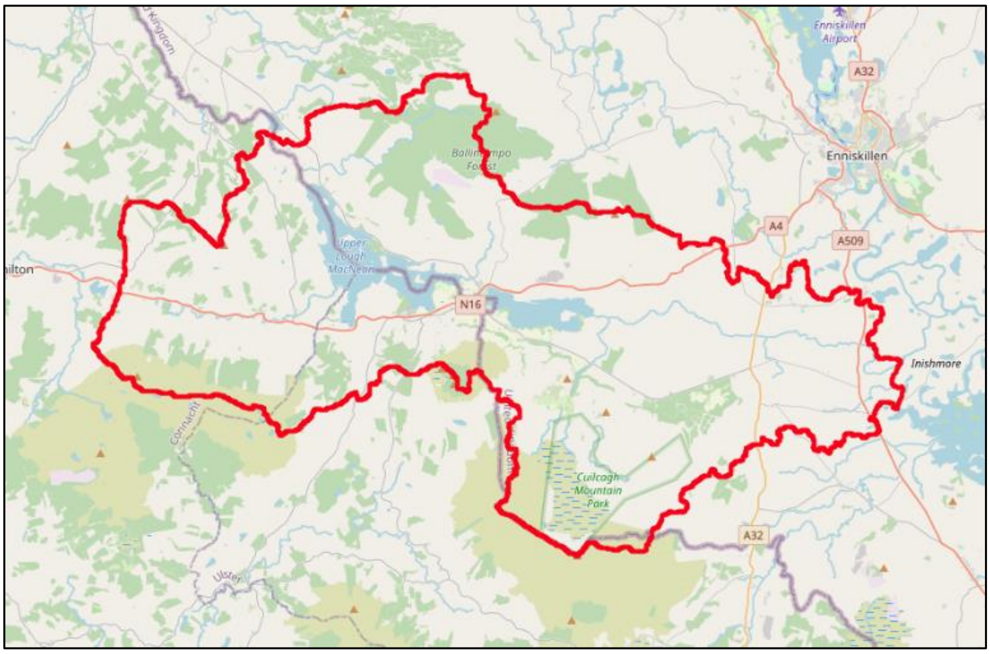
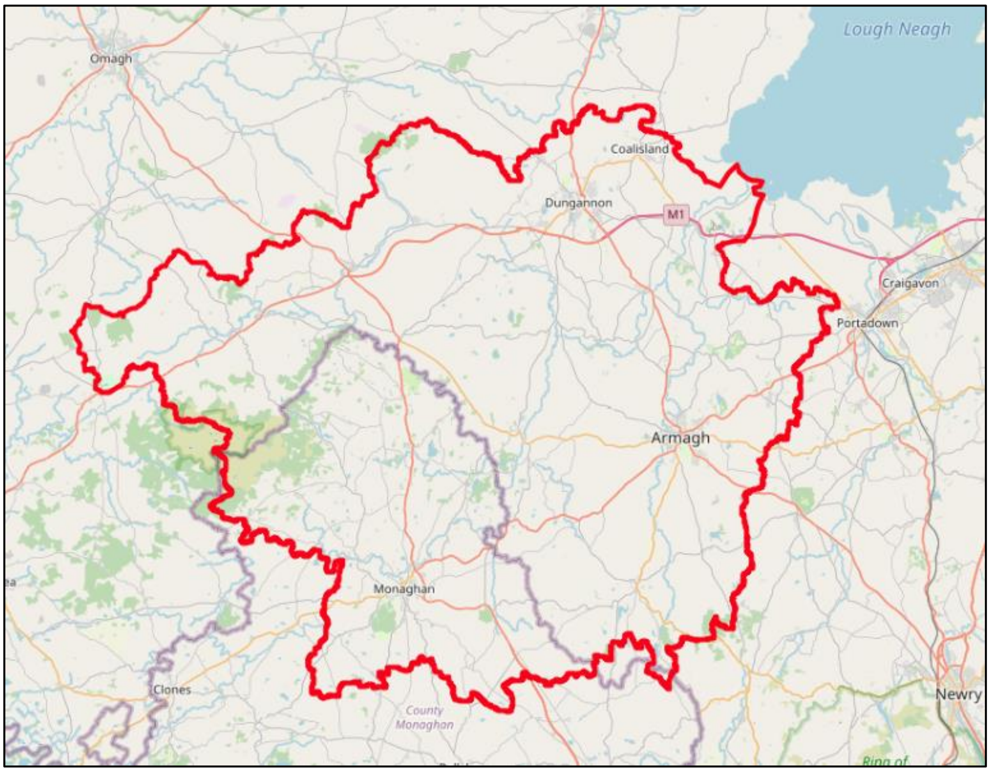
The Hydrogeology of the Arney and Blackwater Catchments

Field Guide

International Association of Hydrogeologists (IAH) Irish Group





CatchmentCARE
Community Actions for Resilient Ecosystems

International Association of Hydrogeologists
the World-wide Groundwater Organisation

2023

Contributors and Excursion Leaders

Lisa Doyle

Lisa is the Inland Fisheries Ireland (IFI) Catchment Officer for the Arney Catchment. Lisa's role was liaising with IFI regional staff and the CatchmentCARE research team, liaising with stakeholders, securing access and overseeing sub-contractors and implementing in-stream and riparian remediation within the Arney Catchment

Caoimhe Hickey

Caoimhe is a karst hydrogeologist with Geological Survey Ireland, where she has worked since 2000. She has been involved in many different projects including resource and source protection, Irelands national groundwater vulnerability map, water framework directive delineation and mapping, EU funded projects such as GeoERA and CatchmentCARE as well as creating and maintaining national maps and databases, such as the national karst landform and national water tracing databases.

She is lucky enough to work predominantly in karst and karst landscapes and has done extensive karst mapping, karst aquifer classification and dye tracing experiments. She has an Earth Science degree and a PhD in Karst Hydrogeology, both from Trinity College Dublin.

John Kelly

John is Technical Director (Geology) at SLR in Belfast. He has 30+ years of experience in base metal, aggregates and industrial mineral exploration and resource assessment, and has undertaken numerous geotechnical assessments of quarries and also been involved in a number of large-scale ground investigation programs for major infrastructure projects. He is a founder member and past-President of the Institute of Geologists of Ireland, and founder member of other key geoscience professional organisations. He lives in the area near Marble Arch caves and enjoys caving and dye tracing.

Alan McCabe

Alan is currently the manager of Glaslough Tyholland Group Water Scheme. Previously, Alan was the Secretary and Project Officer of the Blackwater Catchment Trust and a Project Officer for the CatchmentCARE project. Alan is from Co. Monaghan and currently lives outside Emyvale.

Barbara Olwill

Barbara currently works as a Catchment Scientist with the Local Authority Waters Programme and comes from an agricultural background. Together with an agricultural science degree she studied Planning and Environmental Impact Assessment before training as a Catchment Scientist with LAWPRO. She previously worked in private consultancy preparing Environmental Impact Assessment for a range of projects before a short period with the EPA Catchments Units. Her current role entails Local Catchment Assessment in the border region and based in Monaghan County Council offices in Carrickmacross. Her interest would lie in Land Use Management and Landscape Assessment to drive appropriate measures for protection of water quality.

