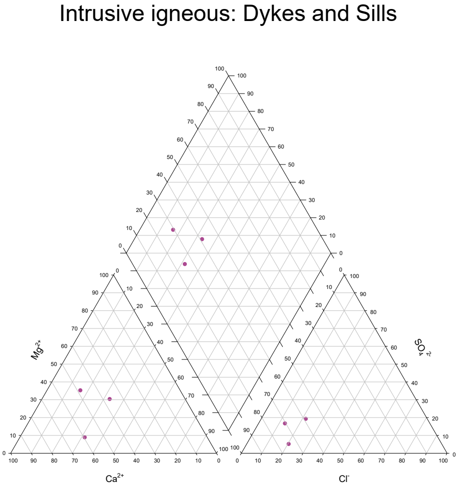
Carboniferous Limestones

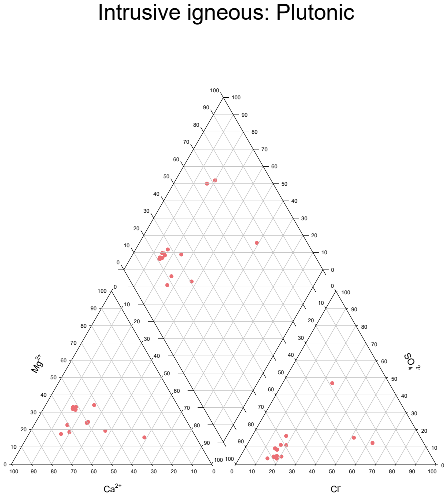
Figure 10 (this page and opposite). Piper (trilinear) diagrams illustrating the distribution of major ion compositions of groundwater in aquifers in Northern Ireland.


‘Old Red Sandstones’


Greywackes


Dalradian


Intrusive igneous: Dykes and Sills


Intrusive igneous: Plutonic

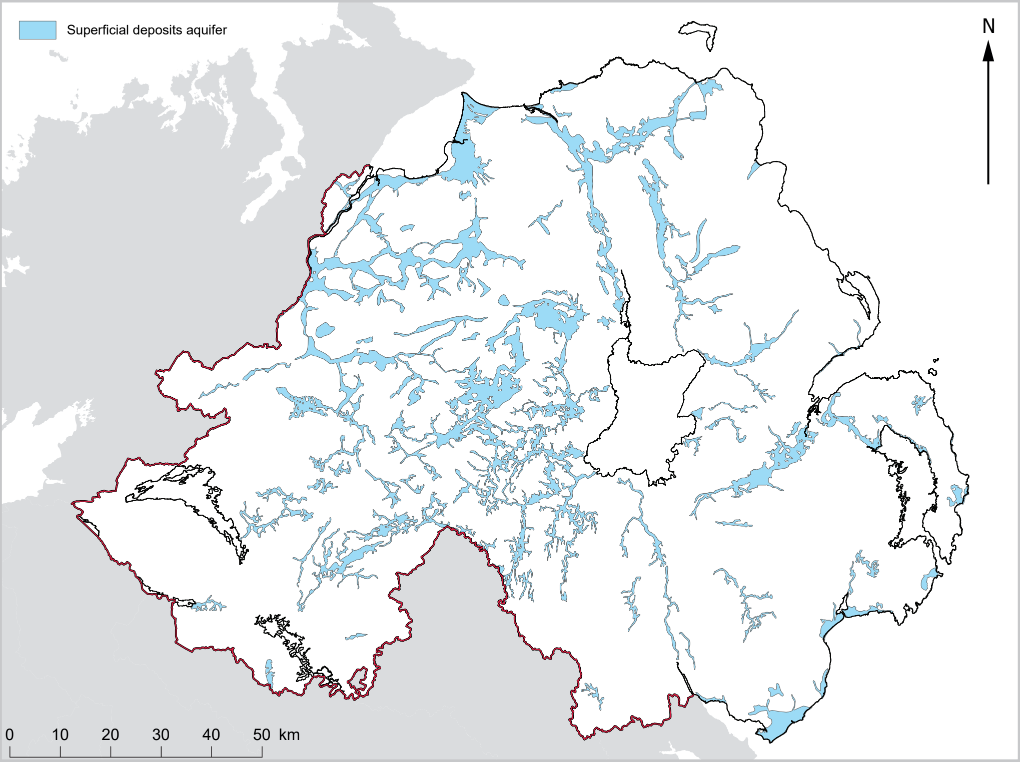


Figure 11. Map of the Superficial deposits aquifers in Northern Ireland. Contains OGL and CC-BY-4.0 Data

Photograph 1. Glaciofluvial landforms in The Sperrins, Co. Tyrone.

Photograph 2. Sand and gravel quarry with layered glaciofluvial deposits.

Aquifer type	Intergranular
Aquifer productivity/groundwater supply potential	High
Aquifer class*	Sh(i)
Typical groundwater flow path length (m)	10s to 100s
Typical groundwater flow depth (m)	1 – 50
Groundwater flow rate	Slow
Dominant baseline groundwater chemistry	Moderately mineralised, moderate pH, bicarbonate – dominated, no dominant cation.

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.5 Superficial deposits aquifers

3.5.1 Geological summary

Superficial deposits (unconsolidated sediments of Quaternary age) form a covering layer that overlies 90 % of the bedrock of Northern Ireland. Most of these sediments formed during deglaciation at the end of the last glacial maximum some 18 000 years ago (Mitchell, 2004). Only some of the superficial deposits form significant aquifers: those that are granular, coarse-grained (and therefore generally permeable) sediments that reach suitable thicknesses (more than 10 m). These include:

- glaciofluvial sands and gravels
- alluvial and estuarine sediments that are dominated by sands and/or gravels,
- some raised beach deposits
- wind-blown sands

Large deposits of glaciofluvial sand and gravels are the most important Superficial deposits aquifers in Northern Ireland. They formed as the result of glacial melting events, during which sediment was deposited by rapid, often high-flow meltwater rivers. They are found as linear outcrops in some of the main valleys across Northern Ireland, such as the Braid, Main, Bann, Lagan, Faughan and Strule, and form broader outwash plains, such as the Mourne Plain (GSNI, 1991). In valleys, alluvial sands and gravels often overlie aquifers in glaciofluvial deposits and may be in hydraulic continuity.

Around the coast are many raised beaches, often formed of coarse-grained, pebbly material deposited during the last glacial maximum and later raised by isostatic rebound and sea-level change. Other potential coastal Superficial deposits aquifers are wind-blown sand deposits, where they form dune systems of sufficient thickness and extent, such as Magilligan, Co. Londonderry and Murlough National Nature Reserve, Co. Down.

3.5.2 Hydrogeological conceptual model

Superficial deposits aquifers have primary (intergranular) porosity, transmitting and storing groundwater in the pore spaces between grains of sand and gravel. They are classed as highly or moderately productive, intergranular flow aquifers (Sh(I) or Sm(I)) (Appendix 1).

These aquifers are highly variable in their geological history, lithology, texture (e.g. sediment sorting), thickness and outcrop area, and therefore typically show a particularly wide range in aquifer properties. However, the available data show that, overall, Superficial deposits aquifers have the highest transmissivity values of all aquifers in Northern Ireland (Figure 7), with a median of 550 m^2/day, a geometric mean of 448 m^2/day, and an interquartile range of 56–1868 m^2/day, based on pumping tests on 36 boreholes (Table 5). This is similar to sand and gravel aquifers in the Republic of Ireland (geometric mean of transmissivity 350 m^2/day; interquartile range 160–1053 m^2/day (Kelly *et al.*, 2015)) and to Quaternary aquifers in Scotland (median transmissivity of 350 m^2/day; interquartile range of 98–844 m^2/day (Graham *et al.*, 2009)).

Gravels and sands of the types that make up these aquifers typically have high porosity and, consequently, high intergranular storage capacity. The available data from 23 tests show an interquartile range in storativity values (most of which are likely to be values for unconfined storage) from 0.0001 to 0.03 (Table 5). These values may underestimate the true storage capacity of these aquifers. Comparison with the few available data for sand and gravel aquifers

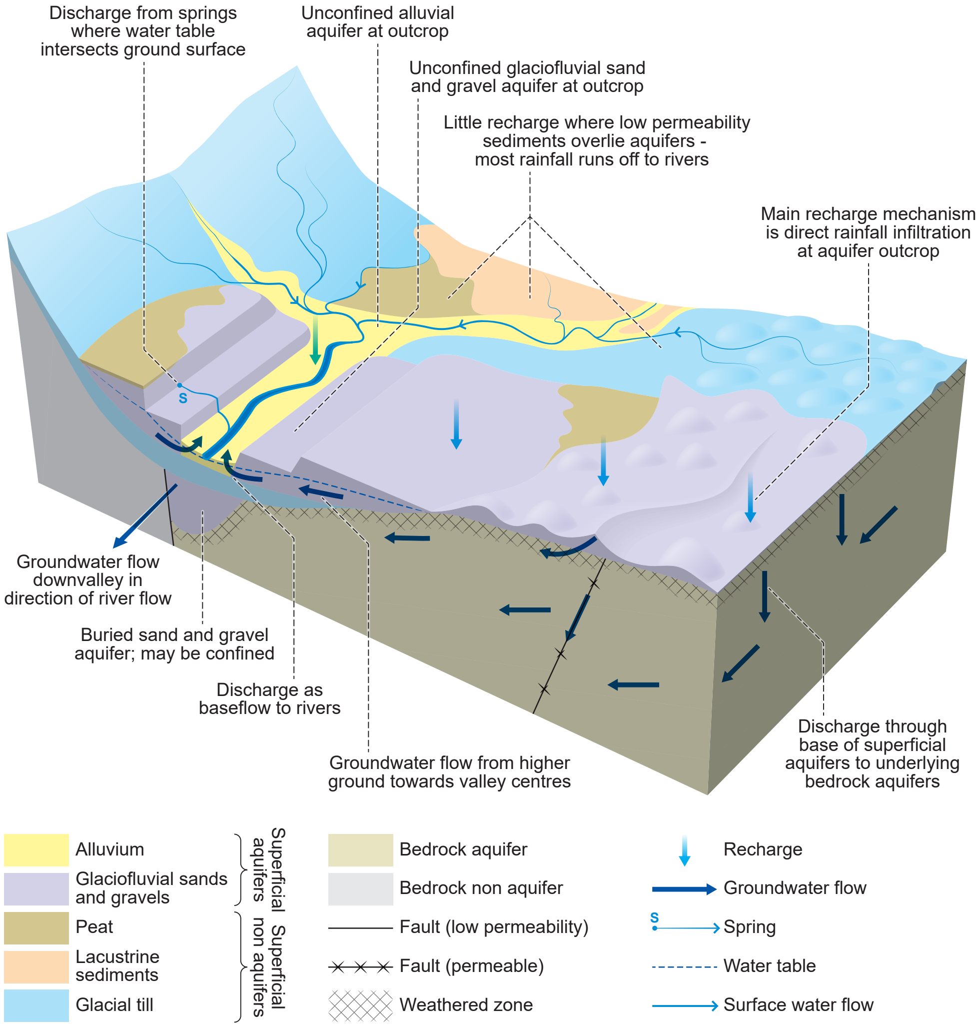


Figure 12. Conceptual model of the hydrogeology of Superficial deposits aquifers in Northern Ireland.

in the Republic of Ireland indicates that specific yield (unconfined storage coefficient) values of 0.1–0.2 are more common; and one study showed a range of storage coefficient values from a single gravel aquifer of 0.0003–0.003 (Kelly *et al*., 2015).

Most groundwater recharge to Superficial deposits aquifers is from direct infiltration of rain falling on the aquifer outcrop (Figure 12) (Robins *et al*., 1994). Some recharge also occurs indirectly, through infiltration of river water through permeable beds and banks or via rainfall run-off onto the aquifer outcrop from less permeable ground, such as glacial till or peat-covered hillslope onto a permeable superficial valley (Figure 12).

Groundwater flow paths in Superficial deposits aquifers are typically short – tens to hundreds of metres – and limited by the relatively small lateral extent of most Superficial deposits aquifer outcrops. The depth of flow is also shallow, limited by the thickness of the permeable superficial deposits (Figure 12). Groundwater flow rates are typically relatively slow (Robins *et al*., 1994).

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Transmissivity (m²/d)	36	100	1	129	550	448	1868	6000
Storativity	23	91	1.36×10^{-06}	0.0001	0.001	0.0013	0.033	0.17
Specific capacity (m³/d/m)	58	0.6	0.1	53.5	157	161	649	12343
Hydraulic conductivity (horizontal) (m/d)	14	100	6.94×10^{-05}	0.004	0.005	0.02	0.56	8.64
Measured yield (m³/d)	69	0.5	2	131	436	266	1241	3819

Table 5. Summary of available aquifer properties data for Superficial deposits aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	173	0	270	347	411	536	644
pH	181	0	6.79	7.03	7.36	7.66	7.86
Dissolved oxygen (mg/L)	10	0	3.29	6.23	7.45	7.5	7.64
Calcium (Ca) (mg/L)	172	0	30.8	33	41	66.1	81.2
Magnesium (Mg) (mg/L)	173	0	12	14.4	19.31	22.2	25.5
Sodium (Na) (mg/L)	173	0	10.1	11.8	15.7	18.2	34.8
Potassium (K) (mg/L)	173	0	0.38	0.52	0.83	1.32	2.63
Chloride (Cl) (mg/L)	174	0	14.2	16.4	19.1	24	38.1
Sulphate (SO_4) (mg/L)	173	0	8.33	11	13.4	17.7	69.4
Bicarbonate (HCO_3) (mg/L)	29	0	152	187.8	196	237	245
Nitrate (as N) (NO_3-N) (mg/L)	182	5	0.2	0.46	2.37	4.78	6
Phosphate (P) (mg/L)	104	0	0.01	0.01	0.03	0.06	0.11
Aluminium (Al) (µg/L)	81	9	0.4	2.43	13	25	51.5
Iron (Fe) (µg/L)	156	0	3	7	29.3	83.4	230
Manganese (Mn) (µg/L)	156	0	1.03	2	11	123	207

* Number of samples.
† Number below detection limit.

Table 6. Summary of baseline chemistry of Superficial deposits aquifers in Northern Ireland, based on samples from 15 groundwater sources.

Most of the larger Superficial deposits aquifers – in particular, large outcrops of glaciofluvial sands and gravels – are in lowland areas. Groundwater levels (water tables) in these aquifers are often closely associated with river levels and are usually shallow, with gentle hydraulic gradients. Depth to groundwater level rises away from rivers and up valley slopes.

Superficial deposits aquifers on higher ground tend to be smaller and include eskers, which typically stand out above the surrounding land. The higher elevation of eskers can result in steeper hydraulic gradients as groundwater recharge to these localised aquifers discharges rapidly. This means that eskers are usually largely unsaturated, with limited potential to support groundwater abstractions.

In sand dunes, groundwater levels are typically shallow, usually less than 1 m below ground level in slack areas between sand dunes. These slack areas often experience groundwater flooding in wet winters when groundwater levels rise above the ground surface (Robins and Wilson, 2017).

Groundwater discharge from Superficial deposits aquifers is often directly to rivers through permeable river banks and beds (Foster, 1969a), but it also occurs via springs, such as those from glaciofluvial gravels at Muntober near Cookstown, which have very large combined flow rates of around 2.2 ML/d (Robins, 1996). Springs in these aquifers can occur because of the heterogeneity of glaciofluvial sediments: for example, lower-permeability layers of silt and clay within the dominant sand and gravel, which restrict downward groundwater flow and direct it towards discharge points on the ground surface, or steep gradients within the aquifers, such as is seen in eskers or river-terrace deposits that are elevated above local rivers.

A lack of extensive investigation to date means that the interaction between rivers and groundwater in Superficial deposits aquifers in Northern Ireland still remains poorly understood. Evidence from similar hydrogeological environments elsewhere in Ireland (Misstear *et al*., 2009a) and in Scotland (Ó Dochartaigh *et al*., 2019; MacDonald *et al*., 2014) shows that groundwater in these aquifers is often closely connected to rivers, but that interactions between the two are complex. Along the length of a single river, the aquifers can be both influent (receiving recharge) and effluent (discharging groundwater as baseflow) at different times of year. Baseflow analysis using the LowFlows Enterprise model for Northern Ireland (Young *et al*., 2003) gives baseflow indices (BFI) of between 0.7 and 1.0 for river stretches underlain by Superficial aquifers, indicating that groundwater discharge is the main source of flow in these stretches.

These aquifers are generally unconfined, but confined and even artesian conditions can occur where aquifer layers are below low-permeability cover, such as peat or clay-rich alluvium; this is most common in relatively deep, laterally extensive glaciofluvial deposits beside rivers. In some cases, multilayered aquifers can occur within buried valley deposits where different aged and sourced sand and gravel deposits are separated by lower-permeability clay or peat deposits, such as at the River Bush, Co. Antrim.

Groundwater in Superficial deposits aquifers is typically moderately mineralised compared to groundwater in most other aquifers in Northern Ireland (the median conductivity – a proxy for overall mineralisation – is 411 microsiemens (µS/cm) with typically slightly alkaline pH (median 7.4) (Figure 8; Table 6). Concentrations of manganese are often above the drinking water quality standard, but iron is rarely above drinking water quality standard (NIEA, 2020). Bicarbonate is the dominant anion, but there is usually no dominant cation (Figure 10).

3.5.3 Groundwater use, history of exploration, management and potential of Superficial deposits aquifers

Prior to the widespread introduction of mains water supply across Northern Ireland from the 1950s, rural private water supplies were often obtained from shallow, large diameter, dug wells that in most cases drew groundwater from Superficial deposits aquifers (Manning, 1971a).

The generally high permeability and groundwater storage capacity of these aquifers makes them a good prospect for large abstractions and meant that they were some of the first aquifers in Northern Ireland to be subject to hydrogeological investigation and exploitation for large-scale use, beginning in the 1960s. A number of abstraction wellfields for public water supply were drilled and brought into commission in the most productive aquifers identified, most of which were glaciofluvial sands and gravels, some with minor overlying alluvial sediments forming part of the aquifer.

Their high permeability and storage capacity and general absence of any significant natural, low-permeability overlying sediments, mean Superficial deposits aquifers receive high rates of recharge. Combined with their generally shallow water tables, this makes them vulnerable to contamination from point and diffuse sources of pollution. Potential pollution sources include:

- septic tank percolation areas
- agricultural spreading of slurry, manure and fertilisers
- crop spraying with herbicide and pesticide

In one Superficial deposits aquifer in the Main Valley, Co. Antrim, groundwater nitrate concentrations, derived largely from agricultural sources, rose close to the drinking water quality standard of 50 mg/l by 2007, which resulted in Northern Ireland Water taking a public water supply wellfield out of service. A precautionary approach to the potential impacts of nitrate on Northern Ireland Water groundwater sources led to all other public water supply groundwater abstraction wellfields in Superficial deposits aquifers being subsequently taken out of service in 2008, despite their high productivity.

As well as containing a significant groundwater resource in their own right, the Superficial deposits aquifers in Northern Ireland provide options for conjunctive water storage. Exploratory studies in the 1960s (Foster, 1969a, b) found that some aquifers in glaciofluvial deposits within river valleys have an overlying strip of relatively low permeability alluvial deposits alongside and beneath the river, which can act as at least a partial barrier between water in the river and groundwater in the underlying glaciofluvial aquifer. This may allow a sustainable conjunctive abstraction regime from both a river and the underlying glaciofluvial deposits, which optimises the available groundwater storage in the aquifer while protecting minimum ecological flow (baseflow) requirements from the aquifer to the river.

Superficial deposits aquifers also present good prospects for supporting potential adaptations towards a low-carbon future in Northern Ireland. The ease of accessing large volumes of groundwater in the aquifers may offer potential for ground source heating and cooling, although as yet this has not been investigated widely.

The potential of Superficial deposits aquifers for buffering surface-water flooding is also present but has not yet been assessed. Evidence from similar valley systems in Scotland has shown a complex coupling of groundwater and surface-water response that may impact on surface-water flooding (Ó Dochartaigh *et al*., 2019; MacDonald *et al*., 2014).

As well as potentially mitigating surface-water flooding, groundwater flooding due to rising water tables in shallow Superficial deposits aquifer settings has been investigated in Scotland and England (MacDonald *et al*., 2008; MacDonald *et al*., 2014). It is likely that similar processes also occur in Northern Ireland and that, with climate predictions showing an increase in intensity and frequency of rainfall events, the potential for groundwater flooding events is likely to increase.

The main limits to useful groundwater resource potential from Superficial deposits aquifers are their often-limited spatial extent, saturated thickness and vulnerability to contamination. In general, their typically high transmissivity and high storage potential, combined with high rates of recharge, make them a good prospect for large water consumer industries that do not necessarily need potable water quality.

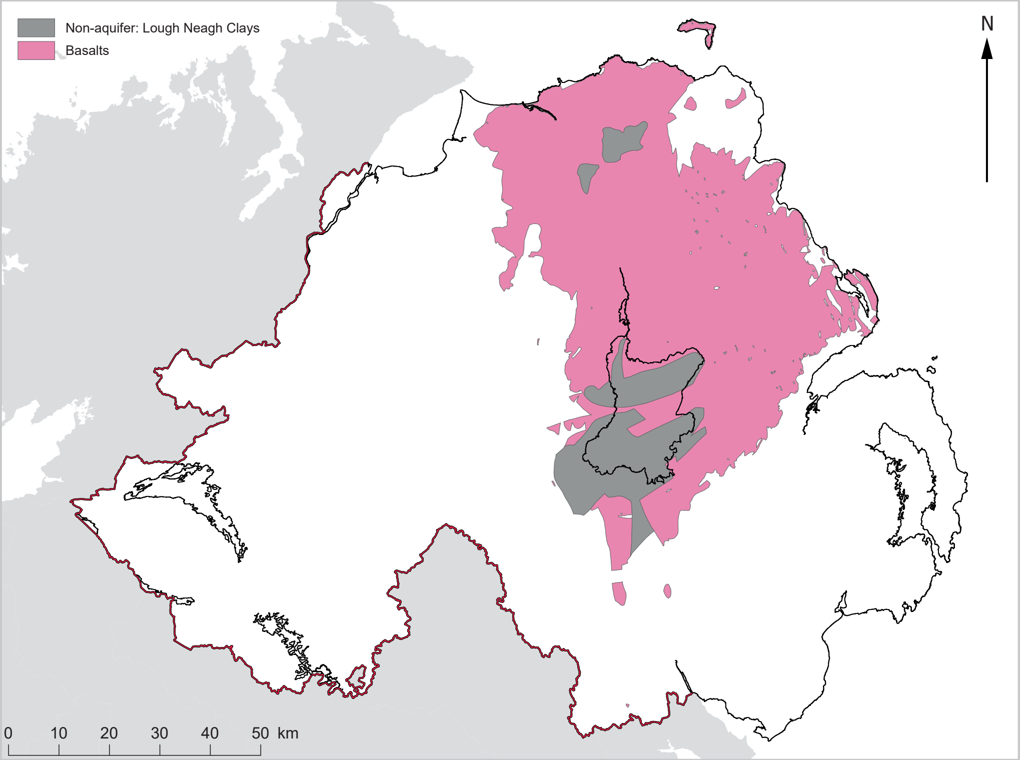


Figure 13. Map of the Basalts aquifers in Northern Ireland. The map also shows the outcrop of the Lough Neagh Clays Group non-aquifer. Contains OGL and CC-BY-4.0 Data

Photograph 3. Cliffs of basalt on the north coast of Co. Antrim.

Photograph 4. Basalt lava flows resting on the Ulster White Limestone Group on Rathlin Island, Co. Antrim.

Aquifer type	Fracture
Aquifer productivity/groundwater supply potential	Moderate
Aquifer class *	Bm(f)
Typical groundwater flow path length (m)	10s to 100s (possibly 1000s in deeper zones)
Typical groundwater flow depth (m)	1–100 (possibly deeper)
Groundwater flow rate	Medium
Dominant baseline groundwater chemistry	Moderately mineralised, high pH, calcium bicarbonate or sodium/potassium bicarbonate type

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.6 Basalts aquifers

3.6.1 Geological summary

The Basalts aquifers are comprised of the Palaeogene Antrim Lava Group, a major series of extrusive igneous basaltic rocks that dominates the landscape across the north-east of Northern Ireland. Also described in this section is the Lough Neagh Clays Group, also of Palaeogene age, a sedimentary rock that crops out around Lough Neagh, and beneath, north-east and south-west of Ballymoney. This unit, despite being a non-aquifer, has a significant hydrogeological effect.

The other main rocks of Palaeogene age in Northern Ireland are intrusive igneous rocks, which are described in Chapter 3.12.

The Antrim Lava Group originally formed as multiple lava flows during regional volcanic activity in the Palaeogene associated with the opening of the Atlantic Ocean. They crop out in much of Co. Antrim, parts of Co. Londonderry, and Co Armagh. They cover a large area of 4009 km^2 or 30 % of Northern Ireland, with a maximum thickness of almost 800 m in the Lough Neagh area. Erosion has some of what may have been an even more extensive original outcrop area. Three main formations are distinguished in the Antrim Lava Group: the Upper Basalt, Interbasaltic and Lower Basalt formations.

Individual lava flows vary in thickness from less than 1 m thick to massive flows up to 45 m thick but are more commonly up to 10 m (Robins *et al.*, 2011). Typically, the thicker lava flows comprise a basal slaggy layer overlain by a massive core and an upper slaggy layer with vesicles (gas cavities) (Robins *et al.*, 2011). Later mineralisation by fluid flow caused some of these vesicles to be infilled with zeolite minerals. Lava flows can be weathered differently from top to base, with the most weathered parts often comprising a red, laterised horizon, typically at the top of each flow, which was exposed at the ground surface during quiet periods between volcanic eruptions.

The Lough Neagh Clays Group is a sequence of clays, sands and lignites up to 500 m thick, deposited in sedimentary basins that formed as a result of fault controlled subsidence in the late Palaeogene (Oligocene). It is associated with areas of flat or gently undulating, low-lying land, usually 15–35 m in elevation that are generally poorly drained because of the low permeability of the sediments. Two formations are distinguished: Ballymoney and Dunaghy. Fractures in the clays and lignites have developed through synsedimentary faulting and fracturing.

3.6.2 Typical overlying sediments and soils

Much of the soil overlying the Lough Neagh Clays Group is low permeability and poorly drained (Cruikshank, 1997). Below the soils is an extensive and often thick (reaching 50 m thick in places) cover of glacial till.

There are extensive areas of blanket peat over much of the Antrim Lava Group. There is usually extensive glacial till, ranging from a thin cover of only one or a few metres to more than 35 m thick. The permeability of glacial till overlying and derived from the basalt has been found to be low (Davis *et al.*, 2015). Across much of the upland Antrim Plateau, the basaltic bedrock is exposed or close to the ground surface.

3.6.3 Hydrogeological conceptual model

3.6.3.1 Lough Neagh Clays Group

The Lough Neagh Clays Group is a non-aquifer. The prevalence of low-permeability clays through the sequence means it has very low potential for storing and transmitting groundwater. Any groundwater flow is thought to be small and to occur predominantly through fractures in the clays or lignites, or locally in lenses of slightly more permeable sands. Any active groundwater flow through the clays is likely to be in the upper few tens of metres, and groundwater flow paths are likely to be short and localised, generally only tens of metres long.

Where they have been measured, groundwater levels are typically shallow, lying close to ground level, and artesian in places where groundwater is confined by overlying low-permeability layers, such as zones of unfractured clays or overlying glacial till or low-permeability soils.

Overall, the Lough Neagh Clays Group is thought to be hydrogeologically significant in restricting recharge to the underlying Basalts aquifers. Recharge is likely to be low, restricted by overlying low-permeability soils and thick glacial till, and has been estimated at less than three % of effective rainfall, or around 5 mm/year (Zenith International Ltd, 2001). For this reason, there is also likely to be minimal groundwater/surface water interaction.

3.6.3.2 Basalts aquifers

The Basalts aquifers have some primary porosity in unfilled vesicles. Groundwater flow and storage occur almost entirely in secondary permeability that has developed in the rock: weathered zones and interconnected fractures, joints and other voids. The Basalts aquifers are classed overall as a moderate productivity fractured aquifer (Bm(f)) (Appendix 1). However, they have highly variable and unpredictable aquifer properties.

The variable weathering of individual lava flows has an impact on hydrogeological properties: the most weathered parts, usually at the top of each flow, have the highest permeability and storage capacity.

Fractures are not present equally throughout the rock, but are focused in particular areas. Fault zones, and possibly also mineralised (zeolite rich) zones, are often associated with enhanced fracturing, which can increase permeability and transmissivity. However, some fractures are infilled with secondary minerals, such as calcite, reducing permeability again. The hydraulic effects of faults and mineralised zones are therefore likely to be variable: some act as preferential conduits for groundwater flow, while some act to restrict flow. The degree of interconnectivity of local fracture networks across the aquifer is also key to the overall transmissivity.