Taly Hunter Williams

Taly is a Senior Hydrogeologist in the Groundwater and Geothermal Unit at Geological Survey Ireland. She has more than 20 years' experience in groundwater characterisation and protection, particularly source protection and resource estimation. Taly managed GSI's input to the CatchmentCARE project.

Paul Wilson

Paul Wilson is a hydrogeologist at the Geological Survey of Northern Ireland. He studied for an MEng in Environmental and Civil Engineering and a PhD in Engineering Hydraulics at The Queen's University of Belfast. His main role is to provide hydrogeological advice and support to the Northern Ireland Government and public. He champions the use and role of groundwater resources for public and private supply as well as for sustaining our rivers and wetland ecosystems. He manages advisory contracts with NI Water, The NIEA, The Department for the Economy and is finishing up an EU funded project drilling groundwater monitoring stations across Northern Ireland. He was the lead author of the book, 'Northern Ireland's Groundwater Environment.'

Programme

Day	Location	Time	Item	Speakers
Sat 14th Oct	Dublin	7:15am	Dublin depart from TOBIN Consulting Engineers, Blanchardstown	
	Arney Catchment	9:45am	Meet at Kinawley Community Centre	
		10:00am - 11:00am	Gortalughan / View Point / Pigeon Pot	JK / THW / CH / LD
		11:15am - 12:00am	Monastir large karst sink	
		12:00am - 1:15pm	Marble Arch Caves Group 1: Cave tour Group 2: VR experience. Surface karst	MAC guides / CH
		1:00pm - 2:00pm	Lunch - Marble Arch Café	
		2:00pm - 3:15pm	Marble Arch Caves Group 1: VR experience. Surface karst. Group 2: Cave tour	
		3:45pm - 4:45pm	Barran Spring	CH / BO / LD
		4:50pm	Arney Bridge River Restoration	
	Enniskillen	5:20pm – 6:00pm	Bus to Belmore Court Hotel	
		6:00pm - 7:30pm	Refresh/relax	
		7:30pm - ??	Dinner / social / Ireland v NZ - Saddlers Bistro	
Sun 15th Oct		7:30am - 8:30am	Breakfast	
		8:30am - 9:20am	Bus to Emyvale	
	Blackwater Catchment (Mountainwater Subcatchment)	9:30am - 1:15pm	Bragan Bog - Source of Mountain Water River (SPA/NHA)	AmcC
			Smouthan - Riparian works. Completed in 2023.	
			Derrykinnigh Beg - Riparian works. 2 years old.	
			Emyvale Weir. Fish barrier.	
			Glaslough Tyholland GWS	
	Blackwater Catchment	1:30pm - 2:30pm	Lunch - Rose Café, Caledon	
		2:30pm - 2:45pm	Bus to Ballytroddan	
		2:45pm - 3:45pm	Ballytroddan - artesian wells, pump tests, geophysics, dyke	PW
	Dublin	3:45pm - 5:30pm	Return to Dublin	

(yellow)	Travel
(blue)	Refreshment
(green)	Site visit

Contents

Preface

This fieldtrip is based around just some of the outputs of the CatchmentCARE project, an EU INTERREG VA-funded project that started in late 2017 and concluded in April this year. The aim of the CatchmentCARE project was to establish water quality improvement projects in three cross-border catchments – the Finn, Blackwater and Arney Catchments, and to install 50 boreholes across the region. The project catchments were selected due to specific waterbodies failing to achieve good ecological status (GES) under Water Framework Directive (WFD), and their cross-border status.

The aims were achieved through catchment actions and community actions, and research that informed policy actions. Actions were selected based on three criteria: measurable impact on water quality; transferable beyond the three catchments; and contribute to a project legacy. The actions selected addressed some of the water quality issues related to hydromorphology, point and diffuse sources of pollution, farm nutrient management practices, characterisation and monitoring of groundwater quality, lag times in response to the implementation of measures, and an economic analysis of the cost of achieving the objectives of the Water Framework Directive in the three catchments.

The eight project partners worked on different aspects of catchment characterisation and water improvement measures. British Geological Survey and Geological Survey Ireland undertook work on the groundwater work package of the project. The groundwater team were tasked with establishing long-term groundwater monitoring stations in the region, comprising 50 boreholes. As well as meeting this aim, 19 springs were monitored in one particular catchment (the Arney).

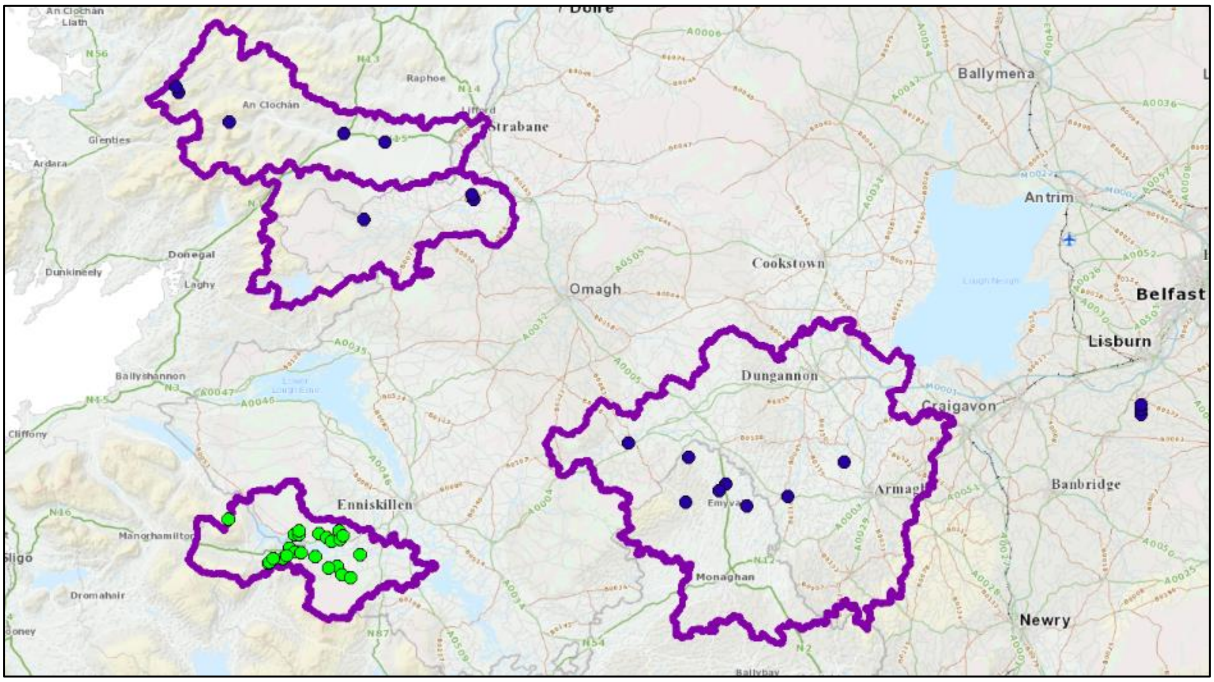


Figure 1 The three CatchmentCARE study catchments – the Finn, Arney and Blackwater. Groundwater Monitoring Stations (GWMSs) are shown in dark blue, and the spring monitoring locations are shown in bright green. The Derg catchment is shown because groundwater monitoring boreholes were also installed there to tie in with the SourceToTap INTERREG VA project. Borehole clusters were also installed at afbi's Hillsborough experimental farm.

Acknowledgements

This is my first year as IAH Field Trip Secretary, and I would like to sincerely thank the CatchmentCARE team for facilitating everything from conceptualising the structure of each day, to organising speakers and reaching out to their network, to their brilliant enthusiasm. Thank you for giving up your time in preparation and delivery of the excursion. You have all made the first year an absolute breeze.

I would also like to thank the staff of the Marble Arch Caves, who have extended great hospitality to us from the outset.

Thanks also to McCaffrey Coaches, and to the McCaffrey Coaches' bus driver, for getting us around safely, and to all of the IAH Committee for help and advice.

The information in this field guide has kindly been provided by the contributors, and taken from the catchmentcare.eu website, including the CatchmentCARE - Work Package WP T1 Scoping and Targeting Report, and other sources.

Work undertaken by the CatchmentCARE Groundwater Team members from Geological Survey Ireland and British Geological Survey was augmented by staff from CDM Smith (Ireland) Ltd (hydrochemical sampling and hydrogeological support) and Studio Liddell (Virtual Reality). Dullea Well Drilling Ltd constructed the groundwater monitoring boreholes under hydrogeologist supervision.

Location Maps

Day 1 – Arney Catchment

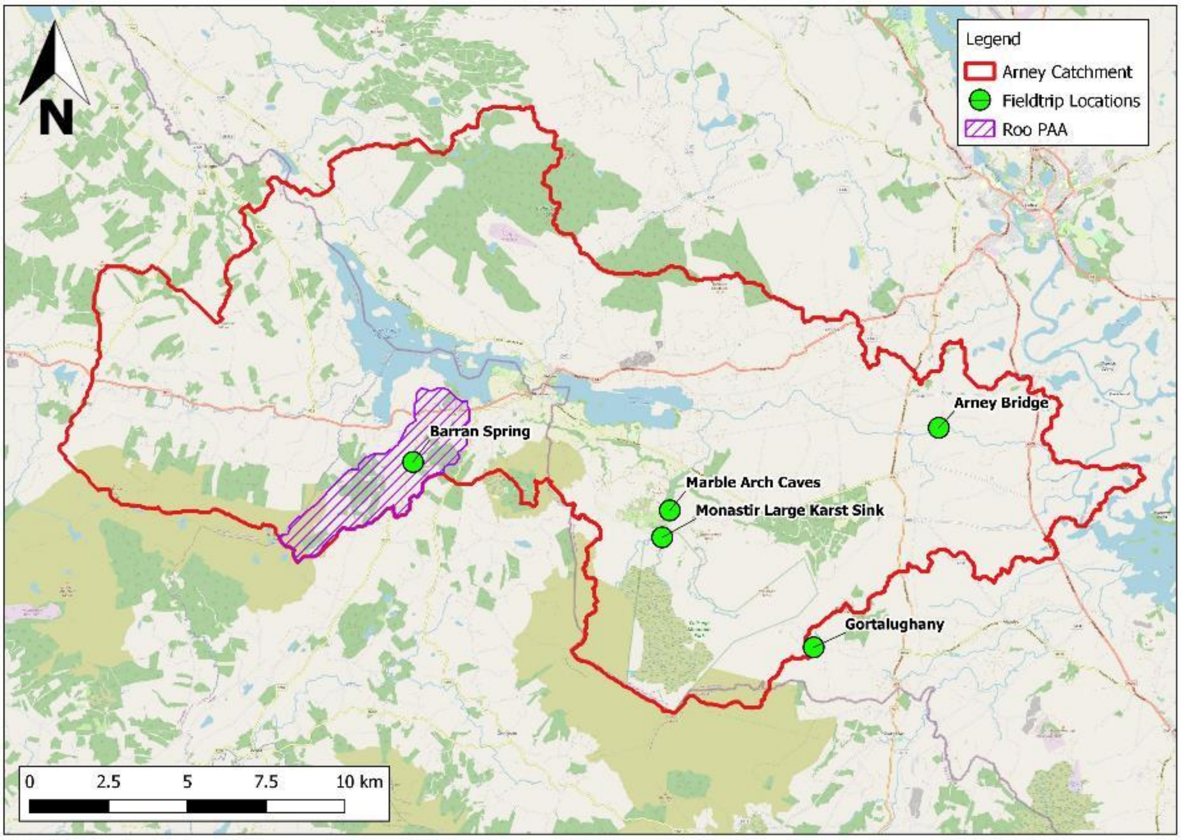


Figure 2 Location map of the Stops for Day 1 in Arney Catchment

The sites visited on Day 1 in the Arney catchment will follow the water from the recharge areas in the upper catchment, to the discharge areas in the springs and rivers of the valley floor near to Lough Macnean Upper. A detailed technical overview of the Arney Catchment is provided in Section 1 of this fieldguide.

Stop 1 – Gortalughany / Pigeon Pot

At this stop, we will be discussing the following:

- An introduction to the overall CatchmentCARE project;
- an introduction to the Arney Catchment;
- the Pigeon Pot cave;
- A summary of the dye tracing work which has been conducted in the catchment; and
- discuss the karst features within the catchment, the limestone pavement, the dry valley and sinks.

Stop 2 – Monstir Large Karst Sink

Ahead of heading down the Marble Arch Caves, we will visit the Monastir large karst sink. The Monastir Sink, also known as the Monastir Doline, acts as a great segway into the Marble Arch Caves.

Stop 3 – Marble Arch Caves

Here we will learn all about the Marble Arch Caves, a series of natural limestone caves. As we will learn, The caves are formed from three rivers draining off the northern slopes of Cuilcagh mountain, which combine underground to form the Cladagh. On the surface, the river emerges from the largest karst resurgence in Ireland, and one of the largest in the United Kingdom. At 11.5 kilometres (7.1 mi) the Marble Arch Caves form the longest known cave system in Northern Ireland, and the karst is considered to be among the finest in the British Isles.

Stop 4 – Barran Spring

At this stop we will discuss the Roo WFD Priority Area for Action (PAA). We will discuss the spring monitoring and associated logger network, hydrochemistry and Q monitoring. We will also discuss the Barran Spring dye trace results and the critical community involvement and outreach programme.

Stop 5 – Arney Bridge

To finish off the day, at the final stop we will look at the river restoration works conducted at Arney Bridge.