The average transmissivity of the Basalts aquifers is low compared to most other aquifers in Northern Ireland (Figure 7), with a median of 13.3 m^2/day and an interquartile range of 5–166 m^2/day (Table 7). Fractured zones in the aquifer, while they can increase transmissivity and allow rapid groundwater flow, are not thought to provide large volumes of storage. Only three values for storativity are available from test pumping, which are highly variable (Table 7), but there is evidence from operational boreholes that some initially high yields fall over time, which seems to be linked to low storage capacity. The variability of aquifer properties in the Basalts aquifers can lead to dry boreholes at one location, while nearby boreholes produce large yields.

In general, borehole yields from the Lower Basalt Formation are usually higher than from the Upper Basalt Formation. The Interbasaltic Formation has generally lower permeability than the rest of the group.

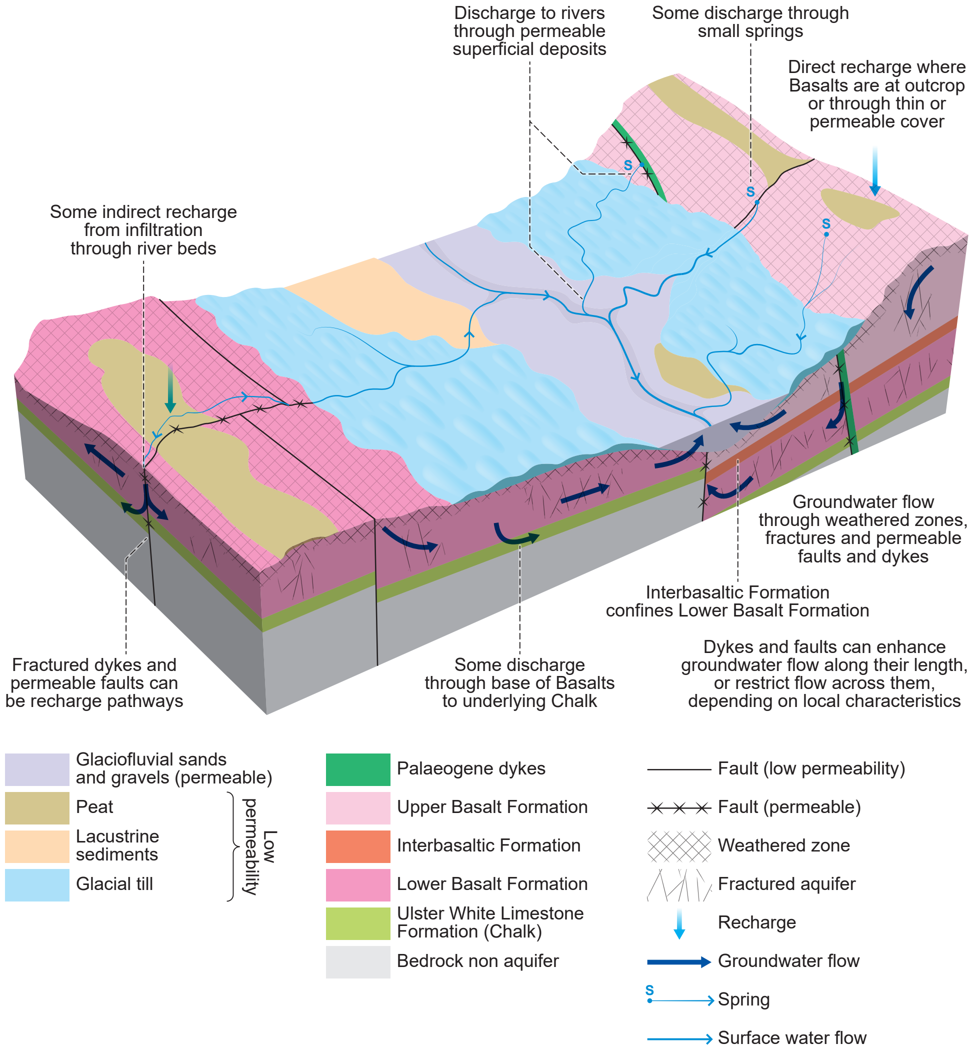


Figure 14. Conceptual model of the hydrogeology of the Basalts aquifers in Northern Ireland.

Recharge to the Basalts aquifers is mainly from direct infiltration of rainfall, where the aquifer is exposed at the surface, or covered by thin and permeable superficial deposits, which is the case across most of the upland aquifer outcrop (Figure 14). Where the aquifer is confined by thick glacial till or other low-permeability superficial deposits or soils, recharge rates are typically low. There may also be some small amount of indirect recharge from rivers where the Basalts aquifers are exposed in river beds. Potential recharge may be higher than actual recharge, as the acceptance capacity for recharge is likely to be limited by the low storage capacity of the aquifer.

Patterns of groundwater flow through the aquifer are dominantly controlled by the presence, size and interconnectedness of the potential water-bearing features: weathered zones, fractures and other voids. Most groundwater flow is thought to be along the most highly weathered zones, which are found at the top of individual lava flows, and along joints and fractures within lava flows. The Interbasaltic Formation, with generally lower permeability, acts to restrict downwards flow to, and largely confines groundwater in, the underlying Lower Basalt Formation.

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean (except Porosity*)	75th Percentile	Maximum
Transmissivity (m^2/d)	10	100%	1.8	5	13	23.5	166	400
Storativity	3	100%	7.47×10^{-05}		0.0016	0.001		0.009
Specific capacity ($m^3/d/m$)	39	87%	0.2	3.0	7	9	23	1739
Hydraulic conductivity (horizontal) (m/d)	13	100%	3.99×10^{-07}	2.84×10^{-06}	0.005	0.0008	0.86	12.4
Porosity (%)	3	100%	5		5	13*		28
Measured yield (m^3/d)	235	19%	0.24	55	109	105	218	1855

* Porosity is an arithmetic mean

Table 7. Summary of available aquifer properties data for the Basalts aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (μS/cm)	1011	0	274	340	443	552	652
pH	1030	0	7.01	7.39	7.73	8.08	8.46
Dissolved oxygen (mg/L)	37	0	4.2	5.2	6.7	8.8	9.68
Calcium (Ca) (mg/L)	998	0	13.5	25	38.1	52.5	63.5
Magnesium (Mg) (mg/L)	1003	0	3.34	9.02	16.7	25	30.8
Sodium (Na) (mg/L)	1015	0	15.3	18.8	23.7	48.2	65.9
Potassium (K) (mg/L)	998	0	0.33	0.48	0.73	1.2	2.34
Chloride (Cl) (mg/L)	1021	0	13.1	17.4	25.4	38.5	66.5
Sulphate (SO_4) (mg/L)	1015	0	6.1	10	14.8	21.9	38.7
Bicarbonate (HCO_3) (mg/L)	889	0	119	151	214	252	278
Nitrate (as N) (NO_3-N) (mg/L)	1036	54	0.1	0.2	0.74	3.54	8.69
Phosphate (P) (mg/L)	998	0	0.33	0.48	0.73	1.2	2.34
Aluminium (Al) (μg/L)	400	53	3.3	8.38	13	25.8	88.28
Iron (Fe) (μg/L)	911	10	7	9	14.8	31.1	90.3
Manganese (Mn) (μg/L)	911	3	1.5	1.5	4	11.1	42.8

* Number of samples.
† Number below detection limit.

Table 8. Summary of baseline chemistry of the Basalts aquifers in Northern Ireland, based on samples from 119 groundwater sources.

Overall, the depth of the active groundwater flow zone is uncertain, but may extend to several hundred metres. Laterally, the anisotropic nature of the rock means that groundwater flow paths are likely to be generally short and strongly influenced by local topography. Given the large area and thickness of the basalts, some more regional flow is likely to occur, but is also likely to be small.

Groundwater levels vary depending on local hydrogeological characteristics. This is illustrated by an example from two boreholes drilled 10 m apart in the Basalts aquifers in the Glenwherry Valley – one targeting a significant fractured zone in the Lower Basalt Formation at 70 m below ground level (mbgl), below the Interbasaltic Formation, and the other targeting a productive aquifer zone in the Upper Basalt Formation, above the Interbasaltic Formation. In the first borehole, the rest water level was 28 mbgl and in the second it was 2 mbgl, showing that the Lower and Upper Basalt formations are hydraulically separated here by the Interbasaltic Formation.

Some of the groundwater in the Basalts aquifers is thought to flow downwards to recharge the underlying Cretaceous (Chalk) aquifer (Chapter 3.7). There are no large spring discharges from either the Upper or Lower Basalt Formations, although there are a number of small local springs, usually seasonally variable. Typical spring yields are between 0.2 and 1.5 l/s, although some yield more than 6 l/s in winter (Bennett, 1978b).

There have been no studies carried out on the interaction between surface waters and groundwater in the Basalts aquifers. However, there is likely to be a degree of interaction, especially where the Basalts aquifers are exposed in river beds, which varies seasonally and along the length of the river, including groundwater discharge to rivers, and recharge from rivers to the Basalts aquifers.

Groundwater in the Basalts aquifers is typically moderately mineralised (median conductivity 443 µS/cm) with a higher pH (median 7.73) compared to most other groundwaters in Northern Ireland (Figure 8, Table 8). The groundwater is of calcium bicarbonate or sodium or potassium bicarbonate type. The latter type may be related to sea water contamination in sites close to the coast.

3.6.4 Groundwater use, history of exploration, management and potential of the Basalts aquifers and Lough Neagh Clays Group non-aquifer

There are no known groundwater abstractions from the Lough Neagh Clays Group, reflecting its very poor groundwater potential.

Historically, boreholes have been drilled into the Basalts aquifers to meet small – to moderate-scale water demands, from private domestic supplies to bottling plants and creameries. Evidence from the Rural Borewell Scheme showed 90 % of boreholes drilled into the Basalts aquifers provided a sustainable yield of at least 1 m^3/d, with many capable of higher sustainable yields, even over 100 m^3/d. The aquifer has not been systematically explored for public water supply, in large part due to the evidence for unpredictable hydrogeological properties. Despite this, the only current public water supply groundwater abstraction in Northern Ireland is from the Basalts aquifers, on the island of Rathlin off the north coast of Co. Antrim. Here, two boreholes, sited only 5 m apart, supply up to 200 m^3/d for island inhabitants and seasonal visitors.

Groundwater in the Basalts aquifers is vulnerable to contamination because of the fractured nature of groundwater flow and storage. This allows for rapid groundwater travel times while providing little storage for dilution of any pollution. Additionally, there is limited protective overlying cover across much of the upland area of the aquifer's outcrop.

More extensive study of the groundwater potential of the Basalts aquifers is needed to show their true groundwater potential. Despite underlying almost a third of Northern Ireland, including some of the main towns (Antrim, Ballymena and Coleraine), relatively little is known about the mechanisms by which groundwater is stored or transmitted through them.

Predicting likely borehole yields and providing reliable groundwater supply prognoses is difficult.

The layering of the basalt flows and the presence of groundwater at different horizons may also present a unique opportunity to use groundwater for geothermal ground source energy. This natural vertical separation may permit abstraction and recharge of groundwater to facilitate removal or addition of heat for low-carbon heating and cooling.

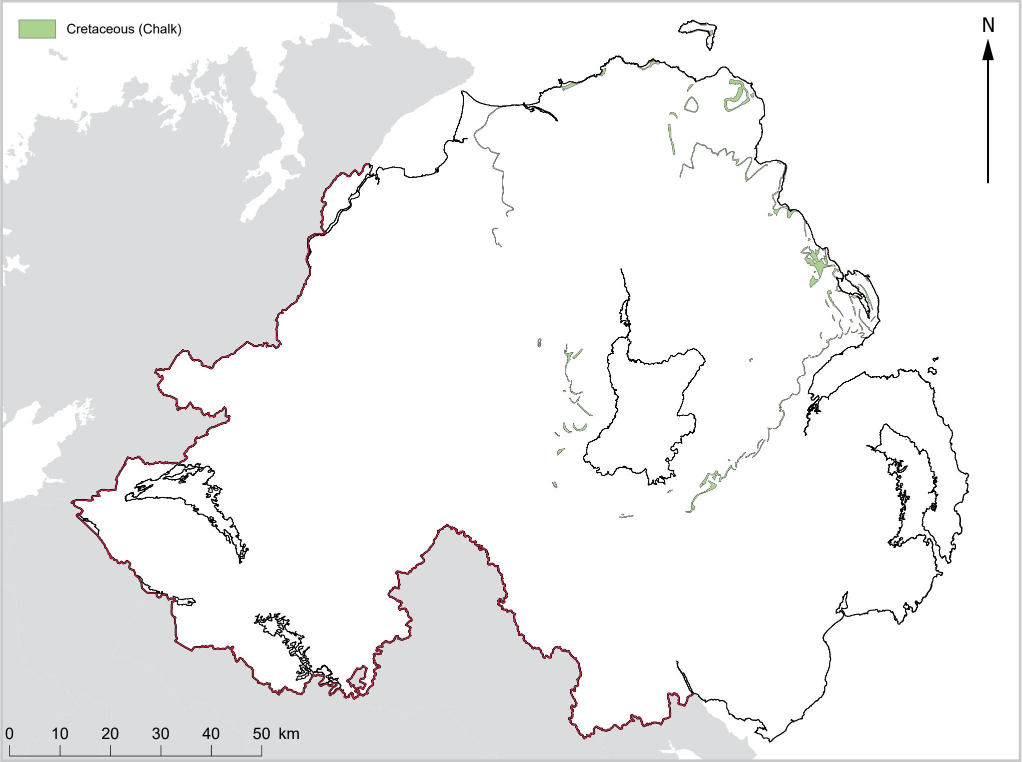


Figure 15. Map of Cretaceous (Chalk) aquifers (Ulster White Limestone and Hibernian Greensands Groups) in Northern Ireland. Contains OGL and CC-BY-4.0 Data

Photograph 5. Rotated Ulster White Limestone Group blocks beneath basalt lava flows at Garron Point, Co. Antrim.

Photograph 6. Spring issuing from the base of the Ulster White Limestone Group, Co. Antrim.

Aquifer type	• Fracture (Ulster White Limestone Group) • Intergranular (Hibernian Greensands Group)
Aquifer productivity/groundwater supply potential	High
Aquifer class *	• Bh(f-k) (Ulster White Limestone Group) • Bh(f-k) (Hibernian Greensands Group)
Typical groundwater flow path length (m)	100s
Typical groundwater flow depth (m)	1–100
Groundwater flow rate	• Ulster White Limestone Group: fast in east; medium in west • Hibernian Greensands Group: probably medium
Dominant baseline groundwater chemistry	Weakly mineralised, high pH, calcium bicarbonate type

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.7 Cretaceous (Chalk) aquifers

3.7.1 Geological summary

Rocks of Cretaceous age in Northern Ireland include the Ulster White Limestone Group (colloquially referred to as 'chalk') and the underlying Hibernian Greensands Group. This Cretaceous sequence has a limited and discontinuous outcrop, modified by Palaeogene faulting.

The Ulster White Limestone Group is the equivalent of the upper part of the Chalk Group in England. It underlies the Antrim Lava Group however its total outcrop area is only 80 km^2 around the periphery of the Antrim Plateau. It is typically about 50 m thick, but in some places it can be more than 150 m thick (Fowler *et al.*; 1961, Fletcher, 1977). It is typically thickly bedded (0.3–1.0 m) with a wide joint spacing (5–10 m). It is a hard limestone, significantly harder than most of the Chalk Group in England, due to a high degree of post depositional pressure dissolution and cementation (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 southern 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 of about 30 m. It comprises a variable sequence including glauconitic sands, sandstones, calcareous mudstones and mudstones. It is underlain by Jurassic or Triassic mudstones.

3.7.2 Typical overlying sediments and soils

Soils directly overlying the Ulster White Limestone Group are usually calcareous, with a high clay content, which, together with steep slopes, can make them liable to landslides. Inland from Larne, there are calcareous brown earths and shallow brown earths with red, calcareous paleosols with a clayey texture (Cruikshank, 1997).

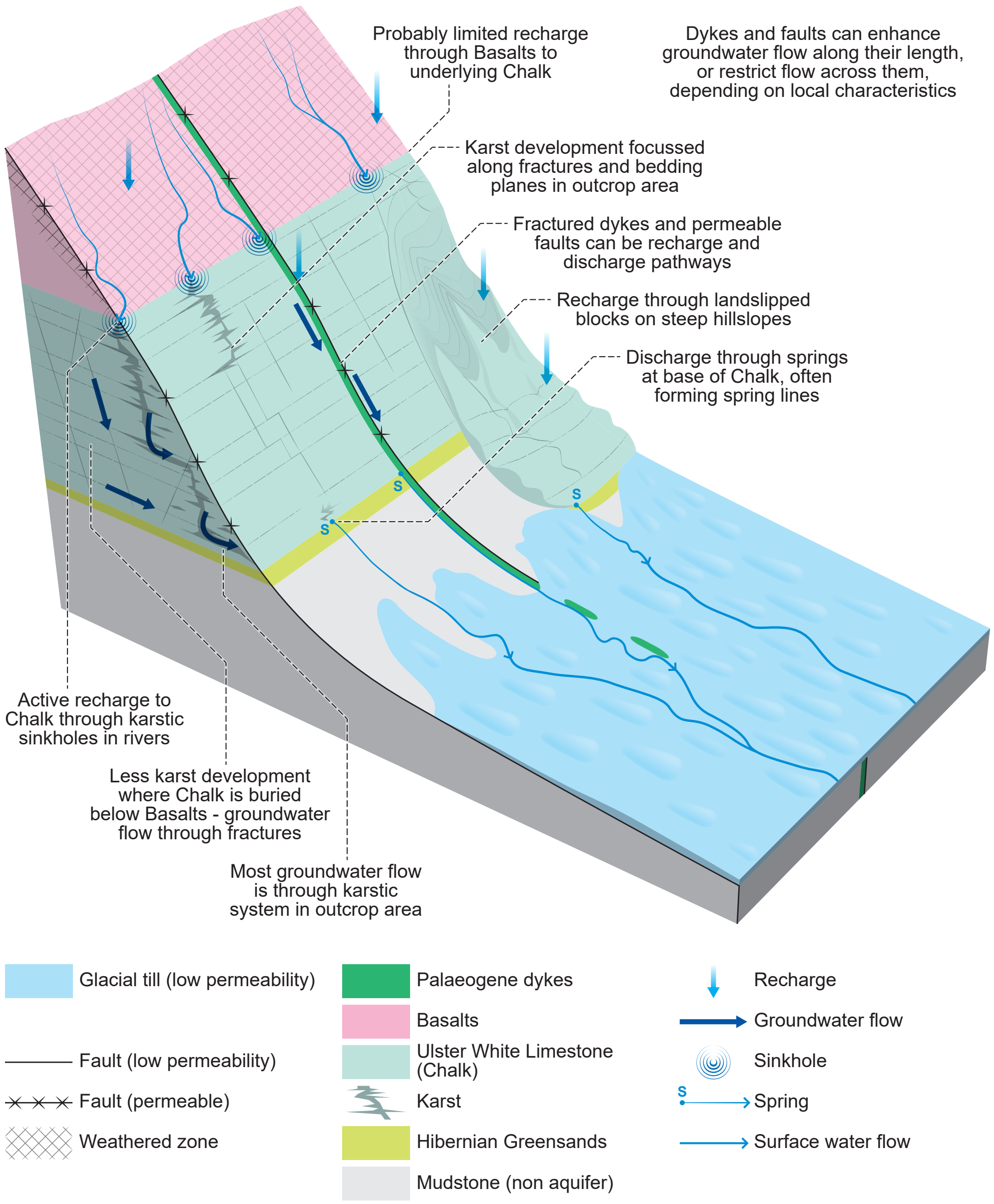
Parts of the Cretaceous outcrop in upland areas are concealed by thin till and peat, but across much of its relatively narrow outcrop there is limited superficial deposit cover.

3.7.3 Hydrogeological conceptual model

The Ulster White Limestone Group and the underlying thin Hibernian Greensands Group are generally classed as a single aquifer group (the Cretaceous (Chalk) aquifers) despite having different hydrogeological properties. This is partly because the available evidence indicates they are hydraulically connected (Foster *et al.*, 1969) and partly because, even together, they form a thin, narrow outcrop that is not distinguished on the widely used 1:250 000 bedrock geological map (GSNI, 1997).

More data are available on the aquifer properties of the Ulster White Limestone Group than the Hibernian Greensands Group. What data are available indicate that the Ulster White Limestone Group has higher permeability than the Hibernian Greensands Group and more rapid groundwater flow through fractures and karstic features. This, combined with its greater thickness, means the Ulster White Limestone Group is considered to be the hydrogeologically dominant part of the sequence.

Groundwater flow and storage in the Cretaceous (Chalk) aquifers are dominated by fractures and karstic flow, with negligible intergranular porosity and permeability. The


Probably limited recharge through Basalts to underlying Chalk

Dykes and faults can enhance groundwater flow along their length, or restrict flow across them, depending on local characteristics

Karst development focussed along fractures and bedding planes in outcrop area

Fractured dykes and permeable faults can be recharge and discharge pathways

Recharge through landslipped blocks on steep hillslopes

Discharge through springs at base of Chalk, often forming spring lines

Active recharge to Chalk through karstic sinkholes in rivers

Less karst development where Chalk is buried below Basalts - groundwater flow through fractures

Most groundwater flow is through karstic system in outcrop area

Figure 16. Conceptual model of the hydrogeology of the Cretaceous (Chalk) aquifers in Northern Ireland.

Cretaceous (Chalk) aquifers are classed as a high-productivity, fractured and/or karstic aquifer (Bh(f-k)) (Appendix 1).

There is significant development of karst in the Cretaceous (Chalk) aquifers. The main active karst zone is in the Ulster White Limestone Group outcrop area, not where it is buried beneath the Antrim Lava Group. Karst development is promoted by groundwater flow and is greatest in areas with concentrated fracturing, such as in some fault zones or along dykes, and along bedding planes and other joints. It may also be concentrated where recharge potential is highest, promoting active groundwater flow. Some of the karst is thought to be palaeokarst, developed before the overlying Antrim Lava Group was erupted (Robins *et al.*, 2011). Major

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Transmissivity (m^2/d)	3	100%	30		360	200		731
Storativity	1	100%	a single measurement with a value of 0.09					
Specific capacity ($m^3/d/m$)	2	100%	21			134		875
Hydraulic conductivity (horizontal) (m/d)	2	100%	3.36×10^{-06}					0.43
Measured yield (m^3/d)	5	20%	17	66	327	212	393	2880

Table 9. Summary of available aquifer properties data for the Cretaceous (Chalk) aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	23	0	203	245	349	397	589
pH	26	0	6.70	7.12	7.51	7.7	7.79
Dissolved oxygen (mg/L)	3	0	8.94	9.15	9.5	9.85	10.1
Calcium (Ca) (mg/L)	23	0	33.0	36.5	39	40.9	42.7
Magnesium (Mg) (mg/L)	23	0	14	14.5	15.7	16.5	16.8
Sodium (Na) (mg/L)	23	0	11.0	11.8	13	13.6	15.4
Potassium (K) (mg/L)	23	0	0.30	0.39	0.44	0.51	0.85
Chloride (Cl) (mg/L)	24	0	17.3	19.7	21.1	23	25.7
Sulphate (SO_4) (mg/L)	23	0	5	6.05	7.53	8.05	10.7
Bicarbonate (HCO_3) (mg/L)	14	0	137	148	159	181	190
Nitrate (as N) (NO_3-N) (mg/L)	25	0	1.68	1.85	2.1	2.8	3.06
Phosphate (P) (mg/L)	14	0	0.007	0.01	0.02	0.07	0.13
Aluminium (Al) (µg/L)	11	2	15.3	22.9	34.4	77.2	100
Iron (Fe) (µg/L)	17	0	5.62	13	21.3	230	288
Manganese (Mn) (µg/L)	17	0	0.75	0.9	8	11	19.9

* Number of samples.
† Number below detection limit.

Table 10. Summary of baseline chemistry of the Cretaceous (Chalk) aquifers in Northern Ireland, based on samples from only two groundwater sources.

sinkholes and springs occur along the Antrim coast, indicating significant active karst conduit systems.

Few hydraulic aquifer properties have been measured for the Cretaceous (Chalk) aquifers, either at outcrop or where it lies below the Antrim Lava Group. Aquifer properties are usually measured in boreholes and few boreholes have been drilled into the Cretaceous (Chalk) aquifers, as its limited outcrop area and the increasing depth to the top of the aquifer away from its outcrop have generally restricted exploitation by boreholes. Only three transmissivity values are available for the aquifer, but they are some of the highest for any bedrock aquifer in Northern Ireland (Figure 7; Table 9). It has been suggested that the highest permeabilities may be in the zone of active karst development in the outcrop area (Robins *et al*., 2011).

Most boreholes drilled into the Ulster White Limestone Group through overlying Antrim Lava Group are relatively low yielding, less than 1 l/s, but a few are higher yielding, including one providing about 21 l/s. It may be that, where the Antrim Lava Group overlie the Ulster White Limestone Group, they tend to inhibit the development of fracture and karst permeability in the underlying Ulster White Limestone Group, and restrict the extent of infiltration and circulation of groundwater, although they can provide some indirect recharge to the Cretaceous (Chalk) aquifers (Barnes, 1999).

Dykes intruded through the Cretaceous (Chalk) aquifers can have a significant local hydrogeological effect (Chapter 3.12.4), although more evidence is needed for their impacts on this aquifer. The usually vertical dykes are often highly fractured and permeable; they can form conduits for preferential vertical groundwater flow, including recharge, and potentially karst development, which will enhance flows even more. It is also possible that dyke intrusion may have ‘baked’ the surrounding calcareous rock and reduced the development of karst and, therefore, permeability, so that dykes act to restrict lateral groundwater flow, as in the Permo-Triassic Sandstones aquifers. However, more evidence is needed to show whether this is a significant effect. Impermeable faults may also act to restrict lateral groundwater flow (Chapter 3.3.3).

The Cretaceous (Chalk) aquifers are recharged mainly in the active karstic outcrop zone, by infiltration of river water through sinkholes of variable size in river beds (Figure 16). Where fractured dykes are present, they are likely to also form preferential recharge pathways. Preferential recharge can also occur along the steep slopes formed by the Ulster White Limestone Group outcrop, which are subject to landsliding: this can enhance fracturing and permeability and increase local recharge, both from direct rainfall infiltration and from infiltration of water from streams flowing over areas where landslides have previously occurred.

In dry weather when river flows are low, the Cretaceous (Chalk) aquifers can accept recharge and rivers often have dry beds because all of their flow has been lost to the underlying aquifer. However, during very wet conditions when river flows are high, the aquifer storage capacity can be exceeded so that it cannot accept more recharge. In this case, groundwater levels rise to the ground surface, including in sinkholes, which then become points of groundwater discharge from the aquifer, feeding the previously dry river beds so that they start to flow again.

Where the Cretaceous (Chalk) aquifers are covered by the Antrim Lava Group, a small amount of indirect recharge is also thought to occur by groundwater draining down from the Basalts aquifers (Figure 16), possibly explaining why virtually no springs issue from the Basalts aquifers in these areas. Water chemistry studies and flow gauging of a number of springs, such as Toberterin near Stewartstown in Co. Tyrone, have indicated that the spring flow is predominantly sourced from the Basalts aquifers (Barnes, 1999).

Controls on the depth of active groundwater flow in the Cretaceous (Chalk) aquifers vary. At outcrop, its limited thickness is the main control. Where it is covered by the Antrim Lava Group, it may be that fracture and karst development is restricted to the upper part of the aquifer, as suggested by Barnes (1999), meaning that active groundwater flow is limited to this upper zone. Lateral groundwater flow paths are likely to be generally short (hundreds of metres), but there is potential for longer flow paths in some parts.

Flows are partly controlled by topography, from higher to lower elevations, but preferential flows along major fractures and karst features have a significant local influence. The presence of vertical igneous dykes may also have a local influence by restricting lateral groundwater flow: although the dykes themselves are often highly fractured and permeable, they can cause low-permeability zones in the adjacent rock, where the intruding molten, igneous rock of the dykes baked the surrounding rock. This effect is better studied in the Permo-Triassic Sandstones aquifers (Chapter 3.5), but may also be significant in the Cretaceous (Chalk) aquifers.

Major fault zones may also influence groundwater flow in some areas. Longer flow paths may occur particularly in the deeper Cretaceous (Chalk) aquifers, where it underlies the Basalts aquifers. In the east, flow paths appear to be faster (e.g. 500–1000 m/day) and shorter, with a 'flashier' groundwater response, compared to slower responses in the west (Barnes, 1999). Barnes (1999) suggests that this indicates rapid flow of young (recently recharged) groundwater in the east and discharge from the base of the Antrim Lava Group in the west. Available groundwater level evidence also suggests there may be a flow divide a few kilometres west of the eastern aquifer outcrop, from which there is eastward flow towards the springs of the Antrim coast, and westward flow towards the centre of the Lough Neagh Basin (Robins *et al.*, 2011). However, it is likely that there is limited groundwater flow in the Cretaceous (Chalk) aquifers in this western area, where it is overlain by the Basalts aquifers, driven only by limited abstraction of groundwater from the aquifer.

Most groundwater discharge from the Cretaceous (Chalk) aquifers is by springs, of which there are many. These typically form at the base of the Ulster White Limestone Group (or the underlying, hydraulically connected Hibernian Greensands Group), which is underlain by low-permeability older rocks, such as Triassic and Jurassic mudstones (Figure 16). Often, springs form in lines at similar elevations along slopes, controlled by the geological boundary between the Cretaceous (Chalk) aquifers and the underlying rocks. One of the largest known of these springs is Carey River Spring, which has been the main discharge point for water draining from Loughareema (the 'Vanishing Lake') in north-east Antrim (see page 47). This has a normal flow rate of at least 30 l/s when the lake is empty and over 200 l/s when the lake is full.

Where the Cretaceous (Chalk) aquifers outcrop, it is typically unconfined, with groundwater often free-flowing through partially filled conduits. This is evidenced by quarries along the east Antrim coast, which remain dry. Groundwater in the aquifer is often only encountered towards its base.

Where the Cretaceous (Chalk) aquifers is present at depth below the Basalts aquifers, available groundwater level data generally show different hydraulic heads. In the west, groundwater heads in the Cretaceous (Chalk) aquifers are generally higher than in the Basalts aquifers. It may be that groundwater in saturated fractures and karst conduits in the aquifer in these areas is typically confined by the overlying, lower-permeability Basalts aquifers. Although downward groundwater flow from the Basalts aquifers is likely to provide a small amount of recharge to the underlying Cretaceous (Chalk) aquifers, overall there is likely to be only weak hydraulic connectivity between the two.

In areas where the Cretaceous (Chalk) aquifers outcrop, there is strong interaction between surface waters and groundwater: many rivers in these areas trace their source to a spring.

Rivers sourced from these areas have complex hydrodynamics that present particular river management challenges. For example, it is common for rivers to dry up temporarily in low-flow periods and to start flowing again following the next significant rainfall.

Groundwater in the Cretaceous (Chalk) aquifers is generally highly vulnerable to contamination, because of rapid groundwater flow and the mostly limited protective cover across its outcrop area.

There are relatively little groundwater chemistry data for the aquifer, with samples from only two sites available. These data indicate that groundwater is typically relatively weakly mineralised (median conductivity 349 µS/cm) and has slightly alkali pH (median 7.51) compared to other aquifers in Northern Ireland (Figure 8; Table 10). The groundwater is typically of calcium bicarbonate type (Figure 10).

3.7.4 Groundwater use, history of exploration, management and potential of the Cretaceous (Chalk) aquifers

Most of the large springs emerging from the base of the Cretaceous (Chalk) aquifers were captured in the past and used for local water supplies. Some, such as Toberterin, Ligoniel, Whitewell and Stradreagh, were used for public water supplies. Today, only a small number of springs are still in use for private supply, largely because of concern over the high vulnerability of groundwater to contamination.

A feasibility study carried out in the 1970s (Bennett, 1978a) investigated the potential for enhancing groundwater flow from fractures in the Cretaceous (Chalk) aquifers by digging an adit (a horizontal tunnel) into the rock. The results suggested that there was the potential for such a project, but there was great uncertainty about whether there is enough recharge to the fracture network to sustain long-term, enhanced groundwater flow.

In some places, karst features have dissolved to form cave networks large enough for exploration by speleologists, some of which, such as Black Burn and Ardclinis, have been surveyed (Kelly *et al.*, 1996). Cave development is, however, much less than in the Carboniferous Limestones in Co. Fermanagh. Research on groundwater flow characteristics in the aquifer, including tracer tests and flow measurements on stream sinks and springs around the edge of the outcrop, provide evidence of distinct differences in groundwater flow behaviour in eastern and western parts of the aquifer (Barnes 1999; Barnes and Worden 1998; Barnes 2000; Barnes *et al.*, 2003).

There is likely to be limited potential for future use of groundwater from the Cretaceous (Chalk) aquifers, in part because of the high vulnerability of groundwater in the aquifer to contamination and in part because of the difficulty in drilling successful abstraction boreholes in the thin aquifer, especially where it is buried at depth below the Antrim Lava Group. Securing reliable groundwater supplies from the aquifer along the steep slopes of the north and east coasts of Northern Ireland can be challenging. Groundwater in these areas tends to flow rapidly through free-flowing fractures to the base of the thin aquifer, making it difficult for boreholes to capture and abstract it. However, there is potential to consider using spring discharges for water supply, thermal energy by heat exchange, or small-scale hydroelectric power generation. Some high-yielding boreholes have been achieved in areas with less steep slopes, such as near Larne and Lurgan.

The Vanishing Lake

Photograph 7. The Vanishing Lake

For part of the year, the Antrim Coast Road between Cushedun and Ballycastle passes a small lake known as Loughareema. But at other times of the year there is no lake, only a small depression without any vegetation. This is the 'Vanishing Lake', a remarkable karstic sinkhole created by a rare combination of geology and the action of water over millennia.

Today, three separate rivers drain into the lake, but in normal conditions, when river flows are low, all of this water drains down through a sinkhole at the bottom of the lake and vanishes – but not for long! We know from testing that the lake empties directly into a network of karstic conduits in the underlying Cretaceous (Chalk) aquifers aquifer (Barnes, 1999), and flows away as groundwater until it appears again 2.5 km away down the Carey Valley, discharging back to the surface at a spring. This is the case for much of the year, so that the 'lake' is empty – but after heavy rainfall, the rivers flowing into the lake are so full that the sinkhole can't take all the water and the water level in the hole backs up, just like in a blocked kitchen sink, so that the lake starts to fill.

The reasons behind this mysterious behaviour lie in the local geology and hydrogeology. The Vanishing Lake is in an area of complicated geology. Dalradian rocks crop out at the ground surface around part of the lake, at the end of a glacial meltwater channel that was created as ice sheets were melting during the last deglaciation some 18 000 years ago. Highly weathered basalt of the Antrim Lava Group crops out around the other part of the lake, with the two rock types of very different ages – the basalts are at least 500 million years younger than the Dalradian – brought together by a fault. The sinkhole in the bottom of the lake lines up with the intersection of this fault and another one that lies at right angles to it.

We know the Ulster White Limestone Group underlies the Antrim Lava Group in this area, but we can't actually see any Ulster White Limestone Group in the base of the sinkhole because of sediment in the hole that covers the deeper rocks. But we do know that the water draining into the lake flows out of the Cretaceous (Chalk) aquifers further down the valley, and we also know that sinkholes are common, so we can be fairly sure that the sinkhole at the base of the Vanishing Lake drains into the aquifer.

Monitoring by GSNI has shown that it can take less than 12 hours for the lake to fill with water during times of high river flow, but, once the rain stops, it takes four to six days of dry weather for all the lake water to drain away through the sinkhole in its base.

Archaeological finds suggest that the lake has been a site of interest for a long time, possibly since early Neolithic times, with worked flints and a burial mound found along its margins.

The lake is famed in folklore and storytelling. One story tells of Colonel James McNeil and his coachman, who met an unfortunate end in the lake in 1896 when they tried to drive their carriage along the flooded road after the lake level had risen rapidly. The carriage slipped off the road and both men and their two horses were lost. Legend has it that it is said that on a foggy evening when the lake is full, you can sometimes make out the impression of a coach travelling along the edge of the lake.

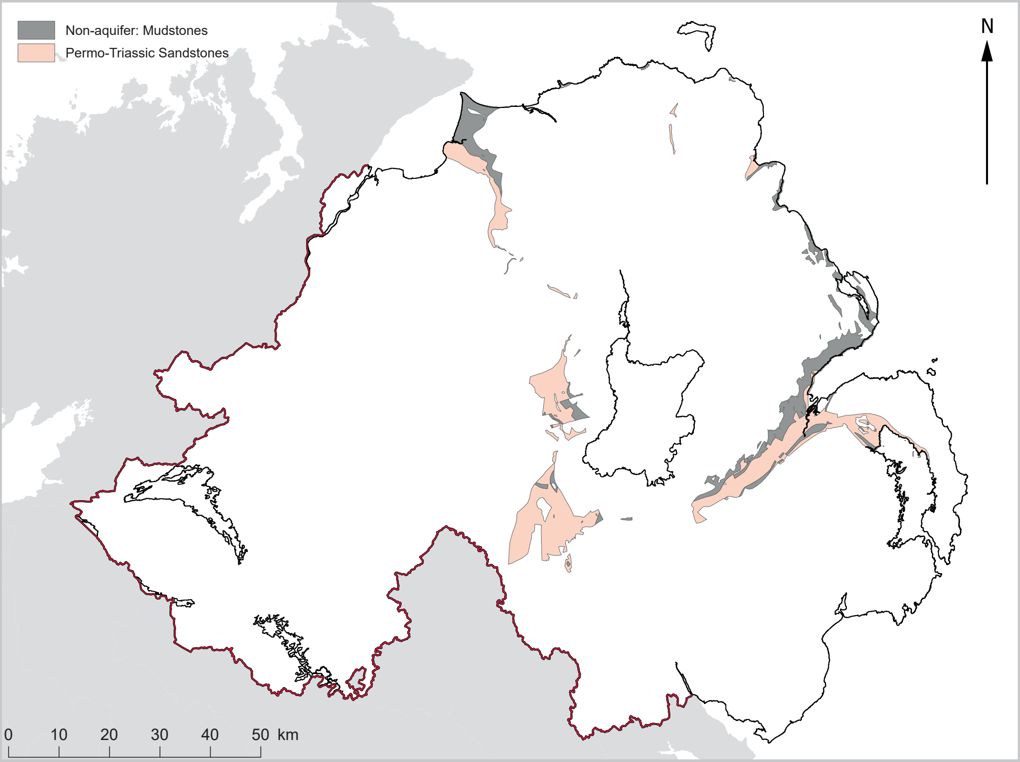
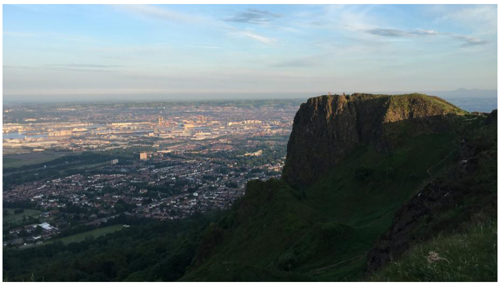


Figure 17. Map of the Permo-Triassic Sandstones aquifers in Northern Ireland. The map also shows the Permian, Triassic and Jurassic mudstones non-aquifer. Contains OGL and CC-BY-4.0 Data

Photograph 8. Scrabo South Quarry; bedding planes and fractures, Co. Down.



Photograph 9. A view of the Lagan Valley from Cave Hill, counties Down and Antrim.

Aquifer type	Intergranular and fracture
Aquifer productivity/groundwater supply potential	High
Aquifer class *	Bh(I-f)
Typical groundwater flow path length (m)	1000s
Typical groundwater flow depth (m)	1–250
Groundwater flow rate	Slow
Dominant baseline groundwater chemistry	Highly mineralised, high pH, bicarbonate dominated with no dominant cation (minority calcium dominated)

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.8 Permo-Triassic Sandstones aquifers

3.8.1 Geological summary

Permian, Triassic and Jurassic sedimentary rocks occur across an area of 4000 km^2 in the north-east of Northern Ireland, but are usually concealed beneath Cretaceous and Palaeogene rocks. The main outcrops at the ground surface are in the Lagan and Enler valleys, south of Dungannon, the Cookstown area and the Roe Valley.

Jurassic rocks crop out in a few places, predominently beneath cliffs of Ulster White Limestone Group and Antrim Lava Group, such as at Islandmagee and White Park Bay. They have been proved at depth in boreholes at Port More and Mire House, with a thickness of 248 m and 125 m respectively. The Jurassic sequence comprises mainly grey, calcareous, marine mudstones with thin bands of nodular limestone: this is the Waterloo Mudstone Formation, which was deposited after a global rise in sea level submerged most of Ireland and Britain (Mitchell, 2004).

Triassic rocks in Northern Ireland comprise two main Groups: the Sherwood Sandstone Group (over 600 m thick below Larne and 300 m thick beneath Belfast) and the overlying Mercia Mudstone Group (over 900 m thick below Larne) (Bennett, 1983). The Sherwood Sandstone Group was deposited hot continental conditions mainly by fluvial processes and consists of red-bed sediments, mainly pink to reddish brown sandstone and silty sandstone with brown mudstone accounting for up to one-third of the total thickness (Mitchell, 2004). The Mercia Mudstone Group is dominated by calcareous mudstone and thin micaceous siltstone bands, with occasional fine-grained, often dolomitic sandstone beds that are generally less than 2.5 m thick. It also includes variable thicknesses of halite beds, and anhydrite and gypsum, all indicative of an evaporitic depositional environment (Mitchell, 2004).

Below the Triassic, the Permian comprises the Red Arch Formation in Co. Antrim, a younger sequence of limestone and halite (about 130 m thick), and mudstones (about 180 m thick) of the Belfast Group. Below this, a sequence of basal conglomerates (about 60 m thick), volcanic rocks (more than 600 m thick) and coarse-grained, weakly cemented sandstones (more than 400 m thick) make up the older Enler Group (Mitchell, 2004).

The whole Permo-Triassic sedimentary sequence has been extensively affected by faulting and the intrusion of Palaeogene igneous dykes. In many places, faults or dykes cut through the sedimentary rocks, dividing them into separate compartments. Dykes were often intruded perpendicular to the strike of the sedimentary strata and, in many cases, have baked and altered the surrounding sandstone and mudstone by causing high pressure and temperature fluid migration through the sedimentary rock (McKinley *et al.*, 2001).

3.8.2 Typical overlying sediments and soils

Much of the area of Sherwood Sandstone Group is concealed by a generally weakly permeable till sequence that is up to 40 m thick. The till is mostly clay-rich, but occasionally sandier. In some areas, marine and/or estuarine clays and glaciofluvial sands and gravels overlie the sandstone instead of, or as well as, till. Occasional isolated eskers are also present on top of till.

Soils over till-covered Sherwood Sandstone Group are typically slightly gleyed (saturated wetland soils). In drier lowland areas away from clay-rich till cover, there are some sandy brown

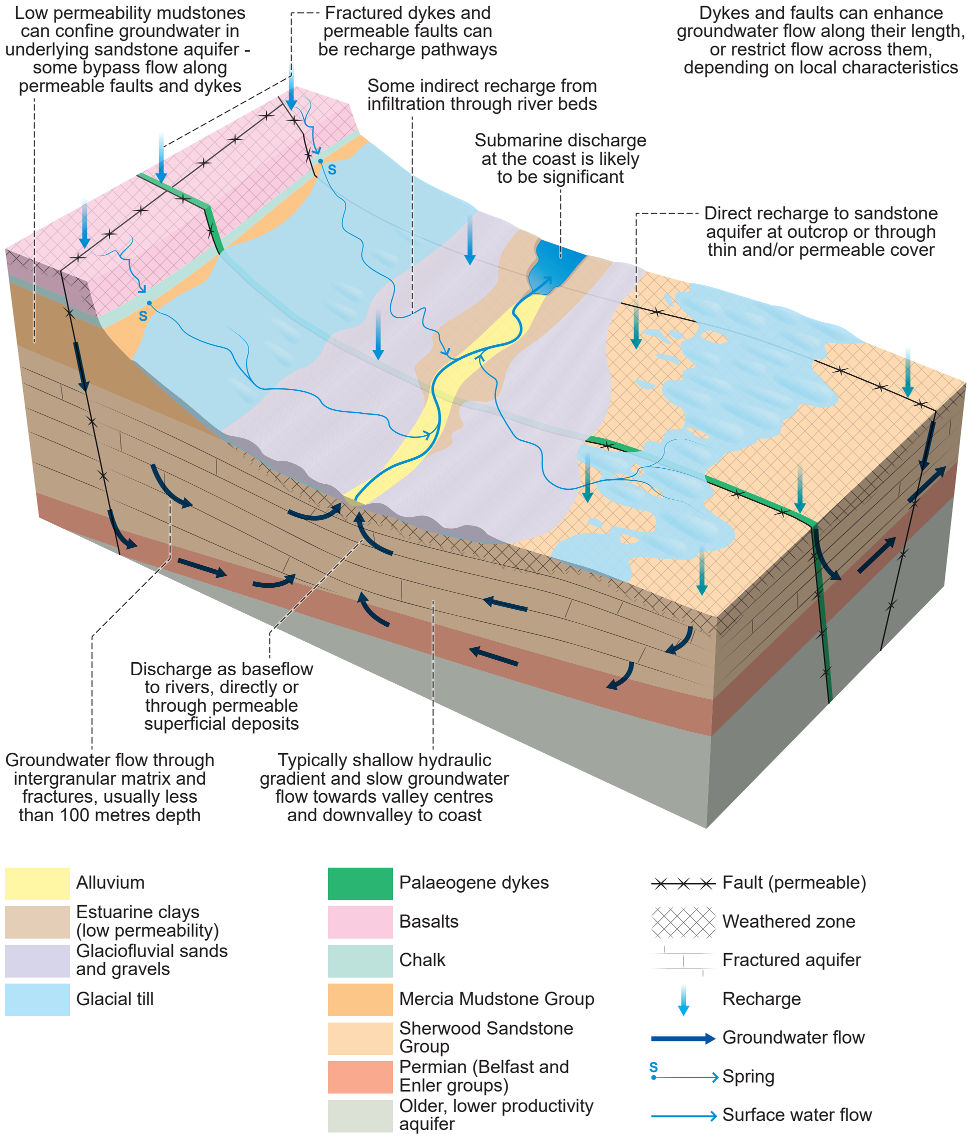


Figure 18. Conceptual model of the hydrogeology of the Permo-Triassic Sandstones aquifers in Northern Ireland.

earths, representing about 20 % of the Sherwood Sandstone Group outcrop area, with sandy or sandy clay loam texture and moderately good or free drainage (Cruikshank, 1997).

3.8.3 Hydrogeological conceptual model

Two sandstone-dominated Groups – the Triassic Sherwood Sandstone Group and the Permian Enler Group – together form the highly productive Permo-Triassic Sandstones aquifers. It is classed as a highly productive aquifer with both intergranular and fracture flow (Bh(i-f)) (Appendix 1). The sandstones of the Permian Enler Group have predominantly intergranular flow with a minor amount of fracture flow. By contrast, in the Triassic Sherwood Sandstone Group, fracture flow has been shown to account for between 30 and 70 % of groundwater flow (Millar, 2019).

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean (except Porosity*)	75th Percentile	Maximum
Transmissivity (m^2/d)	55	100%	0.08	24	73	65	185	4700
Storativity	27	100%	0.00003	0.0003	0.001	0.0010	0.002	0.1
Specific capacity (m^3/d/m)	67	46%	0.2	21	69	66	154	43200
Hydraulic conductivity (horizontal) (m/d)	14	100%	1.01 x 10^{-06}	0.001	0.008	0.04	0.08	373038
Porosity (%)	4	100%	21	23	24	27*	28	40
Measured yield (m^3/d)	181	27%	3	164	469	385	1003	5000

* Porosity is an arithmetic mean

Table 11. Summary of available aquifer properties data for the Permo-Triassic Sandstones aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	408	0	364	450	513	604	690
pH	429	0	7.14	7.44	7.68	7.85	8.01
Dissolved oxygen (mg/L)	44	0	6.0	6.9	8.0	8.3	8.9
Calcium (Ca) (mg/L)	404	0	33.3	39.4	45.7	63	78.5
Magnesium (Mg) (mg/L)	404	0	17.39	21.9	28	31.3	35.67
Sodium (Na) (mg/L)	404	0	10.8	12.0	19.3	23.0	27.6
Potassium (K) (mg/L)	404	0	1.36	1.51	1.93	2.97	4.40
Chloride (Cl) (mg/L)	410	0	24.4	16	23.1	29.2	37.0
Sulphate (SO_4) (mg/L)	404	0	6.33	10.1	29.5	41.4	57.3
Bicarbonate (HCO_3) (mg/L)	327	0	171	195	264	284	324
Nitrate (as N) (NO_3-N) (mg/L)	428	16	0.1	0.2	0.3	2.76	6.20
Phosphate (P) (mg/L)	174	2	0.005	0.005	0.032	0.063	0.117
Aluminium (Al) (µg/L)	162	25	1.8	7.7	13	25.2	100
Iron (Fe) (µg/L)	318	0	7.7	16	45.2	242	698
Manganese (Mn) (µg/L)	86	0	3.5	5	13.5	43.2	58

* Number of samples.
† Number below detection limit.

Table 12. Summary of baseline chemistry of the Permo-Triassic Sandstones aquifers in Northern Ireland, based on samples from 47 groundwater sources.

There is significant variability in aquifer properties within the sandstones, reflecting their lithological heterogeneity. The median transmissivity value, at 73 m^2/day (Table 11) is moderate compared to other aquifers in Northern Ireland, but the interquartile range of 24–185 m^2/day and significantly higher outliers (the maximum recorded transmissivity is 4700 m^2/day) shows the higher aquifer potential in some areas.

In general, storativity values are relatively high compared to other aquifers across Northern Ireland (Figure 7). The transmissivity and storativity of the Permo-Triassic Sandstones aquifers outcrop around Dungannon and Cookstown are considered to be of an order of magnitude lower than those of the Lagan and Enler valleys (Lovelock, 1969).

The sandstone aquifer sequence is interbedded with, and in places overlain by, low-permeability mudstones and minor limestones. Mudstones and limestones of the Belfast Group overlie the Permian sandstones, separating it hydraulically from the overlying Sherwood Sandstone Group. The Sherwood Sandstone Group is in turn overlain by the Mercia Mudstone Group, Penarth Group and Jurassic Waterloo Mudstone Formation.

The low-permeability Triassic and Jurassic mudstones and extensive tills that overlie much of the Permo-Triassic Sandstones aquifers can both act to confine groundwater in the aquifer (Kalin and Roberts, 1997). Sampling of confined groundwater in the Sherwood Sandstone Group below mudstones has shown that deeper groundwater can be too highly mineralised to be potable. However, such groundwater could be considered in the future for potential deep-geothermal exploration.

The processes for how the Permo-Triassic Sandstones aquifers are recharged have been debated for some time and various conceptual models have been proposed, recognising that different processes are likely to be dominant in different parts of the aquifer. It is unlikely that direct recharge of rainfall is the only or dominant mechanism, because the aquifer is rarely exposed at or near the ground surface. However, this may be important in some areas; for example, where superficial deposits are thin or absent on hillslopes. Some recharge may also occur through superficial deposits where these are more permeable, although the widespread presence of low-permeability till is likely to limit this. In a few areas, where rivers flow over exposed parts of the aquifer, there may be indirect recharge through river beds, at least at some times of the year, although at other times groundwater may be discharging to these rivers. Where vertical igneous dykes are present, they may also form preferential recharge pathways, as the dykes are often highly fractured and permeable (Chapter 3.12.4). However, compartmentalisation of the aquifer by dykes or faults, causing hydrological isolation of aquifer blocks, may limit recharge or vary recharge processes in different blocks. Evidence suggests that much of the aquifer is being actively recharged, with groundwater levels in many boreholes indicating a seasonal recharge period during the winter.

A number of estimates of recharge to the Permo-Triassic Sandstones aquifers have been made over the years. For the Enler Valley, these include rates of 128 mm/a (Foster, 1969a) and 92 mm/a (based on numerical modelling by Cronin *et al.* (2005) and Gibbons and Kalin (1997)). For the Lagan Valley, there are widely varying rates of 19 mm/a (Bennett, 1976) and 86 mm/a (Cronin *et al.*, 2005; Gibbons and Kalin 1997).

The NIEA has estimated recharge individually to each groundwater body within the Permo-Triassic Sandstones aquifers (Chapter 4.1.3), derived from baseflow indices calculated as part of the Hydrology of Soil Types (HOST) dataset for Northern Ireland (Neary, 2012):

- 126 mm/a (Belfast groundwater body (GWB))
- 173 mm/a (Moygashel GWB)
- 292 mm/a (Moneymore GWB)
- 337 mm/a (Magilligan GWB)

Groundwater flow directions in the aquifers of the Lagan and Enler valleys, the best studied parts of the Permo-Triassic Sandstones aquifers, are generally towards the centre of the valleys and towards the coast, with a shallow hydraulic gradient of 0.01 (Dickson *et al*., 2016; Yang *et al*., 2004).

Groundwater flow paths in the aquifer can be kilometres long where there are no barriers to flow. Particularly long flow paths may occur along major permeable faults; for example, it has been suggested that exposed faults in the Permo-Triassic Sandstones aquifers in the Lagan Valley are surface expressions of the major Southern Upland fault system, which may be an important preferential groundwater flow path (Kalin and Roberts, 1997).

However, where the Permo-Triassic Sandstones aquifers are interrupted by low-permeability zones, such as mudstones or low-permeability dykes or faults, flow paths can be much shorter and can be complex (Comte *et al*., 2017). The widespread presence of dykes appears to have a major influence on groundwater flow in the Permo-Triassic Sandstones aquifers (Chapter 3.12.4). The dykes themselves are sometimes extensively fractured and/or associated with fractured faults, in which case they can have relatively high permeability and may act as focused recharge conduits (McKinley *et al*., 2001). In some cases, however, dykes are associated with a baked zone in the adjacent sandstone. which, although usually thin, may have reduced intergranular permeability.

Evidence from borehole testing in the Sherwood Sandstone Group in the Lagan Valley shows that dykes, even where only 1–2 m wide, are associated with reduced permeability zones that restrict groundwater flow (Comte *et al*., 2017). Groundwater modelling indicates that the hydraulic conductivity (permeability) of dykes in the Lagan Valley is some three orders of magnitude lower than the surrounding Sherwood Sandstone Group (Comte *et al*., 2017). The resulting reduced groundwater connectivity can, in some cases, restrict flow enough to at least partially compartmentalise the aquifer (Comte *et al*. 2017; Dickson *et al*., 2016). This limits groundwater storage to what is available in each aquifer compartment; it can alter groundwater levels, and it can reduce the flow of groundwater to boreholes (Comte *et al*., 2017; Dickson *et al*., 2016; Kalin and Roberts, 1997).

Groundwater modelling studies of aquifers in the Lagan Valley aquifer suggest that dyke swarms alter groundwater flow directions on a regional scale, with preferential pathways parallel to dyke orientations (Comte *et al*., 2017; Dickson *et al*., 2016). However, there is still much to learn about how dykes and faults influence groundwater flow within the Permo-Triassic aquifer.

Groundwater levels tend to be shallow, typically less than 10 m below ground level. Artesian conditions have been observed in some places, such as Eglish in Co. Tyrone and at Newtownards and Comber in Co. Down, where groundwater in the Sherwood Sandstone Group is confined by overlying low-permeability Permian mudstones and Quaternary tidal-flat deposits. An artesian groundwater head of more than 4 m above ground level was measured at one borehole at the base of Scrabo Hill (McLorinan Consulting, 2010). Annual groundwater level fluctuations tend to be between less than 0.5 m and 1 m.

Groundwater discharge is likely to be dominantly to rivers and both freshwater and marine loughs that cut down into the sandstone aquifer, including Belfast Lough, the lower reaches of the River Blackwater and the River Roe. Studies have indicated different degrees of interaction between the River Lagan and groundwater in the sandstone aquifer in the Lagan Valley. Cronin et al. (2005) and Gibbons and Kalin (1997) use chemical and isotopic evidence to conclude there is little interaction, but Bennett (1976) suggests there is up to 17 000 m^3/d groundwater discharge to the lower reaches of the River Lagan above Belfast. However, more research is still needed in order to understand the detail of discharge mechanisms and amounts from the Permo-Triassic Sandstones aquifers.

Groundwater in the Permo-Triassic Sandstones aquifers is typically more highly mineralised (median conductivity 513 µS/cm) and has a higher pH (median 7.68) than groundwater in most other aquifers in Northern Ireland (Figure 8; Table 12). Bicarbonate is the dominant anion and, in most cases, there is no dominant cation. In a minority of samples, calcium is the dominant cation (Figure 10).

The restriction of groundwater flow caused by low-permeability zones can be accompanied by restricted transport of contaminants and other groundwater chemical constituents, and can lead to markedly different groundwater chemistry in different aquifer 'compartments'. This is seen in a coastal site in the Sherwood Sandstone Group, where a dyke clearly impedes saline intrusion (Wilson, 2011; Comte *et al.*, 2017). Another example in the Sherwood Sandstone Group is between Newtownards and Comber, where two boreholes, 1 km apart and separated by a dyke, both in areas of intensive fertiliser application, show widely different nitrate concentrations of 100 mg/l in the upgradient borehole and 25 mg/l in the downgradient borehole.

3.8.4 Groundwater use, history of exploration, management and potential of the Permo-Triassic Sandstones aquifers

The Permo-Triassic Sandstones aquifers have long been the most significant, well-used and studied aquifer in Northern Ireland. Their potential was first realised in the late 19th century, as drilling technology started to advance (Hartley, 1935; Thompson, 1938). Most groundwater abstraction from the aquifer took place in and around the rapidly expanding city of Belfast. Groundwater was used in a number of industries, including for steam power generation and in the production of carbonated waters. The chemistry of groundwater from the Permo-Triassic Sandstones aquifers made it particularly suitable for the carbonation process and, before the First World War, Belfast was the largest exporter of carbonated waters in the world.