Day 2 – Blackwater Catchment

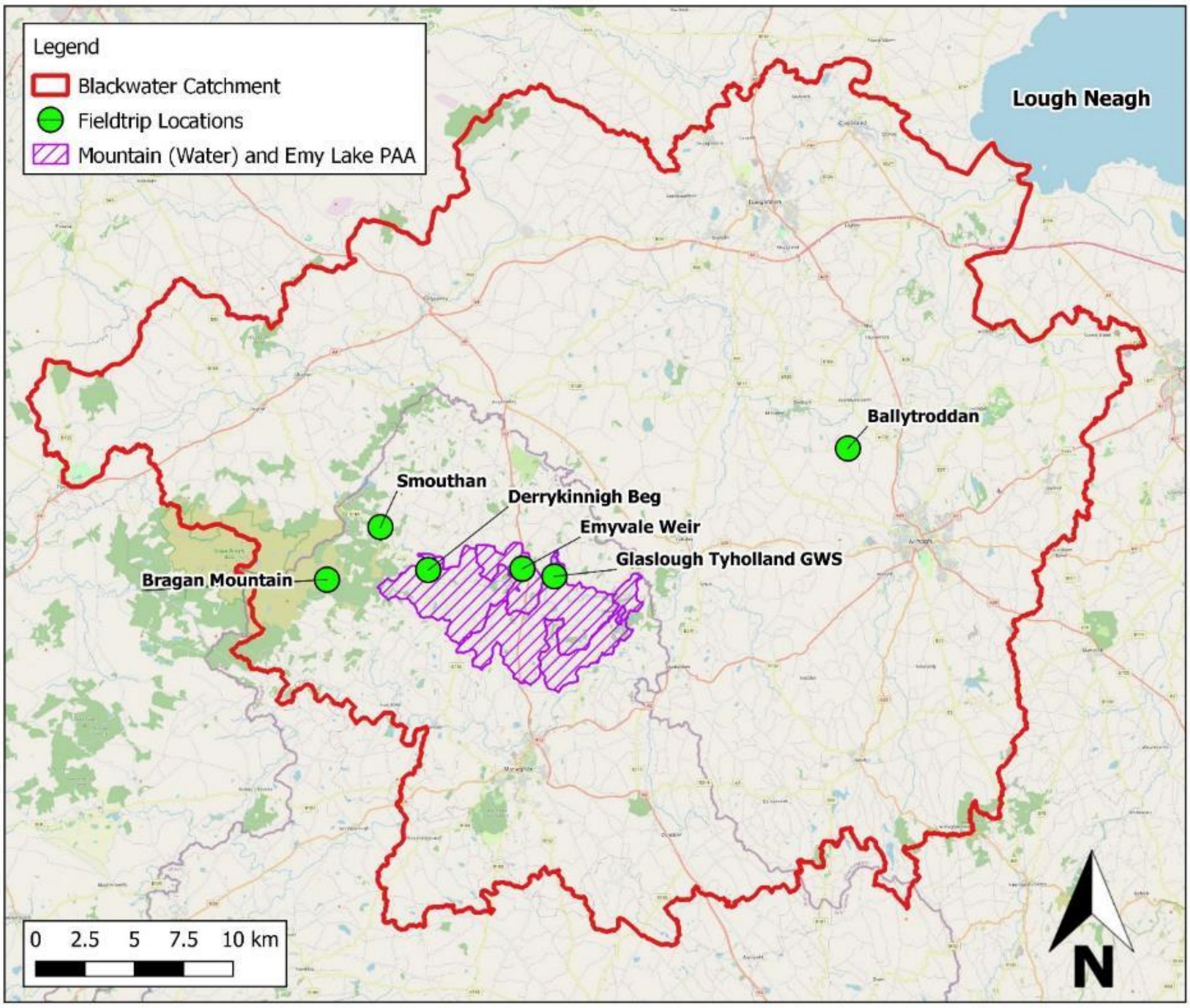


Figure 3 Location map of the Stops for Day 2 in Blackwater Catchment

The sites visited on Day 2 in the Blackwater catchment will focus on river characterisation and restoration work in the Mountainwater River subcatchment (Section 3). We will follow the water from the upper catchment to where some of the flow is diverted to Emy Lough in the valley. We will then dive underground to visit one of the Groundwater Monitoring Stations (GWMSs) installed as part of the project. A detailed technical overview of the Blackwater Catchment is provided in Section 2 of this fieldguide.

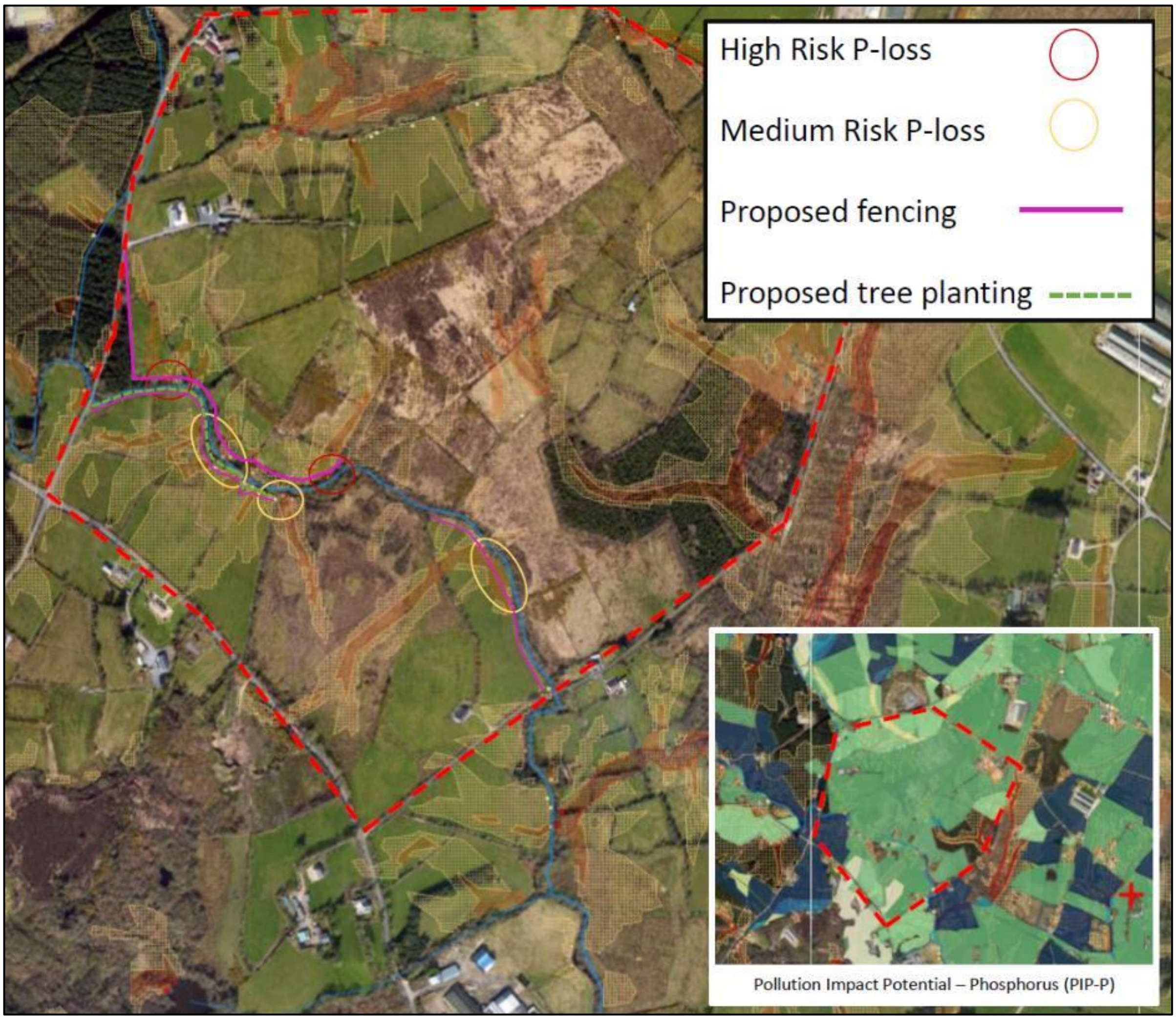
Stop 1 – Bregan Mountain

At this stop, Alan will introduce us to the source of the Mountain Water and a broad overview of the remediation project, stakeholders involved, collaborative efforts etc.