Groundwater abstraction declined as mains electricity coverage expanded and replaced steam power generation. At its peak in the 1930s, an estimated 33 ML/d was abstracted from the Permo-Triassic Sandstones aquifers. Interest returned during the 1960s and 1970s for public water use. Groundwater from the aquifer was already used for public supply at Newtownards and Lisburn, and further development was driven by the Lagan Valley Hydrogeological Study (Bennett, 1976), the largest and most significant study to date of groundwater resources in the Permo-Triassic Sandstones aquifers. The study involved:

- drilling exploration boreholes throughout the aquifer in the Lagan Valley
- characterising aquifer stratigraphy by borehole logging
- carrying out long-duration, high flow rate step-drawdown, and constant rate pumping tests

The study led to the commissioning of a major wellfield in the Lagan and Enler valleys, bringing the total mains water supply sourced from groundwater (including from Superficials Deposits aquifers) in Northern Ireland up to 77 ML/d. After more than 30 years of increasing abstraction from this wellfield, groundwater levels showed no signs of decline and there were no confirmed reports of saline intrusion. However, one artesian observation borehole at Newforge in South Belfast did observe a decline in flow rate during the same period.

Despite the apparent long-term sustainability of the groundwater resource, an asset strategy decision by Northern Ireland Water in the late 2000s saw all groundwater public supplies from the Permo-Triassic Sandstones aquifers taken out of service, in preference for increased use of surface-water sources.

Away from the Lagan Valley area, there has been relatively little exploration of groundwater in the Permo-Triassic Sandstones aquifers. There is some evidence to suggest that the hydraulic properties of Triassic sandstones near Dungannon and Cookstown, and in the Roe Valley (thought to be finer-grained than in the Lagan Valley), are not as promising (Benfield, 1971; Benfield and Price, 1971). Despite this, a number of agri-food businesses successfully utilise groundwater from the Permo-Triassic Sandstones aquifers in these areas. Further study is needed to explore the potential of this part of the aquifer.

Abstraction for private water supplies from the Permo-Triassic Sandstones aquifers increased following the decline in public supply abstraction in the 2000s. Coca-Cola Hellenic Bottlers Ltd centralised its bottling facilities in Lisburn due, in large part, to the high productivity and long-term sustainability of the Permo-Triassic Sandstones aquifers there (Buckley *et al.*, 2009). As of 2017, the total licensed abstraction from this aquifer – all for private commercial supplies – was 27 ML/d.

The Permo-Triassic Sandstones aquifers provides significant resource potential in Northern Ireland, which is currently not fully used. The high aquifer productivity and storage capacity mean the aquifer has significant potential for both water supply and for shallow geothermal (ground source) heating and cooling. Existing varying estimates of recharge should be refined to increase confidence in understanding of the resource and allow future groundwater use to be optimised and effectively managed.

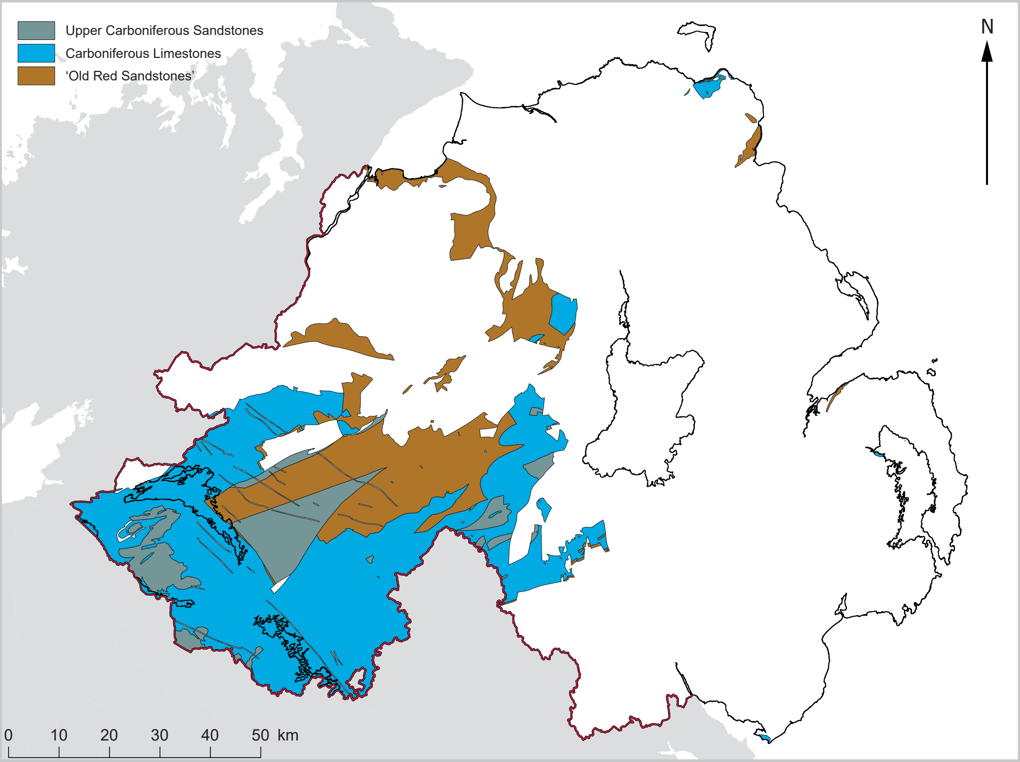


Figure 19. Map of the three component Devonian and Carboniferous aquifers in Northern Ireland: 'Old Red Sandstones', Carboniferous Limestones and Upper Carboniferous Sandstones. Contains OGL and CC-BY-4.0 Data

Photograph 10. Murlough Bay, Co. Antrim.

Photograph 11. Hanging Rock Cave, Co. Fermanagh.

3.9 Devonian and Carboniferous aquifers

3.9.1 Geological summary

Devonian and Carboniferous rocks in Northern Ireland are mostly sedimentary and crop out mainly in the south-west, in counties Fermanagh and Tyrone, with smaller outcrops in counties Londonderry and Armagh and in the north-east of Co. Antrim near Ballycastle and Cushendall. Their lithology is highly variable and they have been divided into three conponent aquifers:

- 'Old Red Sandstones'
- Carboniferous Limestones
- Upper Carboniferous Sandstones

The 'Old Red Sandstones' aquifer is the oldest of these component aquifers, of Devonian and early Carboniferous age, and consists of 'red beds' – clastic sedimentary rocks, equivalent to the Old Red Sandstone Supergroup in Scotland (Mitchell, 2004) with the lower sandstones representing Carboniferous marine transgression. They were formed in continent-edge to shallow-marine environments and are a mixed sequence of mudstones, sandstones and conglomerates with minor evaporates and limestones in relatively thin, discrete beds. The rocks are generally more cemented than the equivalent Old Red Sandstone Supergroup in Scotland. They crop out mainly in an area known as the Fintona Block in west Co. Tyrone and east Co. Fermanagh (including the Shanmullagh and Gortfinbar Conglomerate formations of the Fintona Group) with smaller outcrops across Co. Tyrone (including the Omagh Sandstone

	'Old Red Sandstones' aquifers	Carboniferous Limestones aquifers	Upper Carboniferous Sandstones aquifers
Aquifer type	Fracture	Fracture and karst	Fracture
Aquifer productivity/ groundwater supply potential	Moderate	High	Moderate
Aquifer class *	Bm(f); some Bl(f)	Bh(f-k) (karstic limestones), Bm(f) (sandstones), Bl(f) (mudstones)	Bm(f)
Typical groundwater flow path length (m)	10s – 100s	100s – 1000s	10s –100s (shallow zone) 100s – 1000s (deep zone)
Typical groundwater flow depth (m)	1 – 50	1 – 100	10s – 100s (shallow zone) 100s – 1000s (deep zone)
Groundwater flow rate	Medium	Fast	Medium
Dominant baseline groundwater chemistry	Moderately mineralised, moderate pH, either no dominant cation or a slight dominance by calcium; two distinct anionic groups, one dominated by bicarbonate and the other with no dominant anion	Highly mineralised, moderate pH, calcium bicarbonate type (minor sulphate)	Highly mineralised, high pH, bicarbonate dominated, no dominant cation

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

Group) and in parts of Co. Londonderry (Roe Valley Group), Co. Antrim (Cross Slieve Group) and Co. Armagh.

The Carboniferous Limestones aquifers are younger than the 'Old Red Sandstones' aquifers and comprises a sequence of limestones interbedded with sandstones and mudstones of early Carboniferous age. The limestones are locally dolomitised and often, but not always, karstic.

There are three named Groups within the aquifer: most of the Leitrim Group (except the Glenade Sandstone Formation) and the Armagh and Tyrone Groups. The rocks were formed in a marine and/or fluvio-deltaic environment, with cycles of limestone, mudstone and sandstone deposition. Some of the formations within the overall sequence are particularly karstified, including the Knockmore Limestone Member and other members of the Dartry Limestone Formation, and the Glencar Limestone Formation, all of which are part of the Tyrone Group. These crop out mostly in Co. Fermanagh on higher ground, such as beneath the Cuilcagh and Belmore Mountains. The older Ballyshannon Limestone Formation, also part of the Tyrone Group, is also karstified, but is separated from the karstic rocks higher in the sequence by a series of non-calcareous shale and sandstone formations with no karstification. Beneath this, the Clogher Valley Formation, also part of the Tyrone Group, may also be partly karstified. In general, most of the limestone units are both underlain and overlain by sandstone and mudstone units.

The uppermost and youngest aquifer in the Devonian–Carboniferous sequence is the Upper Carboniferous Sandstones aquifer, of Carboniferous age. This aquifer includes the Coal Measures Group, the Millstone Grit Group and the Ballycastle Group. These form a repetitive sequence of iron-rich sandstones and mudstones with interbedded coal seams, which were formed in swamp environments where river deltas flowed onto lowland plains. The Coal Measures Group is not widespread in Northern Ireland, cropping out mainly near Dungannon, in the Brick Pit at Coalisland, where it was extensively exploited for coal in the past. The Millstone Grit Group crops out near Dungannon in Co. Tyrone and the Ballycastle Group near Ballycastle in Co. Antrim. Other sandstone units in the aquifer include the Topped Mountain Sandstone and Glenade Sandstone formations that mostly crop out over a large portion of Co. Fermanagh.

3.9.2 Typical overlying sediments and soils

Much of the 'Old Red Sandstones' aquifers are overlain by superficial deposits, largely glacial till, although peat is also widespread. Alluvium is restricted to relatively small outcrops in valleys; glaciofluvial sand and gravel deposits occur mainly in the area of the Shanmaghery Sandstone Formation. A few parts of the aquifer have very thin or no superficial deposits cover.

Superficial deposits overlie a significant proportion of the Upper Carboniferous Sandstones and Carboniferous Limestones aquifers. Peat cover is extensive, especially in upland areas, although this is usually less than 3 m thick. Glacial till is also extensive, with drumlins common in Co. Fermanagh, and clay-rich or silty lacustrine sediments in interdrumlin areas, which were formed in periods when Lough Erne was much bigger. A range of tills and associated soil types is seen and, in general, there is a close relationship between till type and the underlying bedrock that formed its main source material. Tills in areas underlain by sandstones and conglomerates are generally sandy and better draining compared to those in areas underlain by limestones and mudstones, which have a more clay-rich matrix.

3.9.3 'Old Red Sandstones' aquifers: hydrogeological conceptual model

The 'Old Red Sandstones' aquifers have low primary porosity and permeability, as a result of compaction and cementation of its sandstones, and the groundwater system is dominated by

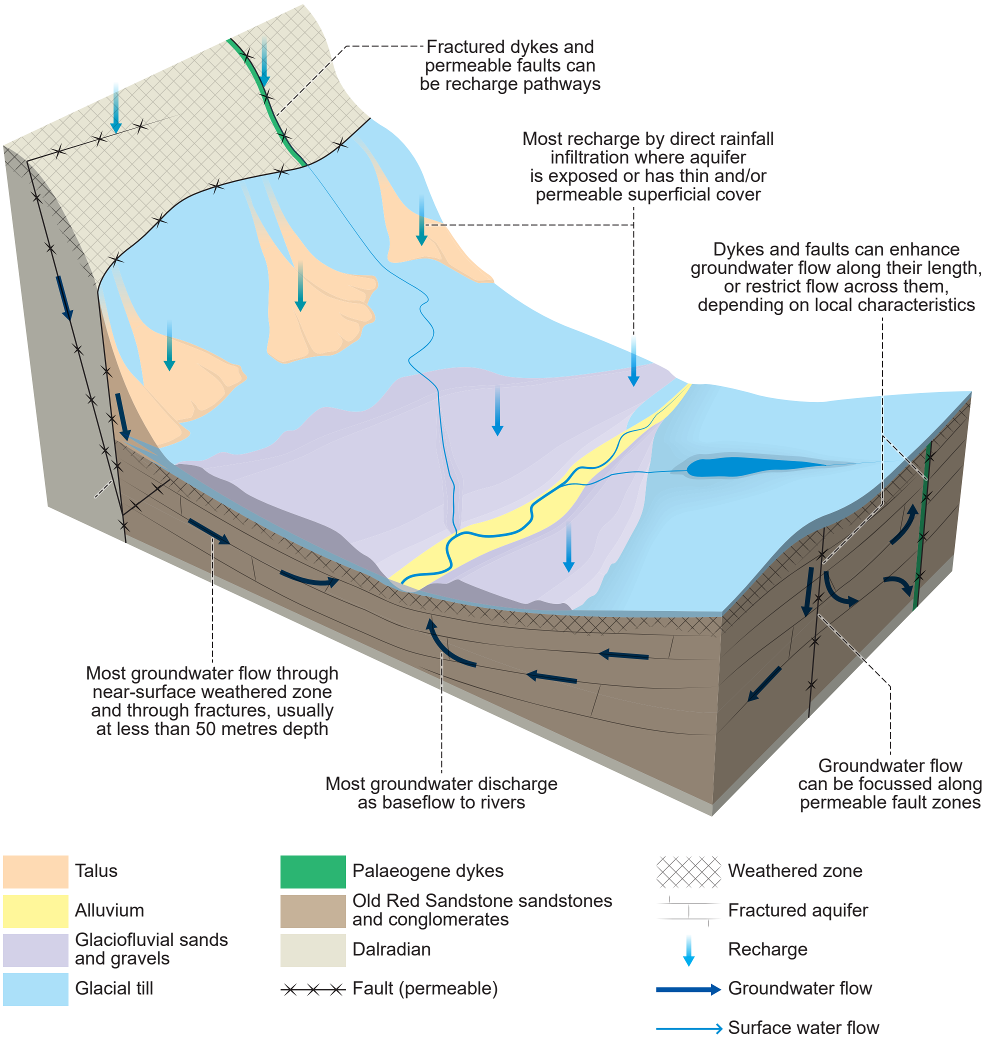


Figure 20. Conceptual model of the hydrogeology of the 'Old Red Sandstone' aquifers.

fracture flow. It is classed as a moderately productive fractured aquifer flow (Bm(f)), with some small areas tending towards low productivity and classed as Bl(f) (Appendix 1).

There has been limited exploration of the 'Old Red Sandstones' aquifers in Northern Ireland and there are no measured transmissivity or storativity values from test pumping. The few available specific capacity values (Table 13) are low compared to other aquifers in Northern Ireland, with a median of 3 m^2/d. The 'Old Red Sandstones' is geologically similar to parts of the 'Old Red Sandstone' aquifer in southern and central Scotland and much of the hydrogeological understanding from Scotland (Ó Dochartaigh *et al*., 2015) is likely to be relevant to the Northern Ireland aquifer.

Most recharge is likely to be from direct rainfall infiltration where the aquifer is exposed at the surface or where overlying superficial deposits are thin and permeable, such as glaciofluvial sands and gravels on lower ground, or talus on hillslopes (Figure 20). Preferential recharge may also occur along permeable faults. Recharge acceptance may be limited by relatively low aquifer storage capacity.

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Specific capacity (m^2/d/m)	8	88%	0.14	0.6	3.1	3	6	295
Measured yield (m^3/d)	59	17%	4	65	131	123	327	2182

Table 13. Summary of available aquifer properties data for the 'Old Red Sandstones' aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	314	0	295	379	473	540	581
pH	317	0	6.61	7.18	7.49	7.68	7.88
Dissolved oxygen (mg/L)	8	0	5.78	6.05	6.45	7.13	8.19
Calcium (Ca) (mg/L)	317	0	34.1	44.5	51.6	62.5	67.3
Magnesium (Mg) (mg/L)	318	0	6.9	12.7	16	20.6	26.4
Sodium (Na) (mg/L)	319	0	11.9	16	19.2	22.1	36.6
Potassium (K) (mg/L)	317	0	1.34	1.52	1.91	2.6	7.05
Chloride (Cl) (mg/L)	321	0	10.8	14.2	16.8	19.3	23.9
Sulphate (SO_4) (mg/L)	320	0	4.2	7.6	9.3	11.4	19.2
Bicarbonate (HCO_3) (mg/L)	293	0	121	230	261	290	326
Nitrate (as N) (NO_3-N) (mg/L)	326	30	0.15	0.2	1.38	2.71	3.37
Phosphate (P) (mg/L)	317	0	1.34	1.52	1.91	2.6	7.05
Aluminium (Al) (µg/L)	142	21	3.15	8	13	27.9	78.0
Iron (Fe) (µg/L)	296	1	6.5	7	12	25.3	230
Manganese (Mn) (µg/L)	296	0	1.5	1.5	4.2	17.2	97.9

* Number of samples.
† Number below detection limit.

Table 14. Summary of baseline chemistry of the 'Old Red Sandstones' aquifers in Northern Ireland, based on samples from 34 groundwater sources.

Most groundwater flow is likely to be at relatively shallow depths, probably less than 100 m, in the zones of weathered and fractured bedrock (Comte *et al.*, 2012) (Figure 20). In the very shallow, near-surface, weathered zone, groundwater flow is likely to be strongly influenced by topography and to broadly follow surface-water drainage patterns. Flow paths are likely to be short: tens to hundreds of metres. In the deeper fractured aquifer, flow paths may be longer, possibly more than 1 km. Here, groundwater flow patterns are likely to be influenced most by the extent and interconnectivity of fracture development, as well as the presence of faults and possibly dykes.

Faulting is relatively extensive across the aquifer and may act to enhance groundwater flow, particularly vertical flow and recharge, in some areas, but it may act as a barrier to flow in others (Chapter 3.3.3). Similarly, the presence of fractured, subvertical dykes through the 'Old Red Sandstones' aquifers can provide conduits for preferential recharge, although, unlike in the more productive Permo-Triassic Sandstones aquifers, these are not thought to form such extensive barriers to lateral flow (Chapter 3.12.4).

Groundwater levels may broadly reflect topography: shallow in valley areas close to rivers, but deeper below higher ground. In areas where the aquifer is overlain by low-permeability mudstones or low-permeability superficial deposits such as thick till, groundwater in the 'Old Red Sandstones' aquifers may be confined and may even be artesian in some low-lying areas.

The extent of interaction between surface waters and groundwater in the 'Old Red Sandstones' aquifers has not been studied. It is likely that interactions will be similar to other fractured aquifers, where most groundwater discharge is as baseflow to rivers, flowing via the shallow, near-surface, weathered zone. There are no reports of any significant springs issuing from the aquifer.

Groundwater in the 'Old Red Sandstones' aquifers is typically moderately mineralised (median conductivity 473 µS/cm) with a moderate pH (median 7.49) compared to other aquifers in Northern Ireland (Figure 8; Table 14). There is either no dominant cation or a slight dominance by calcium. There are two distinct anionic groups; one is dominated by bicarbonate and the other has no dominant anion (Figure 10).

3.9.4 Carboniferous Limestones: hydrogeological conceptual model

The Carboniferous Limestones aquifers underlies a large part of the south-west of Northern Ireland. The limestones in the sequence form the main aquifer and they are classed as highly productive with both fracture and karstic flow (Bh(f-k)) (Appendix 1). Mudstones in the sequence do not form a significant aquifer, but they do play an important role in the migration of groundwater. Little is known about the aquifer properties of the sandstones interbedded with the limestones: they may form relatively productive local aquifers in their own right, but they are also thought to restrict recharge to the limestone beds and therefore constrain the development of karst networks.

Groundwater flows primarily through karstic networks in the limestone beds and, to a lesser extent, through unkarstified fractures (Figure 21). The degree of karstification is partly controlled by the purity of the limestone (the proportion of calcium carbonate, $CaCO_3$); some less pure limestones are dominated more by fractures than karst. Karst develops preferentially along existing groundwater flow features such as fractures, enlarging them to form wider conduits and sometimes even caves. Faults that are associated with extensive fracturing (Chapter 3.3.3) can be the focus of karst development: sinkholes, springs and other karst features often align with mapped faults. However, faults that are associated with low-permeability fault gouge or secondary mineralisation of fractures may restrict groundwater flow and karst development.

Overall, the development of karstic features is highly variable throughout the aquifer and, consequently, so are aquifer properties. The relatively few available transmissivity values (Table 15) show a range over two orders of magnitude, with a relatively high median value compared to other Northern Ireland aquifers. If a borehole encounters well-developed karst features it can provide very high yields and, at their most productive where karst is well developed, the Carboniferous Limestones aquifers form a highly productive aquifer. However, the karstic aquifer system commonly has high transmissivity through karstic features but low storage capacity, as there is little porosity away from karstic features. There is some evidence of boreholes providing initially high yields that fall over time due to insufficient storage capacity. Some faults may also contribute to this effect, if they are zones of low permeability and act to restrict lateral groundwater flow (Chapter 3.3.3). Long-duration test pumping is needed to establish true borehole-sustainable yields.

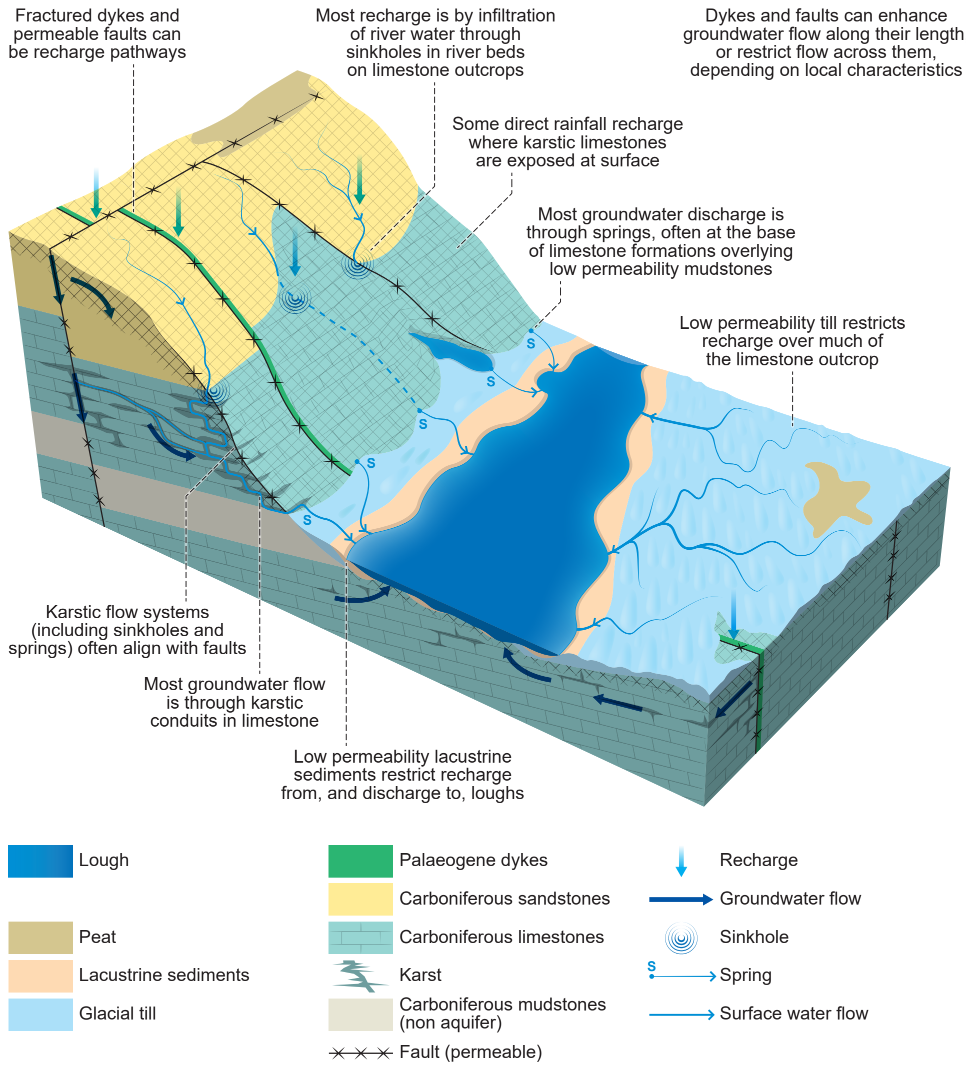


Figure 21. Conceptual model of the hydrogeology of Carboniferous Limestones aquifer.

The main recharge mechanism to the karstic aquifer system is the rapid and largely unrestricted infiltration of river water through karstic sinkholes where rivers flow over limestone outcrops (Figure 21). Fractured, permeable dykes may also form preferential recharge pathways where present. Some direct rainfall recharge to the limestones will occur where they are exposed at the surface, but the low-permeability glacial till that covers much of the aquifer will limit recharge. There is also likely to be little recharge from loughs overlying the aquifer, restricted by low-permeability lacustrine sediments on lough beds.

Flow rates through the aquifer are highly variable, depending not only on the size, interconnectedness and degree of complexity of the karstic system, but also on flow conditions; groundwater flows faster when there is more water in the system during higher flow conditions such as rain storms. Typical flow rates measured in karstic tracer tests are around 2–3 km/d (Brown, 2005).

Groundwater in the aquifer is unconfined, as the karstic networks are usually well connected with the ground surface – almost all rivers that flow over the limestones sink into a karstic system. Groundwater levels can show large fluctuations (tens of metres) from wet to dry periods.

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Transmissivity (m^2/d)	9	100%	10	74	174	189	546	2200
Storativity	4	100%	8.81×10^{-05}		0.00010	0.00014		0.0004
Specific capacity (m^2/d/m)	15	87%	0.64	14	42	43	264	1177
Hydraulic conductivity (horizontal) (m/d)	4	87%	2.31×10^{-07}	5.13×10^{-06}	0.02	0.0005	0.22	0.74
Measured yield (m^3/d)	110	12%	12	101	327	296	873	3382

Table 15. Summary of available aquifer properties data for the Carboniferous Limestones aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (μS/cm)	394	0	267	394	577	685	761
pH	419	0	6.99	7.2	7.39	7.6	7.85
Dissolved oxygen (mg/L)	38	0	4.66	6.43	7.85	9.5	10
Calcium (Ca) (mg/L)	397	0	46.6	62	74.6	105	126
Magnesium (Mg) (mg/L)	399	0	3.81	7.26	19.3	27.0	29.1
Sodium (Na) (mg/L)	401	0	6.4	8.61	16.1	31.5	54.6
Potassium (K) (mg/L)	399	0	0.56	1.16	2.07	2.99	3.92
Chloride (Cl) (mg/L)	401	0	10.1	13.1	16	19.3	24
Sulphate (SO_4) (mg/L)	401	1	4.7	6.9	17.1	27.4	54.6
Bicarbonate (HCO_3) (mg/L)	275	0	171	256	331	378	440
Nitrate (as N) (NO_3-N) (mg/L)	423	27	0.1	0.2	0.3	0.63	1.5
Phosphate (P) (mg/L)	399	0	0.56	1.16	2.07	2.99	3.92
Aluminium (Al) (μg/L)	186	31	1.63	9.83	20.4	36.5	100
Iron (Fe) (μg/L)	322	0	18.3	62.1	192	369	1114
Manganese (Mn) (μg/L)	321	0	1.8	12.3	34	128	215

* Number of samples.
† Number below detection limit.

Table 16. Summary of baseline chemistry of the Carboniferous Limestones aquifers in Northern Ireland, based on samples from 53 groundwater sources.

Groundwater discharge from the karstic limestone is usually as discrete springs, which can form stream sources. These are often at the base of limestone units that overlie low-permeability mudstone units (Figure 21). Some discharge also occurs as baseflow to river beds where the rivers flow directly over the limestones. As with recharge, low-permeability lacustrine sediments below loughs are likely to restrict discharge from the aquifer to loughs.

Groundwater in the Carboniferous Limestones aquifers are typically highly mineralised compared to other aquifers in Northern Ireland (median conductivity 577 µS/cm) and have a neutral pH (median 7.39) (Figure 8; Table 16). Groundwaters are mainly calcium bicarbonate type, with a minority of samples dominated by sulphate instead of bicarbonate (Figure 10).

3.9.5 Upper Carboniferous Sandstones aquifers: hydrogeological conceptual model

The Upper Carboniferous Sandstones aquifers cover only a small area in Northern Ireland and has been little studied, with only a few specific capacity and borehole yield values available (Table 17). It is classed as a moderately productive fractured aquifer (Bm(f)) (Appendix 1).

Much more is known of the hydrogeology of the Upper Carboniferous Sandstones aquifers in Great Britain, where extensive coal mining and its legacy have driven data gathering and understanding (e.g. Ó Dochartaigh *et al.*, 2015; Jones *et al.*, 2000) and these findings are likely to also be true for the aquifer in Northern Ireland. The hydrogeology of the Upper Carboniferous Sandstones aquifers is complex, even where unmined and, where it has been mined, the natural hydrogeology is significantly altered. Where unmined, it typically forms a multilayered aquifer, in which sandstone units effectively act as separate aquifers interspersed with lower-permeability mudstone units. The sandstones are generally fine grained and well cemented, with consequently little primary intergranular porosity or permeability. Groundwater flow and storage occurs mainly in fractures, often associated with jointing and faulting. The storage capacity of these fractures may be low, although the fracture permeability is high, so initially high borehole yields may not be sustainable in the long term (Jones *et al.*, 2000).

The development of fracture permeability across the aquifer has been influenced by its complex lithology and structural history; it is highly variable both laterally and with depth. Sandstone units tend to be much more fractured than mudstone units, creating their higher permeability (Jones *et al.*, 2000). Faulting can also have a major impact on the hydrogeology, but the effects vary (Chapter 3.3.3). Some faults cause extensive fracturing of the surrounding rock, which increases local permeability and enhances vertical groundwater flow, while others have low-permeability infill that restricts lateral groundwater flow and can act to divide the permeable sandstone units into isolated, fault-bounded blocks (Ó Dochartaigh *et al.*, 2015).

Most recharge to the Upper Carboniferous Sandstones aquifers is likely to be from direct rainfall infiltration through overlying superficial deposits, especially where these are thin or more permeable or, rarely, where the aquifer is exposed at the ground surface. Recharge is likely to be strongly influenced by the permeability and thickness of soils and any other overlying superficial deposits. Indirect recharge may also occur through the beds of rivers, either directly into the Upper Carboniferous Sandstones aquifers or via overlying superficial deposits. Recharge is also likely to be influenced by the complex aquifer structure: if the outcrop areas of the sandstone aquifer units are small, they will receive little recharge and, if sandstone blocks have been isolated by faulting, recharge to them may be even more limited (Jones *et al.*, 2000).

Groundwater flow patterns are likely to be complex, reflecting the multilayered aquifer structure, the development of fracture permeability and the impact of faulting. Flow paths are likely to be generally short, probably only tens to hundreds of metres long, especially if restricted by low-permeability faults, although paths may be longer where different sandstone units are hydraulically connected.

There are few groundwater level measurements for the aquifer. Evidence from Scotland (Ó Dochartaigh *et al.*, 2015) shows that groundwater heads often vary between different sandstone units. Shallower units, which crop out at the ground surface, often contain groundwater under unconfined conditions, although these can also be confined by overlying

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Specific capacity (m^3/d/m)	3	100%	9.65		15	7		357.25
Measured yield (m^3/d)	16	19%	12	169	300	309	873	2182

Table 17. Summary of available aquifer properties data for the Upper Carboniferous Sandstones aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	36	0	395	470	498	520	559
pH	36	0	6.99	7.38	7.59	7.72	7.77
Dissolved oxygen (mg/L)	0						
Calcium (Ca) (mg/L)	34	0	48.5	49.4	51.2	52.3	52.9
Magnesium (Mg) (mg/L)	34	0	13.8	14.2	14.7	15.0	15.3
Sodium (Na) (mg/L)	36	0	29.5	32.6	33.9	35.3	36.6
Potassium (K) (mg/L)	34	0	1.86	1.93	2.04	2.17	2.25
Chloride (Cl) (mg/L)	36	0	17.6	19.4	20.1	21.5	22.5
Sulphate (SO_4) (mg/L)	36	0	15.0	15.8	16.3	17.4	17.8
Bicarbonate (HCO_3) (mg/L)	34	0	255	264	272	276.5	283
Nitrate (as N) (NO_3-N) (mg/L)	36	7	0.1	0.18	0.21	0.25	0.29
Phosphate (P) (mg/L)	34	0	1.86	1.93	2.04	2.17	2.25
Aluminium (Al) (µg/L)	15	3	4.24	7.75	13	21.4	26.6
Iron (Fe) (µg/L)	34	0	7	7.23	10.6	15.4	22.9
Manganese (Mn) (µg/L)	34	0	100.0	108	115	118	132

* Number of samples.
† Number below detection limit.

Table 18. Summary of baseline chemistry of the Upper Carboniferous Sandstones aquifers in Northern Ireland, based on samples from five groundwater sources.

low-permeability superficial deposits. Deeper sandstone units are often confined and can show artesian conditions.

Groundwater discharge is likely to be mainly to local rivers, either directly where they cut down into the bedrock aquifer, or indirectly through overlying permeable superficial deposits. It is likely that, as seen in other, better-studied aquifers, groundwater/surface water interaction varies through the year, at times dominated by groundwater discharging to surface water (effluent groundwater) and at others by recharge to the aquifer (influent groundwater).

There is little data on groundwater chemistry in the Upper Carboniferous Sandstones aquifers in Northern Ireland. What is available indicates that groundwaters are typically highly mineralised (median conductivity 498 µS/cm) and have higher pH (median 7.59) compared to other aquifers in Northern Ireland (Figure 8; Table 18). Bicarbonate is the dominant anion, but there is usually no dominant cation (Figure 10).

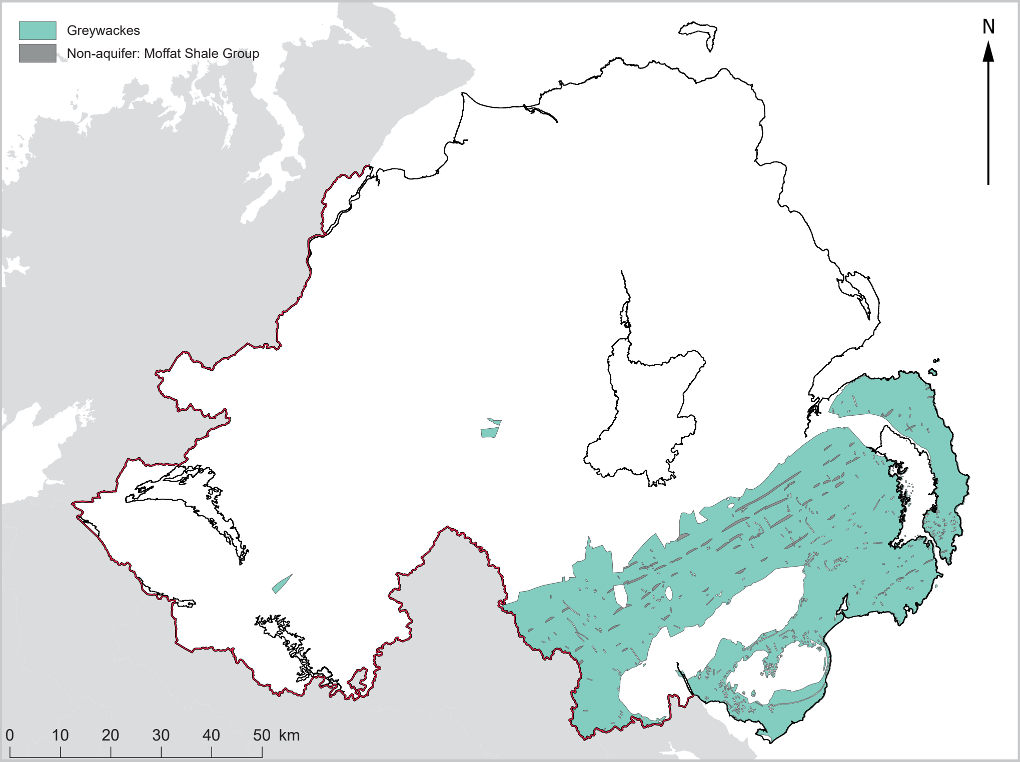


Figure 22. Map of the Greywackes aquifers in Northern Ireland. The map also shows the Moffat Shale Group non-aquifer. Contains OGL and CC-BY-4.0 Data

Photograph 12. Hawick Group, Whitehouse Port, Cloghy, Co. Down.

Photograph 13. Hawick Group, Kearney Point, Portaferry, Co. Down.

Aquifer type	Fracture
Aquifer productivity/groundwater supply potential	Low
Aquifer class *	Bl(f)
Typical groundwater flow path length (m)	10s to 100s
Typical groundwater flow depth (m)	1–50
Groundwater flow rate	Medium
Dominant baseline groundwater chemistry	Moderately mineralised, moderate pH, bicarbonate dominated or no dominant anion; no dominant cation (minority calcium)

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.10 Greywackes aquifers

3.10.1 Geological summary

Silurian and Ordovician rocks in Northern Ireland are dominated by marine sedimentary rocks. They form part of a geological zone known as the Southern Uplands–Down–Longford Terrane, which stretches across much of counties Monaghan, Armagh and Down and continues into the Southern Uplands in the south of Scotland. Five lithostratigraphical groups are recognised:

- Hawick Group
- Gala Group
- Moffat Shale Group
- Crawford Group
- Leadhills Supergroup

In all of these but the Moffat Shale Group, the dominant rock type is greywacke, an archaic but widely used term for a hard lithic sandstone with a mud matrix. These are characterised by turbidites, which formed by underwater gravity flows. They typically have a fine-grained matrix containing a large proportion of rock fragments, in beds that vary from a few centimetres to a few metres thick. These are interbedded with minor siltstone and mudstone beds. The Moffat Shale Group, however, is dominated by organic-rich mudstones and siltstones with occasional limestones. All of the Silurian and Ordovician rocks were marine rocks accreted to a continental margin during the closure of the Iapetus Ocean (Mitchell, 2004). They have been subject to extensive deformation as a result of regional metamorphism and are significantly folded.

3.10.2 Typical overlying sediments and soils

More than half of the area underlain by the Greywackes aquifers is covered by glacial till, which often forms drumlins between 10 and 30 m high, producing the rolling topography characteristic of the south-east of Northern Ireland. Although they mostly consist of till, some drumlins are rock cored and some contain sand and gravel (Hill, 1971), Between the drumlins are interdrumlin hollows in which superficial deposits are thin and the underlying Greywackes aquifers is close to the surface. These hollows are often poorly drained, leading to the formation of peat and inter-drumlin lakes, another key characteristic of this landscape.

In the west of this area, into Co. Armagh, superficial deposits tend to be thicker, and the prevalence of rock at or near the surface diminishes.

Soils associated with this aquifer and the overlying glacial till tend to be highly variable, even over small areas. This is partly controlled by topography, with rocky rankers on drier drumlin hills occurring alongside peaty soils in poorly drained hollows (Cruikshank, 1997).

3.10.3 Hydrogeological conceptual model

The Greywackes aquifers have negligible primary intergranular porosity and are classed as a low-productivity, fracture-flow aquifer (Bl(f)) (Appendix 1). The Moffat Shale Group does not form a significant aquifer in Northern Ireland. The development of fracturing and therefore of permeability across the Greywackes aquifers is highly variable.

The three available transmissivity values cover a wide range, reflecting the variable fracture permeability, although all of the few available specific capacity values are relatively low (Table 19). Much of the limited hydrogeological investigation of this aquifer in Northern Ireland has been associated with quarry development, including sites at Carrowdore (Finlay Concrete

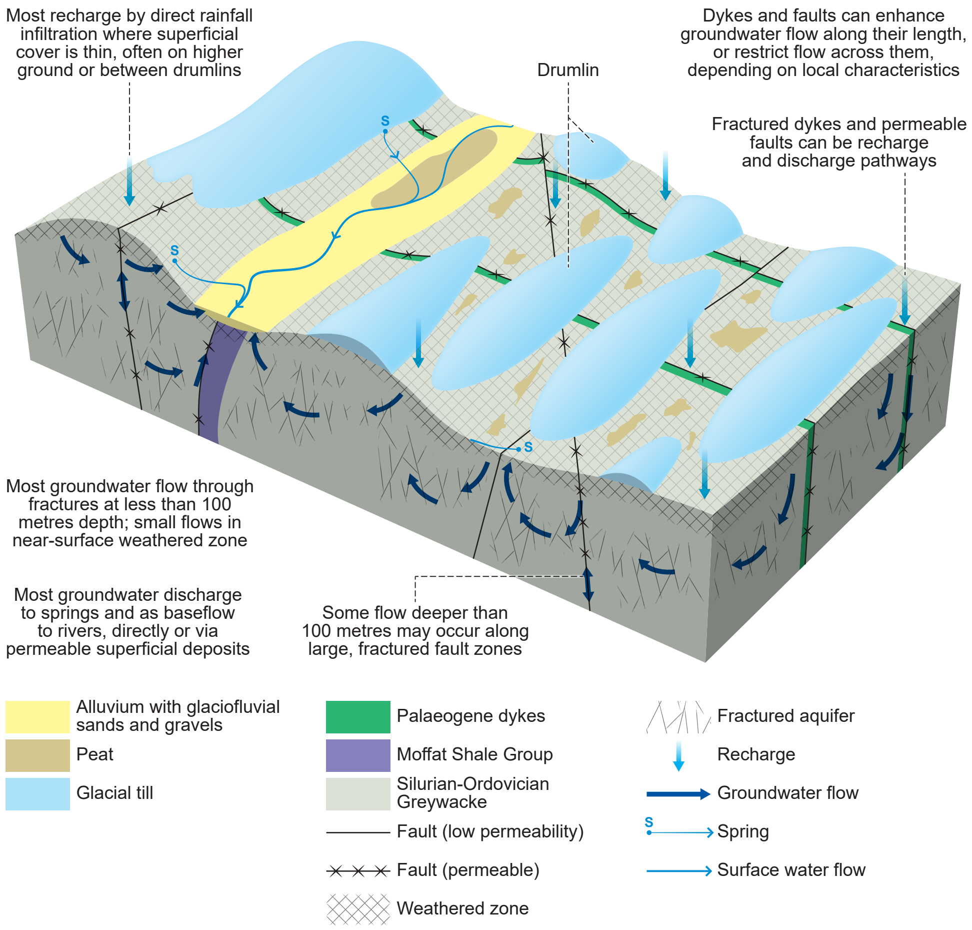


Figure 23. Conceptual model of the hydrogeology of the Greywackes aquifers in Northern Ireland.

Products, 2000) and Lisowen (Hydrogeological and Environmental Services Ltd, 2000). Measured borehole-yield values also reflect the variability in fracture permeability, indicating that some parts of the aquifer are capable of supplying relatively high yields (Table 19) while in other parts, some drilled boreholes are much lower yielding or even dry (Bennett, 1978b). Some boreholes have shown significant water strikes at depths greater than 50 m, indicating that water-bearing fracture systems exist at these depths.

The conceptual model of fractured aquifers described by Comte *et al.* (2012) is partially based on detailed hydrogeological investigations of the Greywackes aquifers at Mount Stewart on the Ards Peninsula. These revealed higher permeabilities at depths of up to 20 m in the Greywackes aquifers and lower permeabilities – but still allowing groundwater flow – at depths of up to about 50 m, which is attributed to a reduction in fracture densities with depth (Comte *et al.*, 2012).

Groundwater recharge is likely to be predominantly by direct rainfall infiltration where superficial deposit cover is thin, which is often on higher ground or in the areas between drumlins (Figure 22). There may be some recharge through thicker overlying sediments where these are sufficiently permeable. There may also be pathways for preferential recharge through faults, if these have caused enhanced fracturing and permeability development in the

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Transmissivity (m^2/d)	3	100%	2.34		8.8	15.5		180
Storativity	1	100%	a single sample with a value of 0.445					
Specific capacity ($m^3/d/m$)	8	88%	0.03	0.26	0.85	1	6	25.9
Hydraulic conductivity (horizontal) (m/d)	14	100%	1.74×10^{-07}	0.002	0.02	0.01	0.44	6.78
Measured yield (m^3/d)	100	8%	1	44	77	69	131	1091

Table 19. Summary of available aquifer properties data for the Greywackes aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	468	0	310	384	470	563	668
pH	469	0	6.65	7.02	7.38	7.7	7.92
Dissolved oxygen (mg/L)	7	0	5.26	5.7	5.9	6.9	7.3
Calcium (Ca) (mg/L)	469	0	32.6	38.3	48.7	60.4	77.1
Magnesium (Mg) (mg/L)	470	0	7.46	10.0	20	26.6	30.4
Sodium (Na) (mg/L)	475	0	9.61	15.7	20.1	33.4	51.5
Potassium (K) (mg/L)	469	0	0.81	1.12	1.56	2.24	4.71
Chloride (Cl) (mg/L)	476	0	14	18.6	30.1	40.4	59.3
Sulphate (SO_4) (mg/L)	475	0	7.66	13.5	20.8	34.4	49.5
Bicarbonate (HCO_3) (mg/L)	445	0	116	175	219	265	307
Nitrate (as N) (NO_3-N) (mg/L)	480	60	0.1	0.2	0.5	4.58	9.09
Phosphate (P) (mg/L)	251	14	0.005	0.03	0.06	0.1	0.17
Aluminium (Al) (µg/L)	238	30	3.24	8	13	32.7	77.4
Iron (Fe) (µg/L)	454	0	7.09	12	25.6	83.2	382
Manganese (Mn) (µg/L)	454	0	1.5	3.63	22.0	155	404

* Number of samples.
† Number below detection limit.

Table 20. Summary of baseline chemistry of the Greywackes aquifers in Northern Ireland, based on samples from 79 groundwater sources.

surrounding aquifer, and through igneous dykes, which are often more fractured and permeable than the surrounding Greywackes (Chapter 3.12.4). Overall, however, recharge to the Greywackes aquifers is likely to be limited by low storage capacity and transmissivity.

The three-layer conceptual model as applied to other fractured aquifers in Ireland is also relevant for the Greywackes aquifers (Comte *et al.*, 2012) (Chapter 3.3.1). The transition zone in the uppermost few metres of the aquifer is often highly weathered, with relatively high permeability, and forms an important pathway for shallow, lateral groundwater flow in the aquifer (Figure 22). In the shallow bedrock zone below this, generally to between 50 and 100 m depth, groundwater flow is dominantly through fractures (Figure 22). Faults that cut through the Greywackes aquifers may have caused enhanced fracturing and permeability development and may form zones of preferential flow. However, some faults can also be zones of low permeability, such as where they contain low-permeability fault gouge, and can act to restrict flow (Chapter 3.3.3).

In the shallow bedrock zone, tracer tests have shown that groundwater flow velocities can be fairly fast, in the order of tens of metres per day (Orr *et al.*, 2017). Groundwater flow patterns are likely to be strongly influenced by topography and, in large part, reflect surface-water drainage patterns. In general, groundwater flow paths through the aquifer are likely to be less than 1 km long. Deeper groundwater flow, below approximately 100 m, is likely to be limited because of the expected poorer development of fracture networks, but it may occur along major fault zones (Figure 22). Any groundwater at these depths is likely to have somewhat longer flow paths and residence times.

Most groundwater discharge is into springs and rivers, either directly or via overlying permeable superficial deposits, such as alluvium in river valleys (Figure 22).

Groundwater levels tend to be only a few metres below ground surface during the wetter winter, which is the main recharge season, but fall during drier periods. Where overlying superficial deposits are thin and/or permeable, groundwater in the Greywackes aquifers is likely to be unconfined, but clay-rich tills have been shown to act to confine groundwater in the underlying bedrock aquifer, as shown at Mount Stewart (Comte *et al.*, 2012).

Groundwater in the Greywackes aquifers is typically moderately mineralised (median conductivity 470 µS/cm) and has a moderate pH (median 7.38) compared to other aquifers in Northern Ireland (Figure 8; Table 20). The dominant anion is bicarbonate, but a large proportion of samples show no dominant anion and a small subset is dominated by chloride. In most samples, there is no dominant cation; where there is, it is usually calcium (Figure 10).

3.10.4 Groundwater use, history of exploration, management and potential of the Greywackes aquifers

The Greywackes aquifers has never been used for public water supply in Northern Ireland. Before the widespread introduction of rural mains water supply in the 1950s, shallow wells dug into the aquifer were widely used for private water supplies, although they are likely to have abstracted only from the very shallow, weathered transition zone. Many will have obtained at least some inflow from overlying superficial deposits.

The area of the Greywackes aquifers is intensively farmed, mainly for dairy and beef cattle, which have high water demands. There has been significant new water borehole drilling for domestic and agricultural water supplies in this region. Most of these boreholes are less than 50 m deep and provide relatively low yields of less than 50 m^3/day. Not all have been successful: dry boreholes are relatively common.

At the groundwater research site at Mount Stewart on the Ards Peninsula, established in 2009, 14 investigation boreholes were drilled into the Greywackes aquifers, to various depths. Research outputs have helped develop better understanding of groundwater flows through the aquifer (Comte *et al.*, 2012; Pilatova, 2013; Nitsche, 2014; Orr *et al.*, 2017; Comte *et al.*, 2018). Geological re-mapping and better characterisation of the geological structure was also done as part of the Tellus project (Young, 2016). This provides a good basis for future targeted hydrogeological investigations aimed at investigating the potential for more reliable, small – to moderate-sized agricultural and industrial groundwater abstractions.

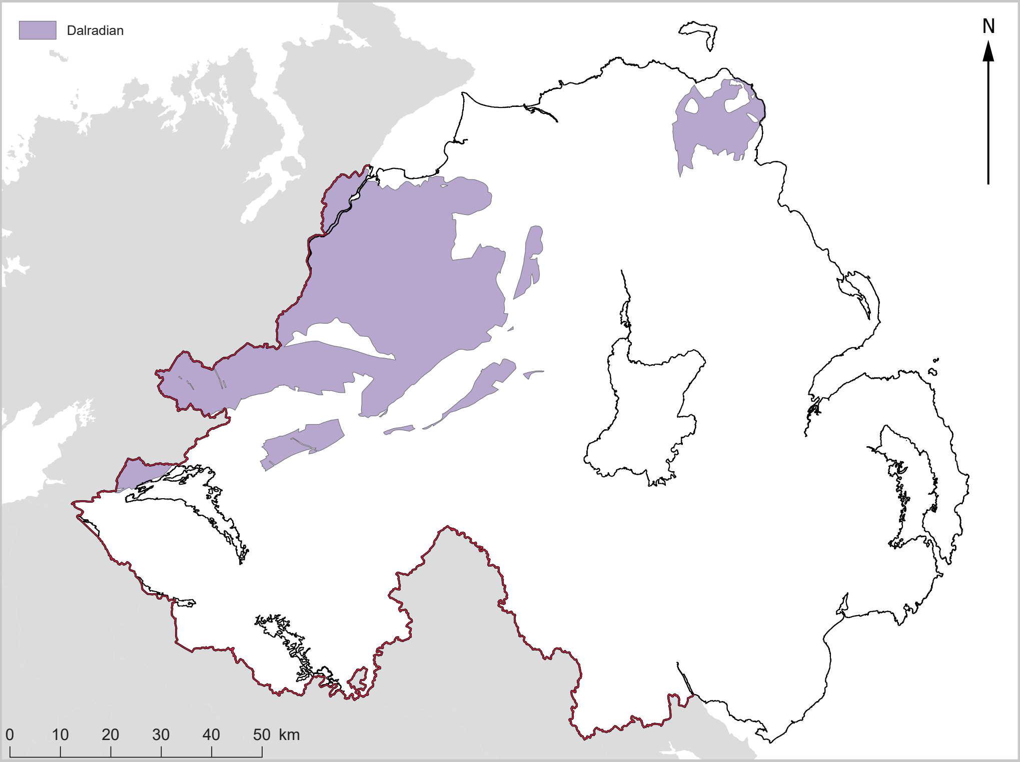
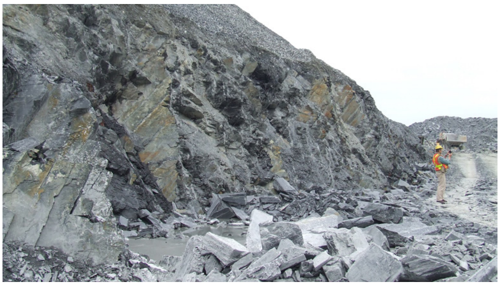


Figure 24. Map of the Dalradian aquifers in Northern Ireland. Contains OGL and CC-BY-4.0 Data

Photograph 14. The Sperrins, Co. Tyrone.



Photograph 15. Semipelite hard rock quarry.

Aquifer type	Fracture
Aquifer productivity/groundwater supply potential	Low
Aquifer class *	Bl(f)
Typical groundwater flow path length (m)	10s to 100s
Typical groundwater flow depth (m)	1–50
Groundwater flow rate	Medium
Dominant baseline groundwater chemistry	Moderately mineralised, low pH, calcium bicarbonate or no dominant anion or cation

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.11 Dalradian aquifers

3.11.1 Geological summary

The Dalradian Supergroup in Northern Ireland is a thick succession of metamorphic rocks of predominantly clastic marine origin. These crop out mainly in the west of Northern Ireland, in counties Londonderry and Tyrone including in the Sperrin Mountains and the Lack Inlier west of Omagh, continuing west across the border into Co. Donegal. There is also a small outcrop in north-east Antrim (Figure 24).

Dalradian rocks were originally deposited in a rift basin in the late Precambrian, some 700–600 Ma ago, and were subject to intense metamorphism during the Grampian Orogeny in the Ordovician. In Northern Ireland, the Dalradian is subdivided as follows:

- Southern Highland Group: the stratigraphy is not clearly defined, but includes a thick succession of turbiditic arenites and pelitic metasediments, with rare volcaniclastic (greenbed) and calcareous schist units
- Argyll Group: comprises mainly schistose psammites in its lower parts, with many thin beds of metalimestone, often dolomitised, in its upper parts
- Appin Group: characterised by dominantly marine-origin metalimestones and phyllitic schists, quartzites and slates

The majority of the Dalradian Supergroup are hard, crystalline rocks that are resistant to weathering often resulting in prominent upland landforms.

Relatively few Palaeogene dykes are seen in the Dalradian Supergroup in Northern Ireland: they are rare in the central and eastern Sperrin Mountains, becoming more common in the western Sperrins and then increasingly so westwards into Co. Donegal (Anderson *et al.*, 2018).

3.11.2 Typical overlying sediments and soils

Across much of their mainly upland extent and around Torr Head, rocks of Dalradian age are exposed at or very near the ground surface. Where not exposed, they are largely overlain by till and relatively thin blanket peat. There are also some extensive areas of glacial sand and gravel, sometimes overlain by alluvium, generally found in river valleys.

Weathering of the quartz-rich Dalradian psammites and quartzites typically produces a sandy soil, with sandy loam textures and a low proportion of clay. Similar soils have developed from some Dalradian metalimestones. Despite their sandy nature, over 60 % of soils overlying Dalradian rocks are classed as surface water gleys, with varying but all limited drainage (Cruikshank, 1997). It is unusual for sandy loam soils to become gleyed and it may be due to a high silt content and a dominantly wet environment.

3.11.3 Hydrogeological conceptual model

The Dalradian aquifers have virtually no primary porosity or intergranular permeability; they are classed as a low-productivity, fractured aquifer (Bl(f)) (Appendix 1). There are little available transmissivity and specific capacity data for the Dalradian aquifers in Northern Ireland. Median values are low to moderate compared to other Northern Ireland aquifers, but there is a wide range (Table 21).