We will also discuss the remediation of Bragan Bog itself, which involved removal of self-seeding conifers and conservation grazing using virtual fencing technology (Nofence).

Stop 2 – Smouthan

At this stop we will look at some riparian which have just been completed in 2023. The works involve fencing off livestock access to the Mountain Water river, creating new buffer zones to plant with native riparian vegetation.

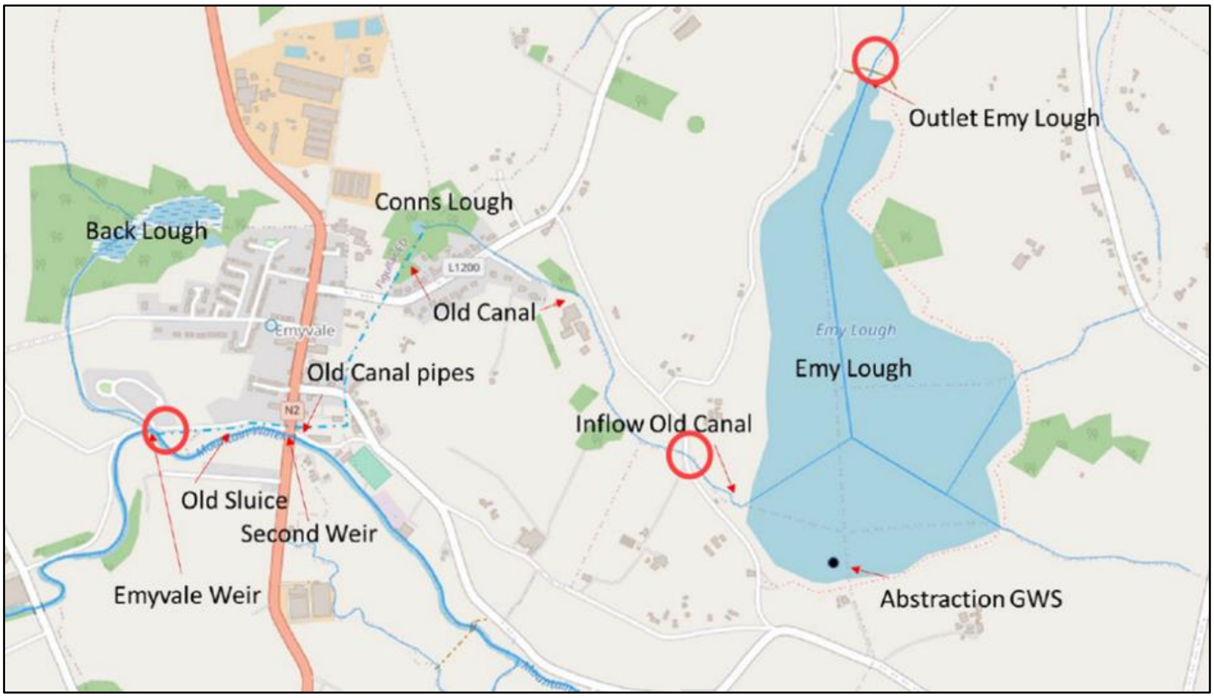


Stop 3 – Derrykinnigh Beg

At this stop we will look at some riparian works which were completed two years ago and have been a remarkable success. This site offers a great comparison point to the recent works just completed at Smouthan.

Stop 4 – Emyvale Weir

At this stop we will look at some of the remediation efforts implemented further downstream in the Blackwater.



Stop 5 – Glaslough Tyholland GWS

At this stop we will discuss how the GWS were impacted by the deteriorating water quality, source protection works and how the GWS benefiting from the recent remediation efforts.

Stop 6 – Ballytroddan

The final stop of the fieldtrip, we will be looking at a borehole cluster forming the Ballytroddan GWMS. The GWMS was constructed and completed as part of the CatchmentCARE network of groundwater monitoring boreholes.

More details on Ballytroddan in Section 4 of this fieldguide.

1. Overview of the Arney Catchment

Introduction

The Arney catchment lies in the North Western International River Basin District and is part of the larger River Erne catchment. It includes parts of Counties Fermanagh, Cavan and Leitrim. The Arney catchment covers an area of 304 km^2, of which two-thirds are in NI and one-third is within Ireland.

The Arney River flows west to join the River Erne just downstream of the outflow from Upper Lough Erne. The catchment is dominated by two major lakes, Lough Macnean Upper (approximately 990 ha) and Lough Macnean Lower (approximately 457 ha), both at an altitude of just over 50 maOD. The Arney is heavily modified in its lower reaches between the lakes and its confluence with the Erne.

The Arney catchment was chosen as one of the three CatchmentCARE study catchments due to its Moderate status under the 2nd Cycle (2015-2021) of the Water Framework Directive (WFD). The WFD assessment by Northern Ireland Environment Agency had identified fish status and river morphology as failing elements in this waterbody. Furthermore, following a comprehensive selection process in 2017, the Roo subcatchment was identified by LAWPRO as a WFD Priority Area for Action in the WFD 2nd Cycle.

Landscape and surface waters

The Arney River flows from west to east (see Figure 4), from Lough Macnean Lower to the River Erne, 15 km away. The Arney River and Upper and Lower Loughs sit in a wide, flat glacial trough that has steep valley sides and rocky scarps, between the uplands of Fermanagh, Belmore and the Cuilcagh Mountains. Thur Mountain (~420 maOD) lies to west of the catchment, Ballaghnabehy and Naweeloge uplands (441 maOD) lie to the southwest, the Cuilcagh Mountains lie the south (max height of 666 maOD) and the Belmore (398 maOD) and Tullybrack Mountains (386 maOD) lie to the north. To the east the valley opens out into the flat Arney Valley, and to the north-west it connects with the Garrison lowlands.

The Glenfarne River and Black River are largest rivers entering Upper Lough Macnean from the west, southwest and northwest of the lake respectively. Numerous rivers and streams enter the southern shore of the Upper Macnean flowing north from the uplands in the southwest, such as the Roo River. South of the lakes many rivers emerge as springs at the lower reaches of the Cuilcagh uplands and flow north into Upper and Lower Lough Macnean. Three main rivers flow south off the Cuilcagh Mountain, the Sruh Croppa, Aghinrawn and Owenbrean. These rivers sink underground and emerge at Cladagh Glen, which flows north into Upper Macnean. The principal river flowing south into the northern shore of the lakes, is the Lurgan River, with numerous smaller streams, many of which start as springs on the southern slope of the Belmore Mountains. The Cornavanogue River rises in a number of parallel rills falling off the southern slopes of Doagh mountain. The river continues south to the N16 road and thence flows eastwards, following the road, to enter Lough Macnean Upper.