This variability reflects the high spatial heterogeneity of permeability and storage development in the aquifer, with depth and laterally, which is controlled by the scale and characteristics of local weathering and fracturing (Comte *et al.*, 2018). The general three-layer

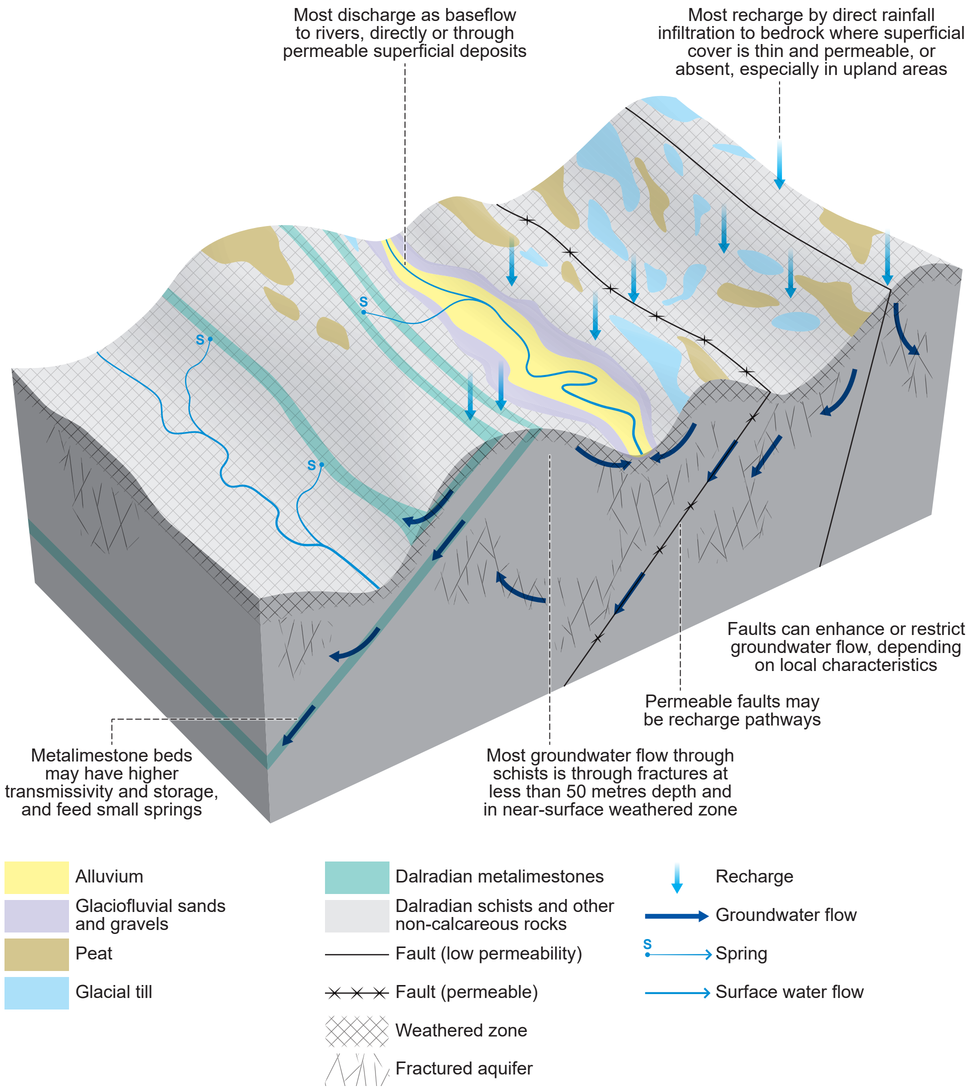


Figure 25. Conceptual model of the hydrogeology of the Dalradian aquifers in Northern Ireland.

conceptual model applied to other fractured aquifers in Ireland is also applicable to Dalradian aquifers (Comte *et al.*, 2012, 2018) (Chapter 3.3.1). Groundwater flow and storage occur only where aquifer rocks are sufficiently weathered or fractured. This is dominantly in a weathered 'transition' zone, which can range from less than 5 m up to 30 m thick, and an underlying zone of fractured bedrock, which can extend to between approximately 50 and 100 m depth. Below this, fracture permeability is less well developed.

Hydraulic conductivity values derived from borehole testing in a Dalradian schists in Co. Donegal showed that the transition zone has mean hydraulic conductivity values close to 10-1 m/d; the fractured bedrock zone has a mean value close to 10-2 m/d, but with large variability of over two orders of magnitude, and the deeper, massive, relatively unfractured bedrock has a mean value of around 6 × 10-3 m/d (Comte *et al.*, 2018).

Storage capacity in the Dalradian aquifers is thought typically to be low, reflecting the limited storage capacity of fractures. Indicative specific yield values from borehole testing in the

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Transmissivity (m^2/d)	3	100%	0.55		65	23.2		350
Specific capacity (m^3/d/m)	22	82%	0.075	0.5	1.5	2.9	15	655
Hydraulic conductivity (horizontal) (m/d)	3	100%	0.10		0.37	0.34		1.00
Measured yield (m^3/d)	52	37%	1	12	33	37	101	2182

Table 21. Summary of available aquifer properties data for the Dalradian aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	217	0	240	340	436	524	605
pH	219	0	6.20	6.53	6.77	7.14	7.44
Dissolved oxygen (mg/L)	3	0	7.72	7.75	7.8	8.75	9.32
Calcium (Ca) (mg/L)	205	0	21.6	38.1	47.9	70.6	85.5
Magnesium (Mg) (mg/L)	208	0	5.30	6.94	10.8	19.6	21.8
Sodium (Na) (mg/L)	220	0	8.60	12.3	14.4	18.6	22.0
Potassium (K) (mg/L)	205	1	1.0	1.24	1.5	2.95	5.83
Chloride (Cl) (mg/L)	219	0	11.2	16	22.4	32.4	38.8
Sulphate (SO$_4$) (mg/L)	219	0	7.44	12.5	19.1	33.39	39.4
Bicarbonate (HCO$_3$) (mg/L)	191	0	74.4	117	201	269	295.6
Nitrate (as N) (NO$_3$-N) (mg/L)	220	15	0.1	0.2	1.21	4.32	6.02
Phosphate (P) (mg/L)	205	1	1.0	1.24	1.5	2.95	5.83
Aluminium (Al) (µg/L)	72	10	7	11.7	13	27.1	50
Iron (Fe) (µg/L)	197	0	8.96	15	42	3260	6264
Manganese (Mn) (µg/L)	197	0	4.26	8.5	53	602	1204

* Number of samples.
† Number below detection limit.

Table 22. Summary of baseline chemistry of the Dalradian aquifers in Northern Ireland, based on samples from 40 groundwater sources.

same study in Co. Donegal were around 3–5 % for the transition zone, 0.1 % for the fractured bedrock zone, and 0.001 % for the deeper bedrock zone (Comte *et al.*, 2018).

At least some of the metalimestone beds within the Dalradian aquifers appear to have higher transmissivity than the surrounding non-calcareous aquifer; some also have karst development, evidenced by the consistent occurrence of small springs discharging from metalimestone beds. The hydrogeology of these metalimestones has not yet been investigated and there are no quantitative data for them.

The heterogeneity in aquifer properties makes siting and drilling successful boreholes difficult. There is a relatively high probability of drilling a borehole that intersects no or too few water-bearing fractures, resulting in a dry or very low-yielding borehole.

Most recharge to the aquifer is likely to be by direct rainfall infiltration where the aquifer is exposed at the surface, usually in upland areas (Figure 25). Some rainfall recharge and indirect recharge from rivers is also likely through overlying permeable sediments, particularly glaciofluvial and alluvial sands and gravels in valleys.

Most groundwater flow occurs within the uppermost few tens of metres of the aquifer, in the transition and fractured bedrock zones (Figure 25). Modelling of the Dalradian aquifers investigated in Co. Donegal suggest over 50 % of flow occurs in the transition zone, with generally short flow path lengths of 10 to 100 m, but it also suggests that there are longer flow paths of 100 to 1000 m in the underlying fractured bedrock and deeper, massive bedrock zones (Comte *et al*., 2018).

Actual groundwater flow velocities in the fracture networks can be reasonably high (tens to hundreds of metres per day) (Comte *et al*., 2012). Fault zones may enhance fracturing and/or weathering and therefore local permeability, and may also increase groundwater storage capacity. Water boreholes have sometimes been sited with the aim of intersecting a fault zone. However, faults can also act to restrict groundwater flow (Chapter 3.3.3): in the same Dalradian rocks in Co. Donegal, tests show that a fault between two boreholes acts as a barrier to groundwater flow and effectively separates groundwater on either side of the fault (Comte *et al*., 2012, 2018; Moe *et al*., 2010).

The residence time of groundwater in the Dalradian aquifers, investigated using groundwater modelling as part of the Co. Donegal study, appears to correlate with flow path lengths, with short residence times of less than one year in the transition zone and longer times, from one year up to several decades (generally less than 50 years), in deeper, fractured and more massive bedrock (Comte *et al*., 2018).

Groundwater in the Dalradian is likely to be mostly unconfined, as the aquifer is largely exposed at the surface. Groundwater levels probably reflect topography, being deeper in upland areas and close to the ground surface below valley floors near rivers. There may be some small areas of confined conditions in low-lying areas, such as in flat valley floors overlain by silty, lower-permeability alluvium; here, groundwater levels in the Dalradian aquifers may rise locally above the top of the aquifer into the superficial deposits.

There is likely to be a high degree of connectivity between groundwater in the Dalradian aquifera and in any overlying Superficial deposits aquifers. In the non-calcareous parts of the aquifer, the main discharge route for groundwater is likely to be baseflow from hydrogeologically active zones of the aquifer (the shallow transition zone and deeper, fractured, bedrock zone) to rivers, either directly where they flow over the Dalradian at outcrop, or via overlying permeable superficial deposits in valleys (Figure 25). In the metalimestone beds, groundwater discharge is likely to be largely via springs, usually small, that flow from karstic features.

Groundwater in the Dalradian aquifers is typically moderately mineralised (median conductivity 436 µS/cm) with a low pH (median 6.77) compared to most other groundwaters in Northern Ireland (Figure 8; Table 22). It is most often of calcium bicarbonate type, with a significant proportion showing no dominant anion or cation (Figure 10).

3.11.4 Groundwater use, history of exploration, management and potential of the Dalradian aquifers

The Dalradian aquifers traditionally provided small groundwater supplies for rural domestic properties and small farms before the introduction of mains water supply, mostly from shallow wells that abstracted from the shallow transition zone. Some small springs flowing from metalimestones were captured and used for small farm and domestic supplies, a few of which are still in use.

There have been no significant investigations of the overall groundwater resource in this aquifer in Northern Ireland, or of how best to use and manage it. Evidence from hydrogeological research on similar Dalradian rocks in Co. Donegal helped to improve understanding of groundwater behaviour in the aquifer, as well as to develop the three-layer conceptual model of hard rock fractured aquifers applied to the Dalradian and other fractured aquifers in Northern Ireland (Comte *et al.*, 2012, 2018) (Chapter 3.3.1).

An investigation of groundwater characteristics in the Dalradian rocks in the Derg catchment was started in 2020 as part of the EU Interreg-funded Catchment CARE project, and is ongoing at the time of writing (2021). As part of this project, the author supervised the drilling of nine boreholes at three sites into superficial deposits, the transition zone and the fractured bedrock zone. A fault containing extensive fault gouge was encountered in the Dalradian at one site, which made drilling conditions difficult and eventually caused the borehole to silt up and be abandoned. At the other two sites, initial evidence suggests that low to moderate yields would be possible from boreholes at different depths in the Dalradian aquifers. Future long-duration pumping tests are needed to prove whether these yields are sustainable.

There is likely to be little potential for large groundwater abstractions from the Dalradian aquifers. There is potential for small borehole supplies and there may be potential to provide small-scale ground-source heating from boreholes with suitable yields, but the heterogeneity of fracture permeability in the aquifer makes successful drilling highly uncertain, even for small yields. The likely low storage capacity also means the long-term sustainability of yields is uncertain. However, groundwater from the Dalradian aquifers is likely to continue to play a significant role in maintaining environmental water flows through the upland catchments it underlies, sustaining important riverine and wetland habitats. More research is needed to better understand this role and the various complex hydrological relationships operating in these fragile catchments.

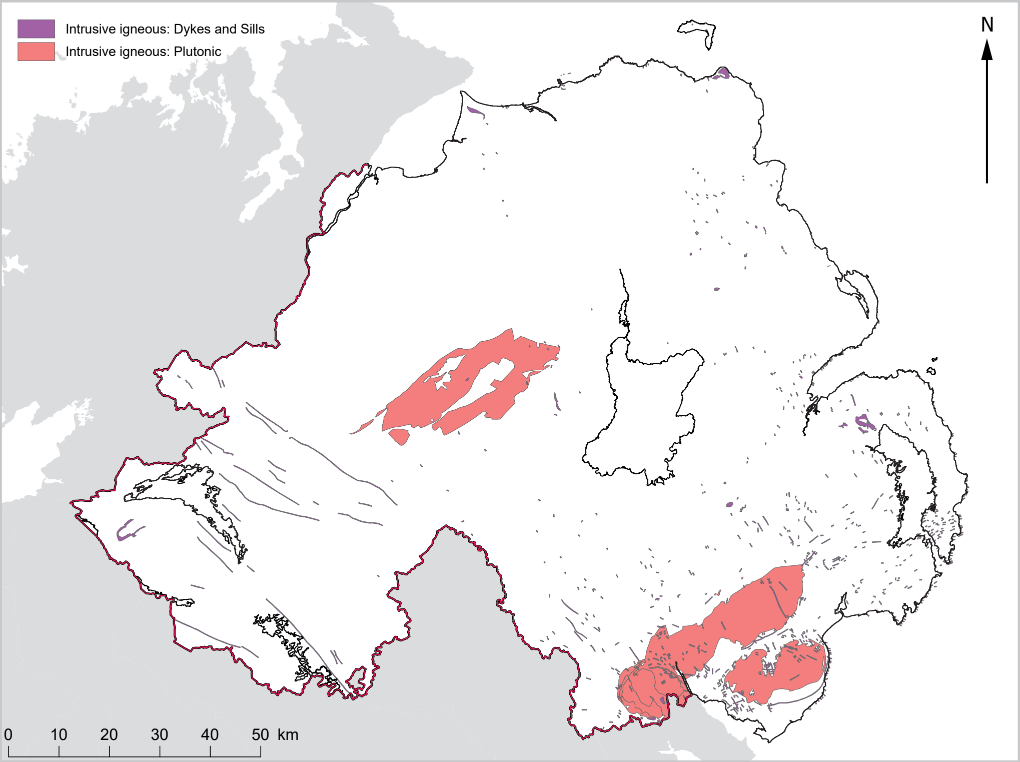


Figure 26. Map of intrusive igneous aquifers in Northern Ireland: Dykes and Sills and Plutonic. Contains OGL and CC-BY-4.0 Data

Photograph 16. Igneous dykes intruding greywacke country rock at a quarry, Co. Down.

Photograph 17. Mourne Mountains, Co. Down.

	Dykes and Sills aquifers	Plutonic aquifers
Aquifer type	Fracture	Fracture
Aquifer productivity/groundwater supply potential	Low	Low
Aquifer class *	Bl(f)	Bl(f)
Typical groundwater flow path length (m)	10s to 100s	10s to 100s
Typical groundwater flow depth (m)	1–50	1–50
Groundwater flow rate	Medium	Medium
Dominant baseline groundwater chemistry	Weakly mineralised, moderate pH, bicarbonate dominated, no dominant cation	Weakly mineralised, low pH, usually bicarbonate dominated with no dominant cation

* Aquifer classification methodology derived from McConvey (2005). See Appendix 1 for explanation of aquifer class codes.

3.12 Intrusive Igneous aquifers

3.12.1 Geological summary

There have been two periods of major igneous intrusive activity in the geological history of Northern Ireland: one in the Palaeozoic and one in the Palaeogene. During the Palaeozoic, the dominant activity was of large-scale, batholithic intrusions of mostly granitic type, with a minor set of smaller dykes. In the Palaeogene, intrusive igneous activity was dominated by a large number of linear, relatively narrow dykes and sills, with some doleritic plugs intruded into volcanic vents. Additionally, there was granitic batholith intrusion in counties Down and Armagh, forming the Mourne Mountains and Slieve Gullion complexes.

3.12.1.1 Dykes and Sills aquifers

Dykes and sills are a significant feature within all the geological units in Northern Ireland. The map in Figure 26 only shows the largest: there are many thousands.

The dykes generally have subvertical dips and most are relatively thin, usually 2 m wide or less. A few are up to about 10 m wide and there are some very rare ‘mega-dykes’ up to 100 m wide (Cooper *et al.*, 2012). They are composed mainly of dolerite and basalt, forming linear dyke swarms that are generally aligned in a north-west to south-east direction. Ongoing research suggests that Palaeogene dykes are commonly associated with pre-existing faults, particularly in Permo-Triassic sandstones and Carboniferous rocks. Most dykes are not thought to be continuous, but generally to diverge and converge, with gaps between different segments. However, some of the largest mega-dykes can be traced for tens of kilometres (Mitchell, 2004). Most of the dykes are of Palaeogene age and formed in association with the opening of the Atlantic Ocean, overlapping spatially and temporally with the Antrim Lava Group (Basalts aquifers) and with the younger central igneous complexes of Slieve Gullion and the Mourne Mountains (Plutonic aquifers) (Cooper *et al.*, 2012).

Once intruded into the surrounding host rock, the generally narrow, thin dykes cooled relatively quickly, which caused them to fracture, sometimes intensively. In more permeable host rocks, intruding dykes were also sometimes associated with superheated pore fluids, which could interact explosively with the molten rock of the dykes and further enhance fracturing. This cooling history is quite different from that of the larger granitic intrusions, which cooled much more slowly and do not show the same degree of fracturing.

Sills of Palaeogene age are less numerous than dykes, but some form major features, such as the Garrison, Magilligan, Scrabo (at least 160 m thick) and Fair Head (82 m thick) sills. A number of larger dolerite intrusions were also emplaced into volcanic vents within the Antrim Lava Group. These are usually circular in outline or elongated along the same general trend as the main Palaeogene dyke swarm and range in diameter from 50 m to 1 km. These are more resistant to erosion than the surrounding basaltic lavas and, in places, they form prominent, steep-sided hills that stand out across the Antrim Plateau, such as Slemish, which is the largest volcanic vent plug in Ireland.

Because many of the dykes and sills are relatively thin and narrow and are buried within surrounding rock, mapping their full extent has been difficult. The Tellus geological mapping project, completed in 2007, changed that through the use of airborne geophysics, which revealed the presence of dykes and other intrusions by their markedly different magnetic signature from the surrounding host rocks (Chacksfield, 2010).

3.12.1.2 Plutonic aquifers

Four key geological units form the main plutonic-type aquifers in Northern Ireland. Two were intruded in the late Palaeozoic: the Tyrone Igneous Complex and the Newry Igneous Complex, both of which include large batholithic intrusions. Those of the older Tyrone Igneous Complex are dominated by gabbro with some dolerite. The younger Newry Igneous Complex is dominated by three distinct granodiorite plutons, intruded through Silurian host rocks.

The other two large plutonic intrusions were emplaced in the Palaeogene: the Slieve Gullion Complex, which was intruded through part of the Newry Igneous Complex, and the Mourne Mountains Complex. These rocks are dominated by granites, felsites and granophyres, but include significant bodies of basalt, dolerite and gabbro, especially in the Slieve Gullion Complex.

These large plutonic intrusions typically cooled slowly, with limited rock fracturing, and they are generally relatively massive in nature. However, there was much local variation in cooling history and, in some areas, more rapid cooling promoted fracture development, resulting in locally highly fractured rocks.

3.12.2 Typical overlying sediments and soils

Because dykes and sills occur across the whole of Northern Ireland, overlying sediments and soils vary considerably, depending on local conditions.

The larger granitic complexes are more resistant to erosion than most other rocks in Northern Ireland and therefore tend to form higher ground, often associated with thin or absent overlying superficial deposits. There are some areas of blanket peat development, which can be up to 6 m thick. Talus (rockfall deposits, or scree) can occur on steeper hill slopes. Glacial till is often present, particularly on lower slopes and in valleys.

3.12.3 Dykes and Sills aquifers: hydrogeological conceptual model

Dykes across Northern Ireland have a dual hydrogeological role. Although not forming a contiguous aquifer, they have distinctive hydrogeological characteristics and are known to be able to produce groundwater, so they are classed here as aquifers in their own right. They can also have a significant impact on the hydrogeology of the usually more laterally and vertically extensive aquifers into which they were intruded, either restricting groundwater flow or acting as a pathway for preferential flow (Chapter 3.12.4).

At present, there is little available hydrogeological information on the Dykes and Sills aquifers in their own right, although recent investigations are leading to new findings (e.g. Comte *et al*., 2017). They have traditionally been thought of as having poor groundwater potential in Northern Ireland and the few available specific capacity values (Table 23) are low. They are classed as a low-productivity, fracture-flow aquifer (Bl(f)) (Appendix 1). However, despite their small volume, the often extensive development of fracturing in dykes, driven by their rapid cooling, can significantly increase their permeability. This may also make them good targets for water supply boreholes, especially where they are present in lower-productivity aquifers such as the Greywackes or Dalradian aquifers. However, more data are needed to assess whether they have enough storage capacity to maintain high borehole yields in the long term.

Most recharge to Dykes and Sills aquifers is likely to occur directly from rainfall infiltration where they crop out at surface or are overlain by permeable superficial deposits. Some recharge may also flow into them from surrounding aquifers, but this is not likely to be significant: where dykes intercept more productive aquifers with higher groundwater flows, there is often a low-permeability zone surrounding the dyke that is likely to restrict flow (Chapter 3.12.4).

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Specific capacity (m^3/d/m)	4	100%	0.16	0.6	1.9	2	8	21.2
Measured yield (m^3/d)	7	71%	2	35	220	90	398	251

Table 23. Summary of available aquifer properties data for the Dykes and Sills aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	7	0	188	245	294	434	533
pH	7	0	6.62	6.83	7.21	7.89	8.1
Dissolved oxygen (mg/L)	0						
Calcium (Ca) (mg/L)	5	0	19.2	23.1	38.2	53.9	66.6
Magnesium (Mg) (mg/L)	5	0	4.58	8.33	16	23.8	24.1
Sodium (Na) (mg/L)	7	0	12.9	14.5	15.8	19.9	21.2
Potassium (K) (mg/L)	5	0	0.79	0.95	0.99	1.44	1.88
Chloride (Cl) (mg/L)	7	0	11.6	13.7	16.5	25.2	28.7
Sulphate (SO_4) (mg/L)	7	0	5.12	11.4	18	26.2	34.8
Bicarbonate (HCO_3) (mg/L)	3	0			83.5		
Nitrate (as N) (NO_3-N) (mg/L)	7	0	0.25	0.5	1.07	3.87	10.8
Phosphate (P) (mg/L)	3	0			0.08		
Aluminium (Al) (µg/L)	3	0			42.2		
Iron (Fe) (µg/L)	3	0			46.3		
Manganese (Mn) (µg/L)	3	0			2.4		

* Number of samples.
† Number below detection limit.

Table 24. Summary of baseline chemistry of Dykes and Sills aquifers in Northern Ireland, based on samples from seven groundwater sources.

Little is known of groundwater flow paths in Dykes and Sills aquifers. Because most are not thought to be continuous, it is probable that flow paths are generally short, on the order of tens to hundreds of metres. However, in the longer mega-dykes there may be interconnected fracture networks over longer distances, creating linear flow conduits.

Little is also known of the extent to which groundwater in Dykes and Sills aquifers interacts with surface waters, although groundwater discharge directly to rivers is likely to be limited because of the small outcrop area. Most groundwater in dykes is likely to flow out of them into the surrounding aquifers.

There is little chemistry data for groundwater in Dykes and Sills aquifers. The few samples are typically weakly mineralised (median conductivity 294 µS/cm) with a moderate pH (median

7.21) compared to other aquifers in Northern Ireland (Figure 8; Table 24), and are dominated by bicarbonate with no dominant cation (Figure 10).

3.12.4 Hydrogeological impact of dykes on other aquifers

Dykes are unique among Northern Ireland's varied geology in having a significant impact on the hydrogeology of other, more extensive aquifers. The full hydrogeological role of dykes is not yet fully understood and is likely to be a key subject for future research, but we know enough to recognise that the role of dykes is a distinctive feature of the hydrogeology of much of Northern Ireland.

Dykes may alter groundwater flow dynamics in the aquifers into which they are intruded in two ways. In some circumstances, they can act to limit and restrict groundwater flow and, in others, they can act as preferential pathways and enhance groundwater flow. There has been largely anecdotal evidence for this from many years of water borehole drilling and hydrogeological studies of productive aquifers, in particular Permo-Triassic Sandstones aquifers, but to date there has been relatively little direct study of the hydrogeological impact of dykes on other aquifers in Northern Ireland.

Where dykes are intruded into high-permeability sedimentary aquifers, there is some evidence that they can be associated with a lower-permeability zone within the surrounding, more permeable aquifer. This effect is best known in the Permo-Triassic Sandstones aquifers (Chapter 3.8) but the reasons for it are still not fully understood. In some cases, it may be due to the characteristics of the dykes themselves: they have no intergranular porosity or permeability and, although they are often jointed and fractured, this may not be extensive enough to increase their permeability to that of the surrounding aquifer.

The lowered permeability associated with dykes is also sometimes attributed to the formation of an altered, baked zone in the sedimentary rocks immediately surrounding the intruded igneous rock – a form of contact metamorphism – which reduces the porosity and permeability of the sedimentary aquifer (McKinley *et al*., 2001). Geological evidence suggests that baked margins around intruded dykes in Northern Ireland are usually not very wide. However, even narrow zones of reduced permeability in an otherwise high-permeability aquifer such as the Permo-Triassic Sandstones aquifers may act to significantly affect local and even regional groundwater flow.

There is evidence that low-permeability zones associated with dykes can restrict groundwater flow enough to at least partially compartmentalise the aquifer, which can limit groundwater storage locally and alter groundwater flow paths and groundwater levels (Comte *et al*. 2017; Dickson *et al*., 2016; Kalin and Roberts, 1997). Groundwater modelling studies of the aquifer in the Lagan Valley also suggest that dyke swarms alter groundwater flow directions on a regional scale, with preferential pathways parallel to dyke orientations (Dickson *et al*., 2016; Comte *et al*., 2017) (Chapter 3.8).

The compartmentalising effect of low-permeability dykes may be advantageous for shallow open-loop geothermal or ground-source heat schemes, where the hydraulic separation of abstraction and re-injection boreholes is needed, and could be achieved by drilling the boreholes on either side of a compartmentalising dyke. Dykes have also been found to have the effect of compartmentalising and potentially concentrating diffuse pollution (Comte *et al*., 2017; Dickson *et al*., 2016).

In other hydrogeological conditions, dykes can have the opposite effect, that of enhancing groundwater flow through aquifers, if the dykes have been weathered and/or fractured enough to create relatively high secondary (fracture) permeability. Enhanced fracturing of dykes can occur as a result of contraction during cooling of the molten rock after its intrusion. Where dykes are intruded into competent rocks such as metamorphic rocks, granites, or well-cemented sandstones, these rocks can also be themselves fractured by the action of the intruding dykes (Comte *et al.*, 2017). In dykes that intercept the ground surface or crop out below thin and/or permeable superficial deposits, this could make them preferential pathways for recharge to infiltrate quickly down into the ground. However, whether this recharge can then flow into the surrounding aquifer depends on the local development of fracturing and permeability in both the dykes and the wider aquifer.

To date, there is little evidence for the effect of dykes on most aquifers in Northern Ireland other than the Permo-Triassic Sandstones aquifers. It is possible that dykes intruding the Cretaceous (Chalk) aquifers (Chapter 3.7) may have had a baking effect on the surrounding rock, reducing local karst development and therefore permeability. However, this is not likely to be the case in lower-productivity aquifers dominated by fracture flow, such as the 'Old Red Sandstones', Upper Carboniferous Sandstones or Greywackes aquifers. In these aquifers, dykes may form relatively higher-permeability zones and act as preferential groundwater flow pathways, via fracturing in both the dykes and the immediately surrounding host aquifer. There is evidence for this from a Precambrian gneiss (an ancient metamorphic hard rock) aquifer in Co. Mayo in the Republic of Ireland, where drilling intersected an intensely fractured and weathered dyke that may have increased local permeability and hydraulic connection between boreholes (Moe *et al.*, 2010).

In these lower-productivity fractured aquifers, dykes may also form pathways for enhanced recharge, although the degree of connectivity between a dyke and the surrounding aquifer will depend on the extent and nature of fracture development in both rocks. During wetter periods, when groundwater storage and levels in the surrounding aquifer are high, dykes could also act as discharge pathways, with upward flow to the ground surface. However, more investigation into the impact of dykes on different aquifers is needed to be more confident about their variable effects.

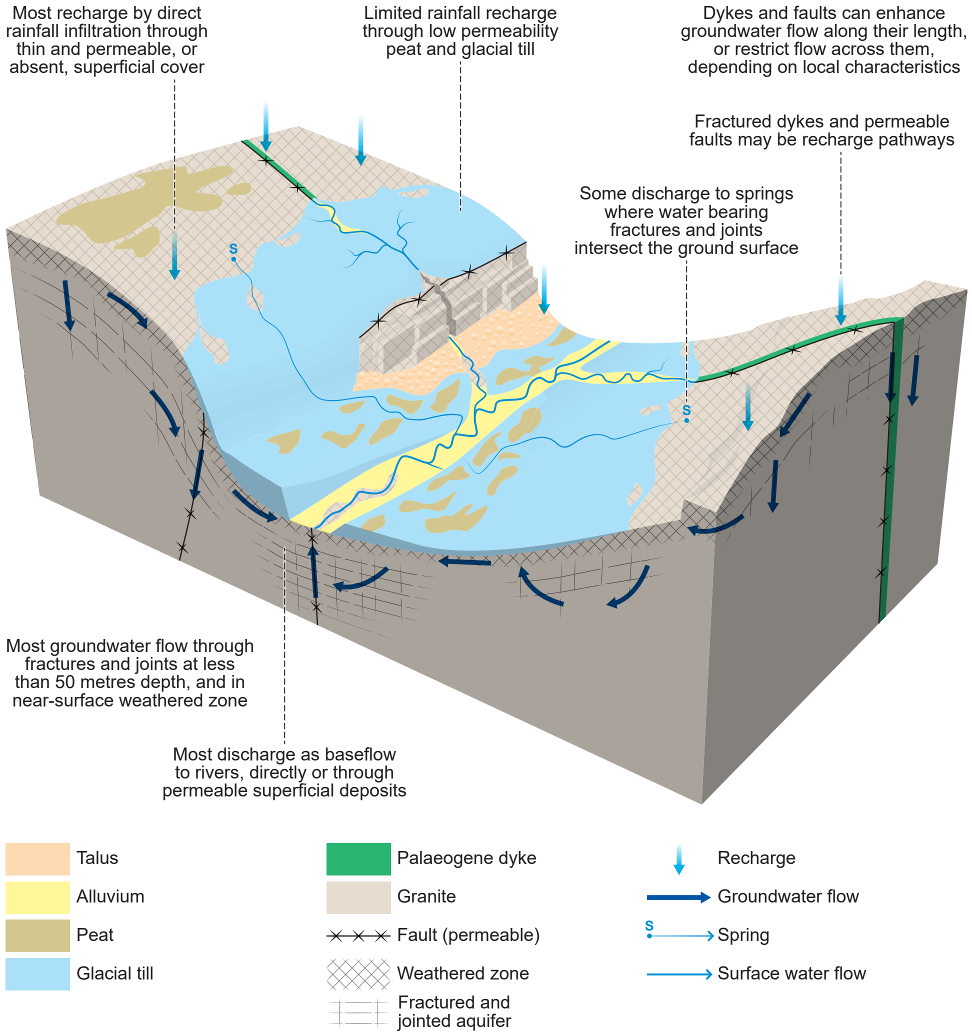
3.12.5 Plutonic aquifers: hydrogeological conceptual model

The main Plutonic aquifers in Northern Ireland are the Tyrone Igneous, Newry Igneous, Mourne Mountains and Slieve Gullion complexes. They are all classed as low-productivity, fractured aquifers (Bl(f)) (Appendix 1).

The three-layer conceptual model as applied to other fractured aquifers in Ireland is also relevant for Plutonic aquifers (Comte *et al.*, 2012) (Chapter 3.3.1). Groundwater flow and storage occur only where the rocks are weathered or fractured: this may be in a weathered 'transition' zone at or near the ground surface, usually up to 5 m thick, or below this in a zone of fractured bedrock that can extend to 50 to 100 m depth. There is thought to be little groundwater flow below 100 m depth.

The transmissivity and storage capacity of the aquifer is strongly controlled by the local development of weathering and fracturing, which can be highly variable. The Plutonic aquifers can develop a distinctive pattern of weathered and fractured 'basins', in which transmissivity and storage capacity are higher, interspaced with zones of more massive rock, with poorer aquifer properties. The few available quantitative aquifer properties data (Table 25) may reflect this variability in aquifer properties, showing generally low borehole yields and specific capacity values, with rare higher values. The expected low storage capacity of the Plutonic aquifers means that the long-term sustainability, particularly of initially higher yields, is uncertain.

Faults or dykes that cut through the Plutonic aquifers may have a significant effect on the development of aquifer transmissivity. Evidence comes from the construction of the Binnian Tunnel, which drains water from the Annalong Valley to the Silent Valley, to boost supply to a



Most recharge by direct rainfall infiltration through thin and permeable, or absent, superficial cover

Limited rainfall recharge through low permeability peat and glacial till

Dykes and faults can enhance groundwater flow along their length, or restrict flow across them, depending on local characteristics

Fractured dykes and permeable faults may be recharge pathways

Some discharge to springs where water bearing fractures and joints intersect the ground surface

Most groundwater flow through fractures and joints at less than 50 metres depth, and in near-surface weathered zone

Most discharge as baseflow to rivers, directly or through permeable superficial deposits

Figure 27. Conceptual model of the hydrogeology of Plutonic aquifers in Northern Ireland.

water treatment works. This tunnel was drilled through granites of the Mourne Mountains Complex and encountered large flows of groundwater when it intersected a hydraulically active structure that may have been a fault or dyke (Robbie, 1955).

Potential recharge to the Plutonic aquifers is likely to be high and dominated by rapid direct rainfall infiltration through the typically thin and permeable, or absent, superficial deposits in the upland areas where this aquifer is common (Figure 27). However, actual recharge is likely to be limited by the low storage capacity of the aquifer. Locally, indirect recharge through river beds may be significant, either through permeable superficial deposits or where rivers cut into the granites. Fractured, permeable dykes and faults may also be conduits for focused recharge.

The main groundwater flow zone is likely to be in the uppermost few tens of metres of the aquifer (Figure 27). Some very shallow, mixed intergranular and fracture flow occurs in the weathered transition zone within about 5 m of rockhead and, below this, groundwater flow and storage are only in fractures (Comte *et al.*, 2012) (Chapter 3.3.1). Some deeper groundwater flows are known and, in most cases, are thought to be associated with fault zones, which can increase the depth of hydraulically active fracture networks. However, groundwater flow paths

Parameter	n*	% Medium or good quality data	Minimum	25th Percentile	Median	Geometric mean	75th Percentile	Maximum
Specific capacity (m^3/d/m)	4	100%	0.143	0.2	13	5	351	1325
Hydraulic conductivity (horizontal) (m/d)	2	100%	0.24					2.60
Measured yield (m^3/d)	26	23%	6	23	71	76	150	5711

Table 25. Summary of available aquifer properties data for the Plutonic aquifers in Northern Ireland.

Parameter	n*	n <dl†	Percentile				
			10th	25th	50th	75th	90th
Conductivity (SEC) (µS/cm)	24	0	142	227	333	537	560
pH	22	0	5.51	5.79	6.43	6.79	7.65
Dissolved oxygen (mg/L)	0						
Calcium (Ca) (mg/L)	19	0	15.3	22.2	32.0	56.4	57.8
Magnesium (Mg) (mg/L)	20	0	4.36	7.85	11.2	21.0	22.3
Sodium (Na) (mg/L)	24	0	7.78	9.06	11.6	17.1	18.2
Potassium (K) (mg/L)	19	0	0.59	0.71	2.3	2.88	3.34
Chloride (Cl) (mg/L)	24	0	9	11.3	15.7	35.0	38.2
Sulphate (SO_4) (mg/L)	23	0	2.88	8.20	11.2	12.9	18.7
Bicarbonate (HCO_3) (mg/L)	18	0	32.3	78.2	119	273	284
Nitrate (as N) (NO_3-N) (mg/L)	24	6	0.15	0.19	0.90	5.57	21.7
Phosphate (P) (mg/L)	16	0	0.02	0.03	0.05	0.50	0.58
Aluminium (Al) (µg/L)	16	4	3.95	12.13	13	26.2	29.3
Iron (Fe) (µg/L)	18	0	16	18	361	14316	15441
Manganese (Mn) (µg/L)	18	0	4.2	4.58	123	795	901

* Number of samples.
† Number below detection limit.

Table 26. Summary of baseline chemistry of the Plutonic aquifers in Northern Ireland, based on samples from 14 groundwater sources.

in the aquifer are usually likely to be short, probably a few tens or hundreds of metres long, and controlled by the limited development and interconnectivity of fractures. The speed of groundwater flow will depend on the size and connectivity of fractures, as well as on hydraulic gradients. Flow rates are likely to be highest in the fractured bedrock zone and in hydraulically active faults, not in the very shallow, weathered transition zone.

Groundwater levels are likely to largely reflect topography and be strongly influenced by a combination of high recharge and low aquifer storage. In lowland areas, groundwater levels are likely to be shallow, within a few metres of the ground surface, but they are likely to be deeper in most upland areas. Artesian conditions are known to occur in some areas; they may develop where groundwater in a hydraulically isolated basin is confined by low-permeability overlying peat.

Most discharge from the Plutonic aquifers is expected to be as baseflow to rivers (Figure 27). Most river flow across the granites is likely to be derived from surface run-off, so that river flows decline significantly during dry periods, but groundwater baseflow makes up a large enough proportion of total river flows to maintain minimum ecological flow requirements in dry periods. Some groundwater discharge is also via small springs, a few of which are known to issue from the aquifer.

There is relatively little data on groundwater chemistry in the Plutonic aquifer. The available data indicate that groundwater is typically weakly mineralised (median conductivity 333 µS/cm) compared to other aquifers and has the lowest pH (median 6.43) of all Northern Ireland aquifers (Figure 8; Table 26). Most samples are dominated by bicarbonate, but a couple have no dominant anion or are dominated by chloride; there is usually no dominant cation, with a few samples showing a slight dominance by calcium (Figure 10).

3.12.6 Groundwater use, history of exploration, management and potential of intrusive igneous aquifers

There has been little large-scale exploration of the potential of groundwater resources from Dykes and Sills or Plutonic aquifers in Northern Ireland, but they were used for rural domestic and small farm supplies, abstracting from shallow wells and springs, before the widespread introduction of mains water in the 1950s. In upland, more remote areas underlain by Plutonic aquifers, there are a number of domestic properties unserved by mains water that continue to rely on groundwater for their water supply.

The low and unpredictable productivity of Plutonic aquifers makes them unsuitable for large groundwater supplies. They are likely to have potential for domestic or small farm supplies from relatively shallow boreholes (to around 50 m depth), although their generally low storage capacity may limit this.

The high-resolution mapping of dykes as part of the Tellus project (Chacksfield, 2010) has already initiated assessment of dykes as targets for groundwater abstraction, especially where they are intruded into low-productivity aquifers. However, further drilling and hydrogeological testing of boreholes in dykes is needed to establish whether dykes can indeed form productive local aquifers and how this varies across Northern Ireland. More research is also needed to establish the degree to which dykes may act as longer, more regional, linear flow pathways.

More research is also needed to establish how dykes act to alter groundwater flow characteristics in the aquifers into which they are intruded, and how this varies in different aquifers. Studies have shown that dykes can play a significant role in compartmentalising groundwater flow in the Permo-Triassic Sandstones aquifers, but there is much more to learn about their impacts on long-term borehole-yield sustainability and contaminant migration through this productive aquifer; as yet, there is little evidence as to how dykes impact other aquifers.

4. Groundwater management in Northern Ireland

4.1 Regulation, Reporting and Protection

The NIEA, an executive agency within the DAERA in Northern Ireland, is responsible for regulating, reporting and protecting groundwater in Northern Ireland. The regulatory framework for groundwater in Northern Ireland is based on a series of European Union (EU) directives, which have been transposed into Northern Ireland's regulations. Despite the UK's exit from the EU in 2020, it is expected that the general approach to water management and protection will continue to be around integrated catchment management, based on the water bodies that were adopted under the Water Framework Directive (WFD). Specific regulations for Northern Ireland with relevance to groundwater include the following (this is not a comprehensive list, but provides an overview):

- Groundwater Regulations (Northern Ireland) 2009 (amended 2009, 2011, 2014 and 2017)
- The Water Environment (Water Framework Directive) Regulations (Northern Ireland) 2017
- The Water (Northern Ireland) Order 1999
- The Private Water Supplies Regulations (Northern Ireland) 2017
- The Water Abstraction and Impoundment (Licensing) Regulations (Northern Ireland) 2006, as amended by The Water Abstraction and Impoundment (Licensing) (Amendment) Regulations (Northern Ireland) 2007
- The Pollution Prevention and Control (Industrial Emissions) Regulations (Northern Ireland) 2013
- The Environmental Liability (Prevention and Remediation) Regulations (Northern Ireland) 2009 (as amended in 2009)
- The Anti-pollution Works Regulations (Northern Ireland) 2003
- Protection of Water Against Agricultural Nitrate Pollution Regulations (Northern Ireland) SR 2004/419
- Nutrient Action Programme Regulations (Northern Ireland) SR 2019/81
- The key EU directives on which these Northern Ireland-specific regulations are based include (not a comprehensive list, but provides an overview):
- The Water Framework Directive (2000/60/EC)
- The Groundwater Directive (2006/118/EC)
- The Nitrates Directive (91/676/EEC)
- The Sustainable Use of Pesticides Directive (2009/128/EC)
- Environmental Liability Directive (2004/35/EC)
- Industrial Emissions Directive (2010/75/EU)

4.1.1 The Water Framework Directive and the Groundwater Directive

The Water Framework Directive (WFD) and the Groundwater Directive (GWD) are the main EU directives covering regulation, management and protection of the groundwater environment in Northern Ireland. In 2000, the WFD established a new, integrated way to protect the water environment. It introduced a holistic approach to the management of water quality and quantity (volumes, flow and level) and requires the protection and improvement of all aspects of the water environment, including rivers, lakes, coastal and transitional waters, and groundwater.

With regards to groundwater, the WFD placed a responsibility on EU member states to ensure groundwater in all 'groundwater bodies', or the management units defined under WFD requirements (Chapter 4.1.3), achieves and maintains good quantitative and qualitative (chemical) status. For this purpose, a river basin management plan (RBMP) is revised and published every six years, taking into consideration linkages with key policy areas such as agriculture, land use, biodiversity, tourism, recreation and flood protection.

The whole of Northern Ireland is a single river basin district for WFD purposes. The RBMP contains a programme of measures, which are specific actions aimed at achieving the WFD objectives:

- maintaining the status of groundwater bodies that are at good status and preventing their deterioration
- improving groundwater bodies at poor status
- ensuring specifically protected sites (e.g. drinking water protected areas) are at good status or in favourable condition

Programmes of measures are implemented through a group of delivery partners, including DAERA's operational, regulatory and policy teams, other government departments, environmental non-governmental organisations and other stakeholders.

The Groundwater Directive (2006/118/EC) (GWD) is a 'daughter' directive of the WFD. It clarifies certain objectives for groundwater quality. The GWD includes criteria for the assessment of good chemical status (good groundwater quality) and for identifying and reversing upward trends in pollution. It also details measures to prevent or limit pollutants.

The United Kingdom Technical Advisory Group (UKTAG) is a partnership of UK environment and conservation agencies that was set up by UK Government administrations to provide coordinated advice on scientific and technical aspects of the WFD. UKTAG has developed guidance and technical notes relating to the principles to be adopted by agencies responsible for implementing the WFD in the UK, which are available from the UKTAG website (https://www.wfduk.org).

4.1.2 Groundwater monitoring

Regional monitoring of groundwater across Northern Ireland began in 2000 and two Northern Ireland-wide monitoring networks are currently managed by the NIEA. The Groundwater Quality Monitoring Network was set up in 2000 for the purposes of assessing the chemical status of groundwater bodies and it included 56 monitoring sites (boreholes or springs) in 2021. The Groundwater Level Monitoring Network was set up in 2007 for the purposes of assessing the quantitative status of groundwater bodies and included 16 monitoring boreholes in 2021. Monitoring data are used to assess compliance with regulatory limits, mostly related to WFD requirements but also to the requirements of other relevant directives.

4.1.3 Groundwater bodies

The 'groundwater body' is the key management unit defined for catchment planning requirements under the WFD. The assessment of the quantitative and qualitative status of groundwater is done for individual groundwater bodies. Groundwater bodies are subdivisions of aquifers, defined primarily on the basis of aquifer type (as described in this book) and subdivided according to river basins. Details of the methodology used for groundwater body delineation can be found in a UKTAG report (United Kingdom Technical Advisory Group, 2011).

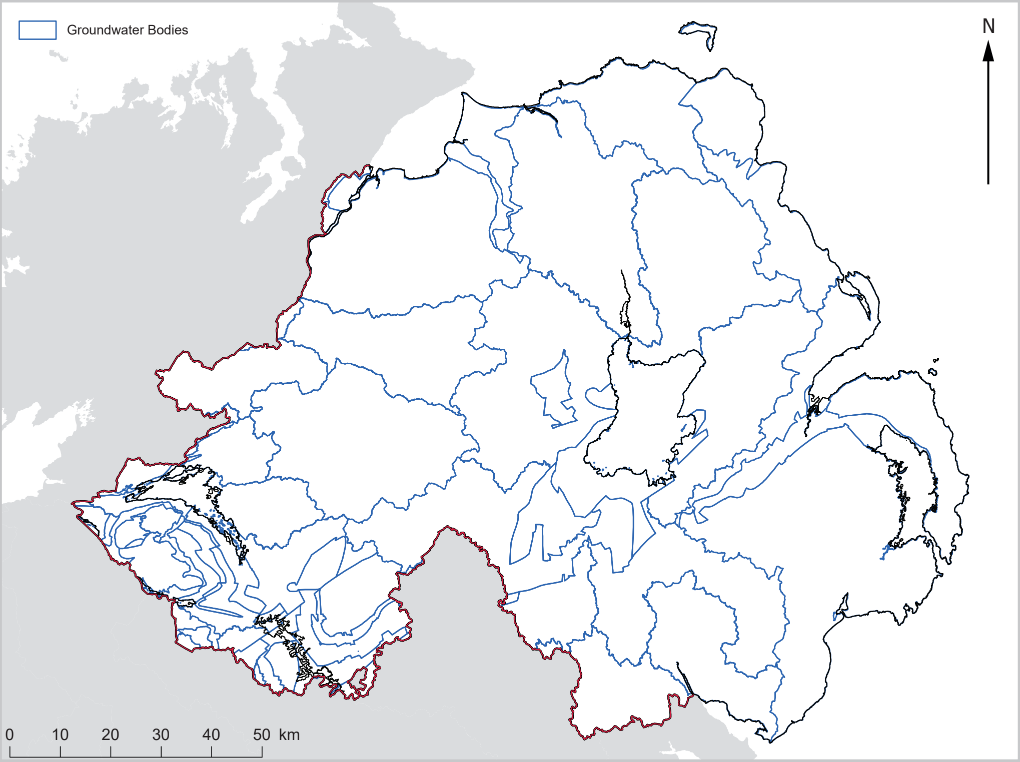


Figure 28. Groundwater bodies in Northern Ireland. Contains public sector information licensed under the Open Government Licence v3.0 (https://www.opendatani.gov.uk/dataset/northern-ireland-groundwater-bodies). Contains OGL and CC-BY-4.0 Data

Northern Ireland is currently divided into 66 bedrock groundwater bodies and nine superficial deposits groundwater bodies (Figure 28). Some groundwater bodies extend across the border with the Republic of Ireland. A digital map of groundwater bodies is available to download, along with other NIEA Water Management Unit digital datasets, from the DAERA website (https://www.daera-ni.gov.uk/).

Groundwater body status is reclassified during each six-year RBMP, using information collected during groundwater monitoring. Classification is done following UKTAG guidance to ensure consistency in assessment across the UK and Ireland (in particular for cross-border bodies). Groundwater bodies are classified as being at 'good' or 'poor' chemical (qualitative) and quantitative status and given an overall good or poor status based on both chemical and quantitative tests. A groundwater body need only be at poor status for either chemical or quantitative tests for it to be classified as being at poor status overall. The methodologies used to assess groundwater body status were developed and updated by UKTAG and are available to view on the UKTAG website (https://www.wfduk.org). A summary of the classification process is illustrated in Figure 29.

In the latest published groundwater status updates, a total of 63 groundwater bodies were classified as being of good status (up from 49 in 2015) and 12 groundwater bodies were classified as poor status (down from 26 in 2015) (NIEA, 2021) (Table 27).

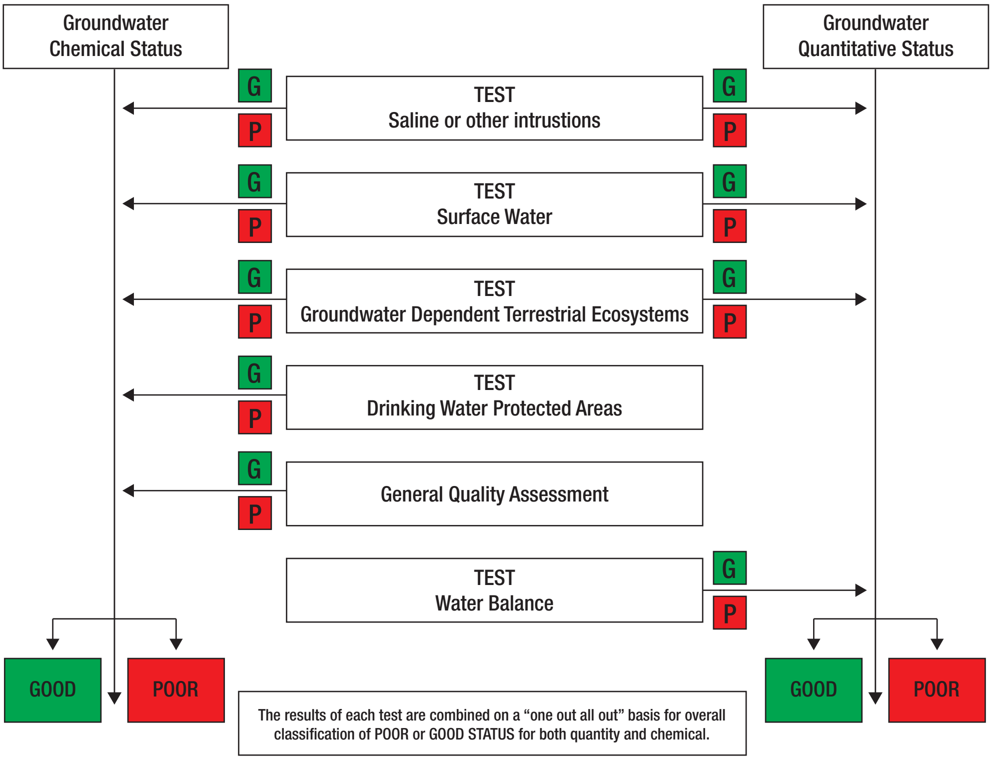


Figure 29. Overview of groundwater body status classification process © UK Technical Advisory Group on the Water Framework Directive.

Year	Total number of groundwater bodies	Overall status	
		Good	Poor
2015	75	49	26
2020	75	63	12

Table 27. Groundwater bodies classification status in Northern Ireland in 2015 and 2020 (NIEA, 2021).

4.1.4 The Nitrates Directive

The Nitrates Directive (91/676/EEC) is concerned with preventing nitrate from agricultural sources polluting ground and surface waters, and with promoting the use of good farming practices towards this goal. Meeting the requirements of the Nitrates Directive for the purposes of groundwater management involves:

- identifying groundwaters with nitrate concentrations exceeding the drinking water standard of 50 mg/l as NO_3
- designating nitrate vulnerable zones (NVZs) for the application of special protection measures, or, as is the case in Northern Ireland, applying measures to the whole territory
- implementing nitrate action programmes (NAPs)
- limiting fertiliser application (mineral and organic), taking into account:
    - crop needs
    - all nitrogen inputs and soil nitrogen supply

    - maximum amount of livestock manure to be applied (corresponding to 170 kg nitrogen per hectare in one year): adopt derogations for higher loading rates if it can be shown scientifically that these rates will not lead to pollution
- monitoring and reporting of nitrate concentrations in groundwater

4.1.5 The Sustainable Use of Pesticides Directive

The Sustainable Use of Pesticides Directive (2009/128/EC) establishes a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment. It also promotes the use of integrated pest management (IPM) and of alternative approaches or techniques, such as non-chemical alternatives to pesticides.

Results from chemical groundwater analyses of samples from the Groundwater Monitoring Network are used to report on positive detections of pesticides and any concentrations of pesticide above the drinking water standard of 0.1 µg/l. These reports are collated annually by the Chemicals Regulation Directorate (CRD) of the Health and Safety Executive, the UK pesticides regulator.

4.1.6 Groundwater protection measures

The following groundwater protection measures are applied in Northern Ireland, with the overall aim of protecting groundwaters from contamination and over-exploitation.

4.1.6.1 Authorisation of Discharges to Groundwater

The Groundwater Directive (2006/118/EC) and Groundwater Regulations (Northern Ireland) 2009 state that measures must be taken to prevent or limit the input of pollutants, with specific objectives to:

- prevent the input of hazardous substances to groundwater
- limit inputs of non-hazardous pollutants into groundwater so as to not cause pollution

Examples of activities that involve the regulation of discharges include, but are not limited to, the disposal of waste sheep dip and pollution, prevention and control (PPC) licenced sites.

UKTAG provides a technical framework to assist environmental agencies across the UK to develop and refine their respective approaches to monitoring, assessing and controlling risks to groundwater, including a report on groundwater hazardous substances (United Kingdom Technical Advisory Group, 2016). In 2021, the NIEA was preparing a consultation on the implementation of this framework to ultimately improve groundwater protection in Northern Ireland. This will play a role in the regulation of specific permitted activities and non-permitted activities that have the potential to impact groundwater.

4.1.6.2 Development Planning Activities

A number of planning activities have the potential to impact on groundwater and are considered as part of the NIEA's statutory consultee role in relation to development planning and management. Activities which may particularly pose a risk to groundwater include:

- landfill sites
- cemetery developments
- redevelopment of contaminated land
- mineral workings

Those applying for planning permission for such activities must carry out a hydrogeological risk assessment, which can be part of an Environmental Impact Assessment (EIA). The assessments are reviewed by the NIEA to confirm that the development will not breach legislative requirements.

These assessments normally take a phased approach, such as a desk study followed by invasive site investigations and quantitative assessments. The hydrogeological information described in this book and accompanying datasets should be used in desk studies and the development of conceptual site models that can be used to simulate proposed activities and assess potential risks. If necessary, these conceptual models should be refined by intrusive site investigations and can be used to inform more detailed quantitative assessments. Where risks are found to be unacceptable, proposed alteration to plans or mitigation measures should be considered.

Further information and practice guides relating to the types of developments and information required are available from the DAERA website (https://www.daera-ni.gov.uk/).

4.1.6.3 Groundwater Abstraction

Groundwater abstraction is regulated through the NIEA's abstraction and impoundment licensing system. For an abstraction greater than 10 m^3/day, the abstraction owner is required to notify the NIEA; a licence is required for abstractions greater than 20 m^3/day. Depending on the particulars of the abstraction, a hydrogeological risk assessment and monitoring of groundwater levels and/or chemistry may be required to inform the licence decision and/or conditions.

The NIEA currently hold groundwater abstraction licences for over 300 registered groundwater abstractions in Northern Ireland.

4.1.6.4 Drinking Water Inspectorate

The Drinking Water Inspectorate (DWI) sits within the NIEA and is responsible for the regulation of drinking water quality in Northern Ireland for both public and private water supplies.

Northern Ireland Water (NI Water) provides public water supplies to over 99 % of the Northern Ireland population; the remainder is served by private water supplies. Although the number of people directly served by a private supply for domestic use is small, many more people make occasional use of private water supplies to commercial activities and public buildings. Almost all (171 of 172) of the private water supplies currently registered with the DWI are sourced from groundwater, either boreholes, wells or springs.

Public water supplies are monitored by NI Water while larger private water supplies are monitored by the DWI. These are supplies that:

- serve more than one household
- are used for drinking in public buildings or workplaces
- are used in commercial food and drink production

The quality of drinking water is assessed against the European and National Drinking Water Quality Standards (NIEA, 2020). Where a drinking water supply fails to meet these standards or is deemed to be a potential risk to human health, the DWI has the power to serve notices on the water providers to restrict or prohibit the use of the water and secure undertakings to improve the water quality. Where necessary, enforcement action can be taken if there is failure to comply with a notice.

For all private water supplies monitored by the DWI, a risk assessment is also carried out to identify potential risks to water quality. The DWI provides guidance on groundwater-source protection to mitigate these contamination risks, help safeguard groundwater sources and improve drinking water quality.

4.2 The Sustainable Use of Groundwater Resources in Northern Ireland

The regulation and protection of the sustainable use of groundwater in Northern Ireland is the responsibility of the NIEA. There are also a number of other stakeholders with an interest in the effective and efficient use of groundwater resources in Northern Ireland. These include:

- Northern Ireland Water (NI Water)
- Department for Infrastructure
- Invest Northern Ireland (Invest NI)
- Department for the Economy

They recognise that groundwater resources are a valuable resource, but are often forgotten about since they are largely out of sight. However, in Northern Ireland as in the rest of world, there is a growing need for reliable, good-quality public and private water supplies, driven by climate, environmental and societal changes. The groundwater resources that are present across Northern Ireland, as shown in this book, can help meet that need.

Using groundwater resources sustainably needs a balanced approach, with appropriate regulation to ensure resources are not overexploited or contaminated, and appropriate exploration and investigation to identify and develop new supplies in the right places. This is a multidepartmental challenge that will need the support of all stakeholders and the provision of reliable hydrogeological data, maps and tools to enable informed decisions on the sustainable use of our groundwater resources.

Another recent innovation was the establishment, in 2018, of a Groundwater Resources Working Group, which brought together key researchers and water resource managers to address the challenges of optimising the future sustainable use of groundwater and reducing the risks of groundwater exploration and development in Northern Ireland. These challenges fall under the remit of three key government departments:

- Department of Agriculture, Environment and Rural Affairs
- Department for Infrastructure
- Department for the Economy

Through the working group, these departments will work together to identify what is needed to meet these challenges, and will develop a groundwater resources strategy for Northern Ireland. This strategy may include recommendations for new legislation, a groundwater research platform and key data and resource requirements needed for its successful implementation. This book, as a synthesis of hydrogeological understanding in Northern Ireland developed over many decades, including significant new knowledge acquired in the last 25 years, is a key resource for future developments.