The larger Lough Macnean Upper has wooded promontories and sheltered bays with fringing reed swamps, fen and carr woodland. Surrounding fields are largely wet, rush-dominated grassland. Lough Macnean Lower is confined by a steep limestone escarpment. It has a more developed agricultural shoreline, with open wet meadows contrasting with occasional thick woodlands. Limestone soils along the southern shores and lower slopes produce better quality grassland and these are farmed intensively. Farm units are smaller to the north of the loughs, but there is also intensive sheep and cattle grazing. The valley has some significant archaeological sites, including raths and crannogs.

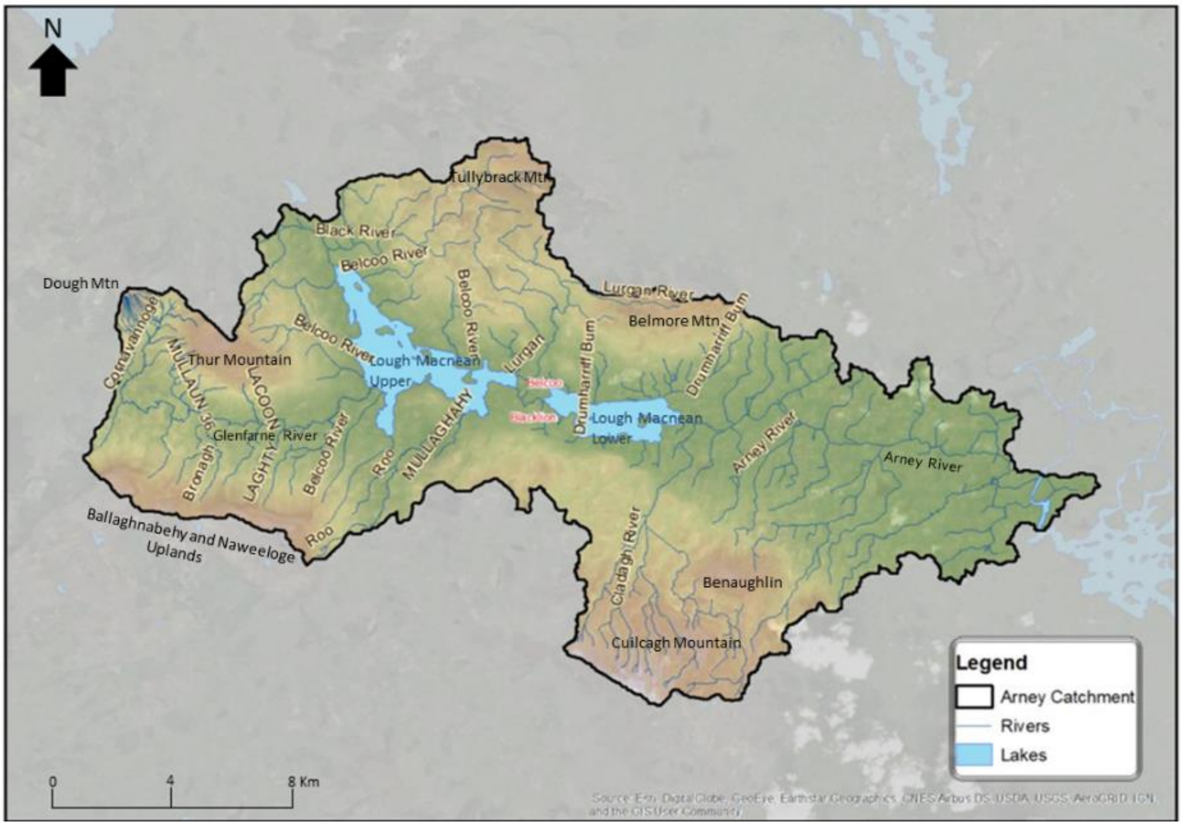


Figure 4 Topography and main surface water bodies in the Arney catchment (from catchmentcare.eu)

Bedrock geology

The bedrock geology is shown in Figure 5. The majority of the Arney catchment is composed of Dinantian-age rocks (360 – 330 Mya (Million years ago)), although there are Namurian lithologies (326 – 313 Mya) towards the west. The uplands surrounding the lakes are largely composed of shale and sandstone. The lower land in the valley is mostly composed of limestone and shale.

The oldest rocks are found in the east of the catchment starting with the Clogher Valley Formation (composed of siltstones and shales), the Ballyshannon Limestone Formation and then the overlying Bundoran Shale Formation. These are then overlain by The Mullaghmore Sandstone Formation and the Benbulben Shale Formation and the Glencar Limestone Formation (composed of alternating layers of calcareous shales and limestones).

The central third of the catchment is underlain by limestone of the Dartry Limestone Formation (and its Knockmore Limestone Member), which is karstified. In the Arney catchment much of the Darty Limestone is dominated by the Knockmore Limestone Member. This includes the north-facing flank of the Cuilcagh Mountain, which is home to the Marble Arch Cave system and many other caves and karst landforms.

These limestones are overlain by the Glenade Sandstone Formation, which is very widespread in the north of the catchment underlying the northern part of the Belmore and Tullybracks uplands, as well as parts of the Cuilcagh Mountains.

The uplands in the west of the catchment are composed of alternating layers of younger (Namurian age) sandstone and shales. These rocks underlie the uplands of the Thur, Doagh, Ballaghnabehy and Naweeloge.

The rocks have undergone substantial deformation, with significant faults throughout, and folding in east of the catchment. The rocks of the Bundoran Shale Formation up to and including the Glencar Formation are deformed into a classic anticline shape (i.e. rocks were deformed into an arch or ridge shape where the oldest rocks are at the centre and youngest rocks are draped over them). Faulting has resulted in dolomitisation of the limestone in places. There are also a number of dolerite dykes in the catchment such as the large dyke running northwest to southeast through the Cuilcagh Mountains, and the east to west dykes of Belmore Mountain.