5. Hydrogeology in Northern Ireland: a timeline

5.1 Early Industrial Use of Groundwater

Hydrogeology as a science is partly a product of the invention of the steam engine and mechanical drilling, which allowed water boreholes to be drilled much deeper than hand-dug wells. In Northern Ireland, this led to an expansion of borehole drilling in the late 19th century, particularly into the highly productive Permo-Triassic Sandstones aquifer beneath Belfast. New, deep boreholes abstracted vast quantities of water to power the steam engines that, in turn, drove industry. At the peak of industrial abstraction in the 1930s, it is estimated that groundwater was being pumped out of aquifers at a rate of 33 ML/d. The introduction of mains electricity from the 1950s led to less reliance on steam power and, with that, a decline of groundwater abstraction from the Permo-Triassic Sandstones.

The chemistry of groundwater from the Permo-Triassic Sandstones aquifers was as important to industrial development as the quantity of groundwater available. Groundwater in the Permo-Triassic Sandstones aquifers is typically of good natural quality for drinking with no need for treatment and is relatively highly mineralised – 'hard' water – with stable chemistry over time. This makes it particularly suitable for carbonating and bottling, supporting the development of a major aerated water trade in Belfast in the second half of the 19th century. Companies such as W. A. Ross and Sons at Corn Market in Belfast, William Corry and Company, and Wheeler and Company Ltd. all drilled boreholes to supply bottling plants that exported around the world. In 1884, the Belfast Morning News named another local company, Cantrell and Cochrane Ltd (now C&C Group), the largest soft drinks manufacturer in the world.

5.2 First Hydrogeological Studies

The first geologists to investigate groundwater in Northern Ireland, between the 1920s and the late 1940s, were Professor J K Charlesworth and J J Hartley of Queen's University Belfast. Hartley had a particular interest in the hydrogeology of the Belfast area, meticulously detailing the location of abstraction boreholes and measuring and recording depths to groundwater level in them. He was also the first to provide a borehole prognosis enquiry service: in the GSNI archives are Hartley's handwritten duplicate response letters to farmers and other private landowners with his opinion on the likely result should they drill a water supply borehole.

5.3 The Geological Survey of Northern Ireland (GSNI)

When GSNI was established in 1947, its geologists started to advocate for the development of groundwater supplies to the rural and urban district councils, who at that time were responsible for public water supplies. By 1964, groundwater from boreholes was supplying 9 ML/d to public supply, with even more being taken from springs.

The early 1970s were a key time in the development of groundwater supplies and the science of hydrogeology in Northern Ireland. Although not by title a hydrogeologist, in 1971 Peter Manning published a pamphlet with the Institution of Civil Engineers, The Development of the Groundwater Resources of Northern Ireland (Manning, 1971b), which was followed in 1973 by the establishment of a single government body, the Water Service, responsible for the supply of public water.

The Water Service funded the first official hydrogeologist post in GSNI, which was filled by Peter Bennett until 1989, who led a small team providing hydrogeological expertise to groundwater investigations carried out by the Water Service (now Northern Ireland Water). This was a key time for the development of hydrogeological understanding in Northern Ireland. The Lagan Valley project was one of the most important, involving strategic drilling of investigation, observation and production boreholes for public water supply in the Permo-Triassic Sandstones aquifer in the Lagan and Enler valleys and proving the high productivity of this aquifer.

By the 1990s, groundwater was providing 77 ML/d for public supply – 11 % of total demand in Northern Ireland – with excess capacity available. At the same time, at least 25 ML/d was being abstracted for industrial supplies. By the late 1980s, funding for large-scale hydrogeological investigations had declined, but this period of well-funded groundwater resource investigations for water supply provided a solid foundation for later hydrogeological studies and groundwater protection work.

During the 1990s, the role of GSNI hydrogeologist was taken on by Nick Robins of BGS, who built on the foundation of Bennett's work with systematic surveys of boreholes across Northern Ireland. In particular, Robins began to fill a gap identified by Bennett: knowledge about the quality of groundwater from Northern Ireland's aquifers. He published a summary of the hydrogeology of Northern Ireland, sometimes called the 'red book' (Robins, 1996), which for many years has been the first go-to reference for any hydrogeologist working on groundwater in Northern Ireland.

Peter McConvey, the third of GSNI's hydrogeologists, joined GSNI in 2000, when the Department of the Environment (DoE) recognised a need to address new drivers for groundwater management, particularly the EU Water Framework Directive. The DoE established a service level agreement (SLA) with the GSNI for the provision of hydrogeological services, which was managed by McConvey until 2009.

This was an exciting time, when hydrogeologists from around Europe came together to define common approaches to managing, protecting, monitoring and reporting on the status of groundwater resources within the EU's member states. There was a shift in emphasis from viewing groundwater solely as a source of water supply for human use, with groundwater protection focused on individual borehole or spring sources, to a recognition of its wider role in the environment and the need to protect the whole groundwater resource. To meet the new legislative requirements, two groundwater observation networks were set up to monitor groundwater quality and groundwater levels across Northern Ireland, providing essential data to underpin groundwater management.

During this time, NI Water moved away from use of groundwater towards centralised surface water supply, treatment and distribution. With groundwater no longer a significant contributor to public water supply, it was more challenging to maintain the profile of groundwater as an important water resource and an essential ecosystem service, which requires investment for investigation and assessment.

After 2009, the post of GSNI hydrogeologist was filled first by Melanie Wrigley for two years, and then by Paul Wilson, who had been assistant to both McConvey and Wrigley. This was a time of economic downturn and falling government budgets, and GSNI funding from the NIEA ended in 2015. However, the DfE, the main funder of GSNI, recognised that increasing the use of groundwater resources again can help business development and economic growth and has continued to fund a groundwater resources programme as part of their SLA with GSNI. To date, this has included:

- the creation of the Northern Ireland Groundwater Data Repository (NIGDR), the first groundwater database for Northern Ireland

- the establishment of a Groundwater Resources Stakeholder Working Group
- the compilation and publication of this book and accompanying aquifer map of Northern Ireland

Hopefully this is only the start of a new resurgence of interest in, and development of, sustainable groundwater resources in Northern Ireland, accompanied by further advancements in understanding of the hydrogeology and groundwater processes in its aquifers.

5.4 Research

Since the 1990s, there has been ongoing research into the hydrogeology of Northern Ireland, particularly by researchers at Queen's University Belfast. Some notable examples that have improved understanding of groundwater in different aquifers have been:

- a wide-reaching study of the Chalk aquifer by Stephen Barnes (e.g. Barnes, 1999; Barnes *et al.*, 2003; Barnes and Worden, 1998)
- studies of different aspects of the Permo-Triassic Sandstones aquifer in the Lagan Valley, including modelling groundwater flow processes and investigating groundwater residence time by Bob Kalin and students such as Adrian Cronin (e.g. Cronin *et al.*, 2005; Gibbons and Kalin, 1997; Kalin and Roberts, 1997; Yang *et al.*, 2004)
- investigations of the hydrogeology of igneous dykes, and of groundwater/surface water interactions in fractured bedrock, by Ray Flynn, Jean Christophe Comte and Ulrich Ofterdinger (e.g. Comte *et al.*, 2012, 2017, 2018; Dickson *et al.*, 2016)

This important work continues, but a more strategic research platform is much needed for Northern Ireland's groundwater, in order to support a new generation of hydrogeologists and to better equip Northern Ireland to respond to future global challenges.

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Appendix 1.
Water Framework Directive aquifer classification

A new aquifer classification scheme was devised for Northern Ireland specifically for the purposes of Water Framework Directive groundwater characterisation (McConvey, 2005). The classification comprises eight aquifer classes, based on geological strata type, relative aquifer productivity and groundwater flow type. The scheme considered:

- the requirements of the Water Framework Directive
- compatibility with existing aquifer classification schemes for Northern Ireland and the Republic of Ireland
- the availability of hydrogeological data

This aquifer classification scheme is still in use for some purposes. It is summarised in Table 28 and described in detail in McConvey (2005).

Aquifer Category	Symbol	Description
Bedrock		
High productivity Fracture flow	Bh (f)	High to moderate yields probable, however, dependence on fracture flow makes poorer yields possible. Generally includes element of regional flow (in kilometres).
High productivity Fracture/intergranular flow	Bh (I-f)	High to moderate yields probable, however, part dependence on fracture flow makes poorer yields possible. Dual porosity. Generally includes element of regional flow.
High productivity Fracture flow with karstic element	Bh (f-k)	High to moderate yields probable, however, dependence on fracture flow makes poorer yields possible. Evidence of karstic flow. Generally includes element of regional flow.
Moderate productivity Fracture flow	Bm (f)	High to moderate yields possible in places, however, dependence on fracture flow makes poorer yields possible. Possible element of regional flow but local flow significant.
Limited productivity Fracture flow	Bl (f)	Moderate yields unusual. Smaller supplies common. Regional flow limited. Mainly shallow, local flow.
Poor productivity Fracture flow	Bp (f)	Small supplies may be possible but strata rarely exploited. No regional flow. Limited local flow.
Superficial deposits		
High productivity Intergranular flow	Sh (I)	High to moderate yields probable in most areas. Permeability high.
Moderate productivity Intergranular flow	Sm (I)	Moderate yields possible. Permeability moderate.

Aquifer type: **B** – Bedrock **S** – Superficial deposits
Productivity: **h** – high **m** – moderate **l** – limited **p** – poor
Flow type: **f** – fracture **I** – Intergranular

Table 28. Aquifer productivity and groundwater flow type categories and descriptions used for Water Framework Directive characterisation in Northern Ireland (McConvey, 2005).

Appendix 2.
Groundwater Recharge Map

A map of groundwater recharge for Northern Ireland (Figure 6) was produced by GSNI (Neary, 2012). It is not publicly available, but has been used by the NIEA in catchment water-balance assessments as part of ongoing water-management activities and for assessing new applications for abstraction licenses. It has also been used by GSNI for groundwater resource potential assessments.

The recharge map was developed using a modified version of the method used by the Geological Survey of Ireland to create a map of recharge across the Republic of Ireland (Misstear *et al.* 2009a). The methodology for developing the map is described in detail by Gibson (2010) and Neary (2012) and summarised here.

The main inputs used to derive the recharge map were:

- Precipitation (Ppn): 1 km gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2012) (Tanguy *et al.*, 2014)
- Potential evapotranspiration (PE): 1 km gridded estimates of annual PE for the period 1971–2000, developed by the Meteorological Office Northern Ireland and used under license to the NIEA

Potential groundwater recharge was estimated using the equation:

$$\mathrm{GWPR} = \mathrm{RC}\,(\mathrm{Ppn} - 0.95\mathrm{PE})$$

Where:
GWPR is groundwater potential recharge (in millimetres)
Ppn is precipitation (in millimetres)
PE is potential evapotranspiration (in millimetres)
RC is recharge coefficient

Recharge coefficients were allocated according to different groundwater vulnerability classes, as shown in the groundwater vulnerability screening map developed for Northern Ireland by Ball *et al.* (2005), which is available to view on the GSNI GeoIndex. This used a different method to that used for groundwater vulnerability mapping in the Republic of Ireland, so the different groundwater vulnerability classes used in Northern Ireland were mapped on to the equivalent hydrogeological settings used by Misstear *et al.* (2009a) (Table 29). Table 28 also shows the minimum, inner range and maximum recharge coefficient values allocated to each groundwater vulnerability class. The final groundwater recharge map for Northern Ireland was derived using the median value of the inner range of recharge coefficients.

Hydrogeological setting (based on Misstear et al. (2009a))	Recharge coefficient			Northern Ireland vulnerability class
	Min	Inner range	Max	
High permeability subsoil (sand and gravel)	60	80–90	100	5, 4
Moderate permeability subsoil overlain by well-drained soils	25	50–70	80	3
Moderate permeability subsoil overlain by poorly drained soils	10	20–40	50	2
Low permeability subsoil	2	20	40	1

Table 29. Recharge coefficients from Table 5 of Misstear *et al.* (2009b) as they relate to groundwater vulnerability classes in Northern Ireland.

‘Effective rainfall’ was calculated by subtracting actual evapotranspiration (AE) from total precipitation. AE is often computed as 0.95PE for grassland in Ireland (Misstear *et al*., 2009a). Because not all aquifers will be able to accept all of the groundwater potential recharge, the Working Group on Groundwater (2005) suggested that upper limits be applied to potential recharge values for poor and locally important aquifers, to represent the inability of these aquifers to accept all potential recharge. This is the ‘recharge acceptance’. For Northern Ireland, bedrock aquifers classed as either poor or low productivity potential were assumed to be in this category and an upper limit for actual recharge of 100 mm/a for poor productivity and 200 mm/a for low productivity was applied.

Appendix 3. Glossary

Abstraction (Q)
The removal of water from a reservoir (for groundwater, removal from an aquifer), usually by pumping. Often expressed as l/s, m^3/d or ML/d. See also yield.

Anion
A negatively charged ion.

Aquiclude
An effectively impermeable geological formation that cannot transmit groundwater, and prevents the flow of groundwater from one aquifer to another. Rare: most geological formations are not completely impermeable. See also aquitard and non-aquifer.

Aquifer
A geological formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table or confined by an overlying impermeable or weakly permeable horizon.

Aquitard
A low permeability geological formation that restricts the flow of groundwater from one aquifer to another. See also non-aquifer and aquiclude.

Artesian groundwater
Groundwater in a confined aquifer that is under pressure, so that when tapped by a borehole or well it is able to rise above the level at which it is first encountered.

Artificial recharge
The deliberate replenishment of groundwater by means of spreading basins, recharge wells, irrigation, or other means to induce infiltration of surface water.

Baseflow
Natural discharge of groundwater from an aquifer, via springs and seepages, to rivers. It is baseflow that sustains the low flow of surface water streams and rivers during prolonged dry weather.

Baseflow index (BFI)
An estimate of the contribution of groundwater to surface flow, taken as a proportion of total stream flow. BFI varies with time, so comparisons are only valid for the same period of time for long-term averages.

Bypass flow
Movement of recharge water (usually intermittently) through fractures in the unsaturated zone of a dual-porosity aquifer.

Cation
A positively charged ion.

Conductivity
The measure of the ability of an electrolyte solution to conduct electricity, sometimes called specific electrical conductance (SEC). The SI unit of conductivity is Siemens per metre (S/m).

Confined aquifer
An aquifer whose upper boundary is formed of low-permeability rocks or unconsolidated deposits that confine the groundwater under greater than atmospheric pressure. Groundwater in these aquifers can become

artesian, where the piezometric or potentiometric level is above ground level, resulting in overflow under artesian pressure.

Conjunctive use
The managed use of both surface and groundwater to meet variable demand. A common feature of conjunctive use schemes is the use of groundwater storage during dry periods to augment surface supplies, thus creating more storage capacity to be replenished during the subsequent recharge period.

Drawdown(s)
The reduction of the pressure head in an aquifer as the result of the withdrawal of groundwater.

Effective rainfall [mm/d, mm/a]
The proportion of rainfall that is available for runoff and groundwater recharge after satisfying actual evaporation and any soil moisture deficit.

Ephemeral stream
A stream that remains dry during some of the year. Ephemeral flow may result from a rising water table intersecting the stream bed, or from periods of rainfall and surface flow.

Esker
A meandering ridge of gravel deposited in a meltwater channel beneath a retreating glacier.

Evapotranspiration [mm/d, mm/a]
The amount of water that would be lost from the ground surface by evaporation and transpiration from plants if sufficient water was available in the soil to meet the demand is termed ‘potential evapotranspiration’ (PE). The proportion of PE that is actually evapotranspired under the prevailing soil moisture conditions is termed ‘actual evapotranspiration’ (AE).

Fracture
A term is often used to refer to any parting in a rock. ‘Fracture’ does not imply any particular orientation or origin, thus joints and faults are fractures, but a fracture is only referred to as a joint or fault if the relevant mode of formation is known. The term ‘fissure’ is commonly used by hydrogeologists, but its meaning is imprecise.

Fracture flow
The preferential flow of groundwater through dilated cracks, joints, bedding planes or other features of secondary porosity within an aquifer. It does not include preferential groundwater flow through a thin, high-permeability horizon of an aquifer.

Flow path or flow pattern
The direction of groundwater flow in an aquifer, reflecting the movement of groundwater from a recharge zone to a discharge zone.

Gaining river
A river that gains water from groundwater through its permeable bed and banks or directly from spring discharge. If the flow in a river increases along a stretch where no new tributaries or rivers join it, it has gained more water from groundwater.

Good groundwater body status
The status achieved by a groundwater body when both its quantitative status and its chemical status are at least ‘good’, as defined by the Water Framework Directive.

Groundwater body
A distinct volume of groundwater within an aquifer or aquifers, as defined under the Water Framework Directive.

Groundwater flooding
The emergence of groundwater at the ground surface or the rising of groundwater, through natural processes, into artificial ground or structures.

Groundwater level
See hydraulic head, piezometric level, potentiometric level, pressure head, rest water level, water table.

Groundwater rebound
Rising groundwater levels resulting from a reduction in abstraction rates following a period of high abstraction during which groundwater levels were kept artificially low. The classic scenario is in cities overlying major aquifers where groundwater levels were depressed by decades of substantial industrial groundwater abstraction, such as London. A decline in industrial activities allowed depressed groundwater levels to recover. Groundwater rebound can cause negative effects, such as a risk of flooding to subsurface infrastructure (e.g. tunnels and the basements of buildings) as well as changes in geotechnical and geochemical properties that could result in settlement and corrosion of deeply founded structures.

Hydraulic conductivity (k) [m/d]
For an isotropic porous medium and homogenous fluid, the volume of water that moves in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Commonly, though imprecisely, taken to be synonymous with permeability and to refer to both matrix (intergranular) and fracture components of groundwater flow.

Hydraulic gradient
Slope of the water table or potentiometric surface; the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head [m]
The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. For a borehole, the hydraulic head is equal to the distance between the water level in the borehole and the datum plane. See also piezometric level, potentiometric level, pressure head, water table.

Interquartile (also interquartile range)
A measure of statistical dispersion: the middle portion of a set of numerical data, equal to the difference between 75th and 25th percentiles.

Karst
Limestone terrains produced by dissolution and erosion by groundwater. Karstic limestone is characterised by the absence of surface drainage and sinks, and rising rivers connected underground by flow along major fissures or in cave systems.

Licensed quantity
The volume of water, usually expressed as m^3/d, which a user is allowed to withdraw from a groundwater source under the terms of an abstraction license issued by the DAERA.

Lithology
A description of what a rock is made of (its physical composition) and texture.

Losing river
A river that loses flow to groundwater by percolation through its permeable bed. An influent river that loses substantial amounts of its flow may be ephemeral.

Median
The middle value of a set of data, equal to the 50th percentile.

Non-aquifer
A rock formation that does not form an aquifer. See also aquiclude and aquitard.

Percentile
In statistics, a value below which a given percentage of data in a group fall. For example, the 50th percentile (the median) is the value below which 50 % of the data points in the group are found.

Permeability (K) (specific or intrinsic permeability)
In a general sense, refers to the capacity of a geological formation to transmit water. Such water may move through the rock matrix (intergranular permeability) or through fractures, fissures, joints, faults, cleavage or other partings (fracture or secondary permeability).

A stricter definition of permeability is a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is the property of the medium only and is independent of the fluid. Commonly, but imprecisely, permeability is taken to be synonymous with the term hydraulic conductivity, which implies the fluid in question is water.

Piezometric level
See potentiometric level.

Poor groundwater body status
The status achieved by a groundwater body when either its quantitative status and its chemical status are ‘poor’ as defined by the Water Framework Directive.

Porosity
The ratio of the volume of the interstices to the total volume of rock or superficial deposits expressed as a fraction. Effective porosity includes only the interconnected pore spaces available for groundwater transmission; measurements of porosity in the laboratory usually exclude any void spaces caused by cracks or joints (secondary porosity).

Potentiometric level
An imaginary surface representing the elevation and pressure head of groundwater and defined by the level to which water rises in a borehole or piezometer. The ‘water table’ is the potentiometric surface in an unconfined aquifer. An older term is piezometric level. See also groundwater level, hydraulic head, pressure head.

Pressure head
Hydrostatic pressure expressed as the height of a column of water that the pressure can support with reference to a specific level such as land surface. The hydraulic head is the height of the free surface of a body of water above a given surface or subsurface point. See also groundwater level, piezometric level, potentiometric level, water table.

Pumping test
A field testing procedure to quantify aquifer properties at a site that involves pumping water out of (or, less commonly, injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata. There are several different procedures employed depending on the physical properties to be quantified:

- a constant-rate pumping test is conducted at a steady rate of discharge or injection
- a step test increases the discharge in stages to a maximum value
- a bailing test is conducted during the drilling process, using the bailer drilling tool as a water withdrawal method

Quartile
A statistical division of a group of data points into four parts (quarters) of more-or-less equal size.

Recharge
Inflow of water to an aquifer from the surface, from sources such as the direct infiltration of rainfall, leakage from an adjacent formation, or leakage from a watercourse overlying the aquifer.

Rest water level (RWL)
The standing water level in a borehole or well when it is not being pumped. Also termed static water level.

River basin district
The area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters, which is identified under Article 3(1) of the Water Framework Directive as the main unit for management of river basins.

Runoff
The flow of water on the ground surface when excess rainwater, meltwater or other surface water cannot infiltrate into the ground. This can occur over impermeable or low permeability materials, or when permeable soil and/or superficial deposits are fully saturated by water. Also known as surface runoff. Runoff drains to surface water streams and rivers.

Saline intrusion
The entry of sea water into a coastal aquifer. It may be caused by overpumping fresh water from the aquifer or insufficient natural head on the freshwater aquifer. Sea water is more dense than fresh water and it may form a wedge beneath the fresh water adjacent to the coast.

Sinkhole
The point where a sinking stream goes underground, particularly in a karstic aquifer system. See also swallow hole.

Specific capacity (Sc) [$m^3/d/m$]
The rate of discharge of water pumped from a borehole divided by the resulting drawdown of the rest water level in the borehole.

Specific electrical conductance (SEC)
The measure of the ability of an electrolyte solution to conduct electricity, sometimes called conductivity. The SI unit of SEC is Siemens per metre (S/m).

Specific storage (Ss)
The volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (for a saturated aquifer).

Specific yield (Sy)
The amount of water in storage released from a column of aquifer of unit cross-sectional area under unit decline of head. Expressed as a dimensionless proportion of the saturated mass of that aquifer unit. Effectively synonymous with storage, in an unconfined aquifer. Equivalent to effective porosity.

Storativity (coefficient of storage) (S)
The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Swallow hole
The point where a sinking stream goes underground, particularly in a karstic aquifer system. See also sinkhole.

Surface runoff.
See runoff.

Transmissivity (T) [m^2/d]
The integral of the hydraulic conductivity of an aquifer over its saturated thickness. It relates to the ability of an aquifer to transmit water through its entire thickness.

Unconfined aquifer
A partially saturated aquifer that contains a water table that is free to fluctuate vertically under atmospheric pressure, in response to discharge or recharge.

Unconsolidated deposit or sediment
A deposit or sediment consisting of loose grains that are not held together by cement. Glaciofluvial deposits are a typical example of an unconsolidated aquifer.

Unsaturated zone or vadose zone
The zone between the land surface and the water table. It includes the capillary fringe and may contain water under pressure less than that of the atmosphere.

Vulnerability
The sensitivity of a groundwater system to contamination. Intrinsic vulnerability considers the hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contaminant scenario. Specific vulnerability takes these latter factors into account.

Water Framework Directive (WFD)
The European Water Framework Directive (2000/60/EC; European Parliament, 2000), which came into force in December 2000. It is the most significant piece of European legislation relating to water management for at least two decades. The directive provides a framework to pull together existing legislation relating to water and expands the scope of water protection to all waters. The main aims of the directive are to prevent further deterioration and promote enhancement of the status (quality and quantity) of water bodies and related ecosystems. This includes the progressive reduction in the pollution of groundwater.

Water table
The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere; the uppermost surface of a saturated aquifer. The rest (or static) water level in a borehole in an unconfined aquifer is equal to the water table. See also piezometric surface and potentiometric surface.

Yield (Q)
The volume of water pumped or discharged from a borehole, well or spring. Often expressed as l/s, m^3/d or ML/d. See also abstraction.

Appendix 4.
Volume and flow-rate conversions

Volume	Millilitre (ml)			
Millilitre (ml)	1	Litre (l)		
Litre (l)	1000	1	Cubic metre (m^3)	
Cubic metre (m^3)	1 000 000	1000	1	Megalitre (ML)
Megalitre (ML)	1 000 000 000	1 000 000	1000	1

Volume	Litres per second (l/s)			
Litres per second (l/s)	1	Cubic metres per day (m^3/d)		
Cubic metres per day (m^3/d)	86.4	1	Megalitres per day (ML/d)	
Megalitres per day (ML/d)	0.08	0.001	1	Gallons per hour (GPH)
Gallons per hour (GPH)	792	9.2	9200	1

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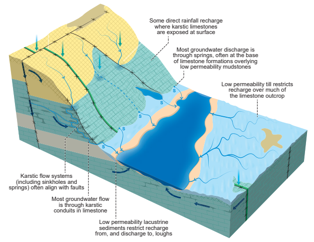
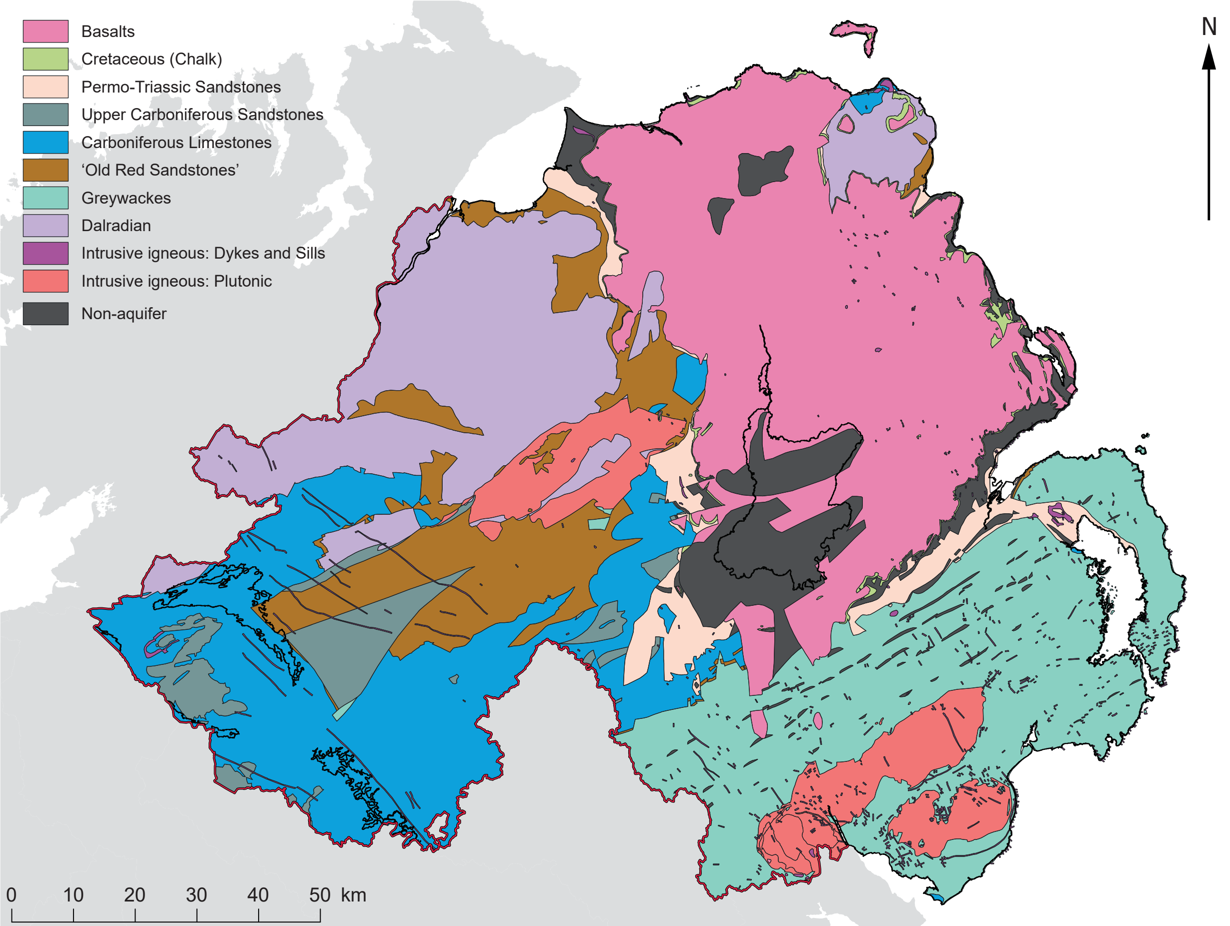


Superficial Deposits | Basalts | Cretaceous (Chalk) | Permo-Triassic Sandstones Upper Carboniferous Sandstones | Carboniferous Limestones | 'Old Red Sandstones' Greywackes | Dalradian | Intrusive igneous: Dykes and Sills | Intrusive igneous: Plutonic



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