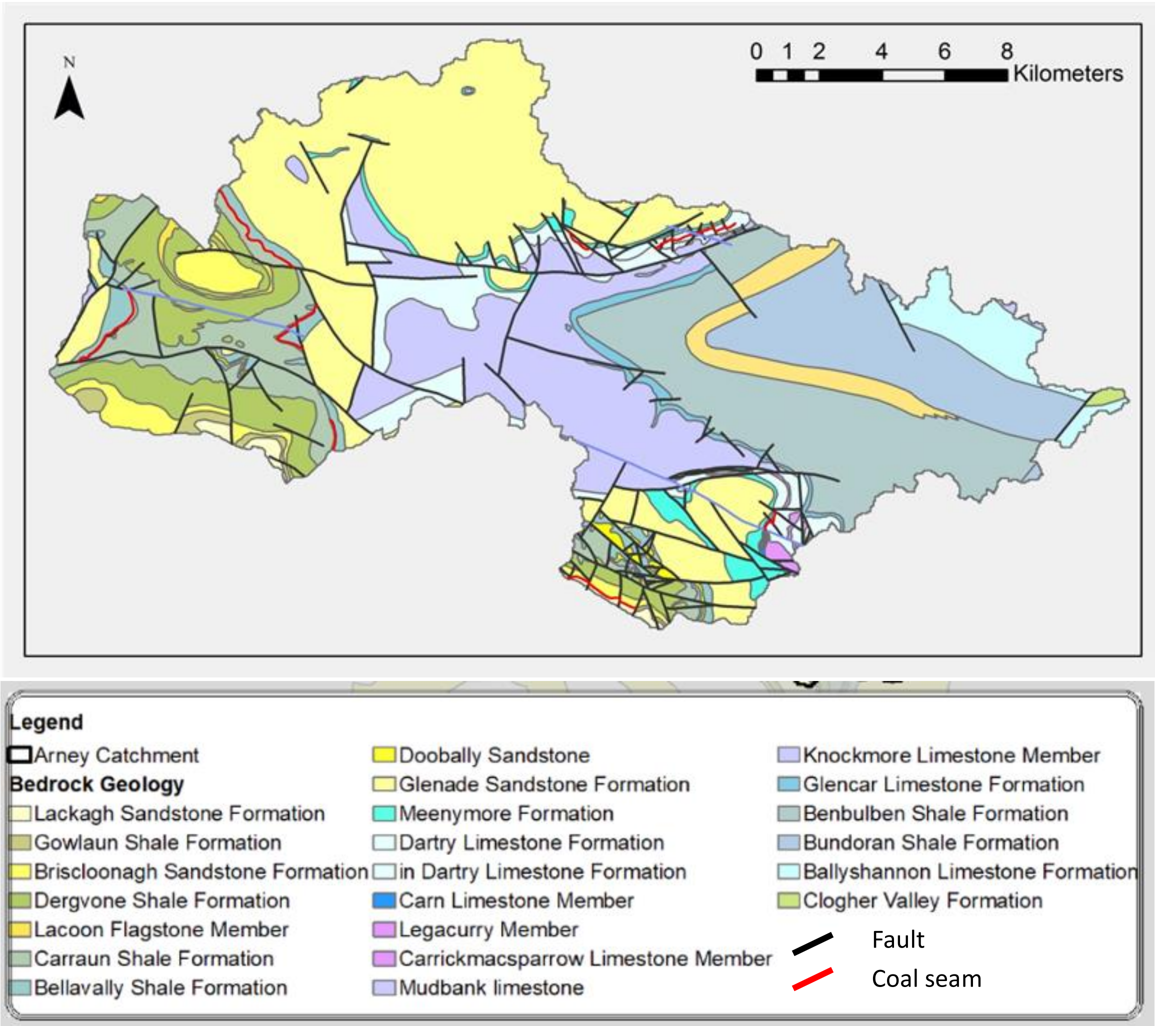


Figure 5 Bedrock geology underlying the Arney catchment (Data source: GSI and GSNI) (from catchmentcare.eu)

Soils and subsoil geology

The upland catchment areas are largely covered by blanket peat (see Figure 6). Smaller areas of cut peat also occur in the Arney lowlands. There are some areas of exposed bedrock and karstified bedrock outcrop or subcrop such as at Corratirrim, south of Blacklion. However, the greater part of the catchment is covered by glacial tills ('boulder clay') derived from Namurian sandstones and shales, and from limestones.

The river valley floors are covered by alluvial sands and silts particularly along the lower Lurgan and Cornavanogue rivers, along the Belcoo River, and the Arney River from the lower lake to the A32. Lacustrine alluvial clay, silts and sand deposits occur along the Arney further to the east near Upper Lough Erne.

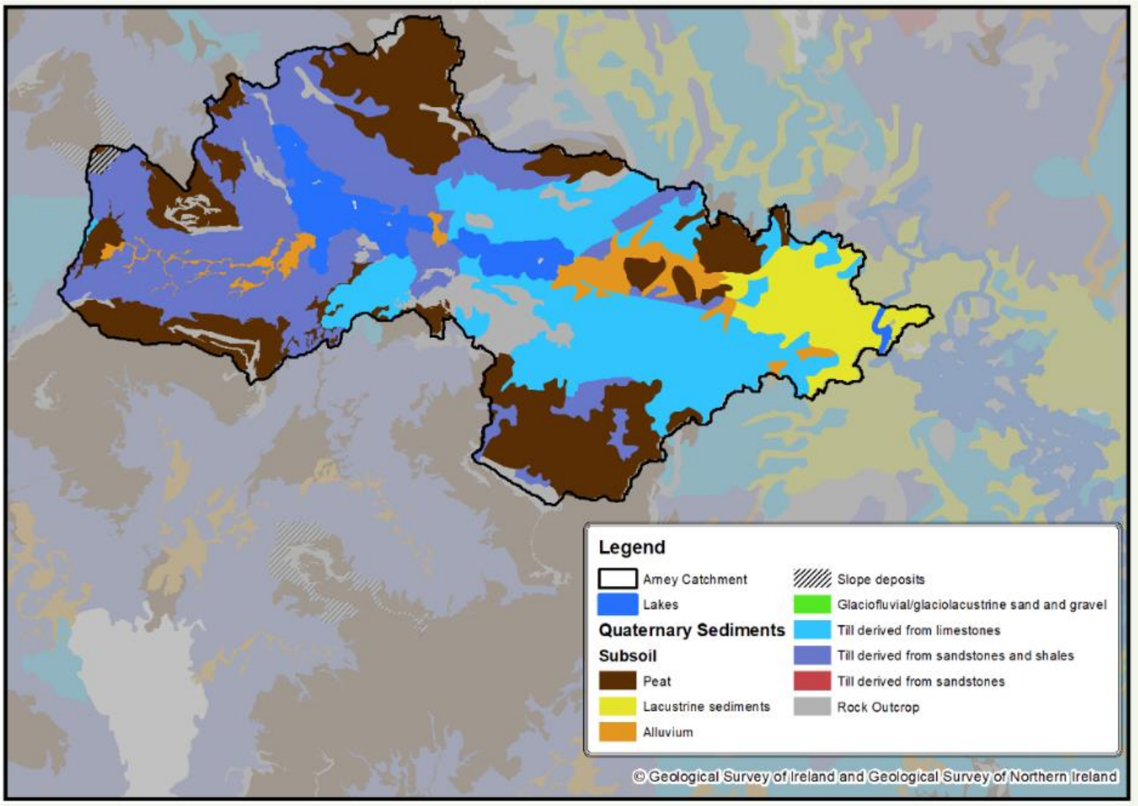


Figure 6 Subsoil Geology in the River Arney Catchment (Data source: GSI and GSNI) (from catchmentcare.eu)

The mineral soils (Figure 7) of the upland catchment are substantially gleys and leptosols. Soils in the eastern lowland catchment are largely poorly drained stagnosols and acidic. Fluvisols are most extensive in the riverine and lacustrine alluvial deposits along the Arney River.

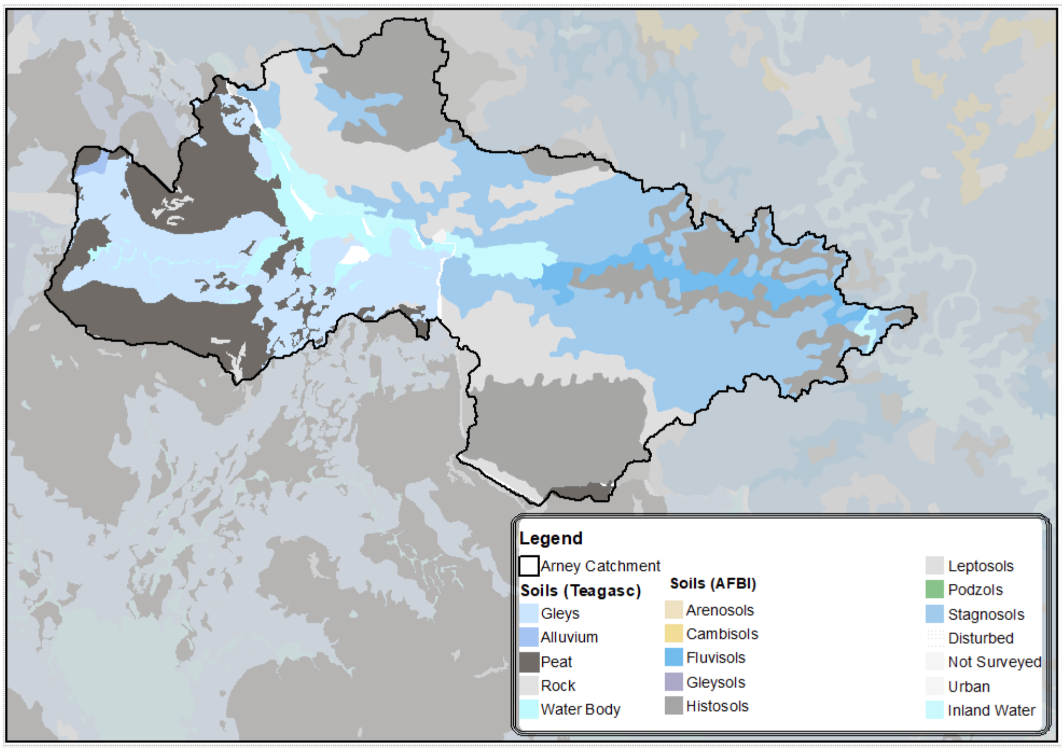


Figure 7 Soil Types in the River Arney Catchment (Data source: Teagasc and AFBI) (from catchmentcare.eu)

Hydrogeology

The principal aquifers in the Arney Catchment are hosted by the Dartry Limestone Formation (and its members). These rocks are highly karstified, and are classified in Ireland as Regionally Important Karst aquifers (Rkc), and in Northern Ireland as High Productivity Fracture flow with karstic element Bh (f-k).

The Arney catchment is a famous example of a classical karst landscape and one of Ireland's premier caving areas. As these aquifers are highly karstified, rainwater recharges the aquifer via numerous stream sinks, enclosed depressions and caves, as well as diffusely through subsoils. This groundwater emerges at springs towards the base of the limestone, after subsurface flowpaths of up to several km. Many of the streams that flow into the main Arney River (such as the Cladagh River), as well into the Upper and Lower Lough Macnean (such as the Roo), are fed by springs emerging from the limestone.

There is a high density of karst features in the limestone of the Arney Catchment. The karst features are shown on Figure 8. The area is littered with enclosed depression or dolines. These range in size from deep potholes to small solution dimples. Some of these function as large swallow holes with streams and rivers sinking into the ground. The are many explored cave systems the most famous of which is the Marble Arch Cave system. The many caves that make up the Marble Arch Cave system are fed by a large area of the Cuilcagh Mountain. The Sruh Croppa, Aghinrawn and Owenbrean rivers sink underground as they flow down off the sandstone and reach the underlying limestone to the north. These rivers flow through the Marble Arch Cave and emerge again as the Cladagh River, at the base of the Dartry Limestone at the contact with the underlying Glencar Limestone.

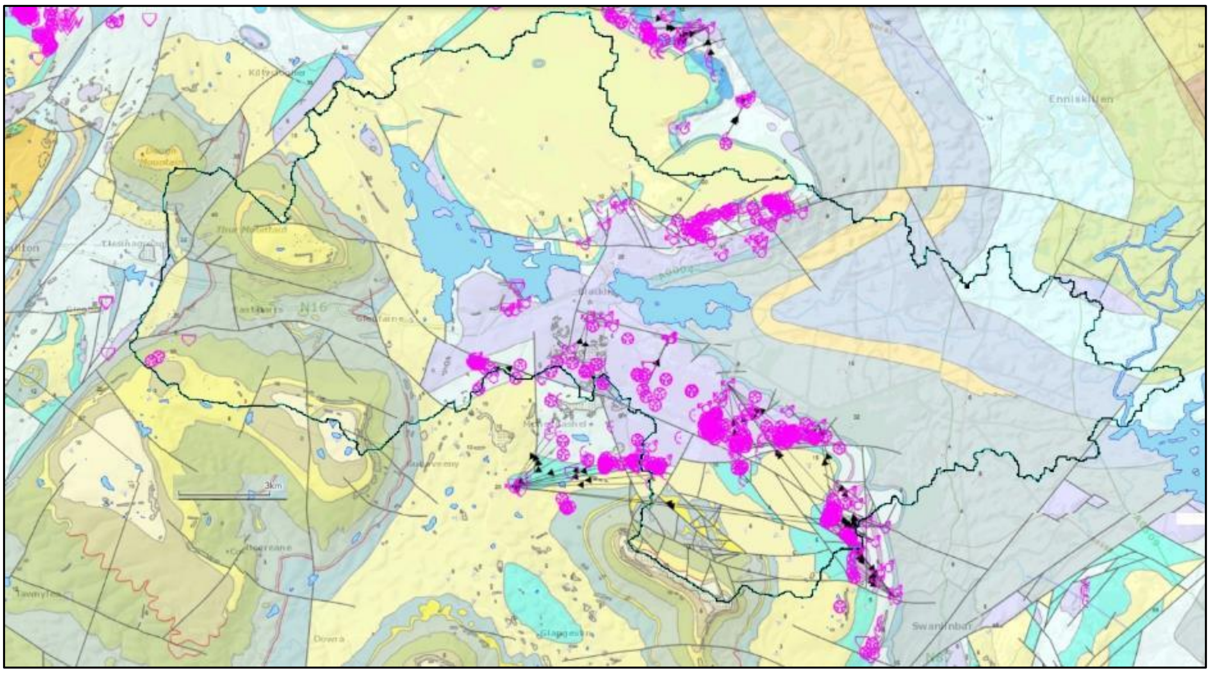


Figure 8 Karst features and proven underground connections in the River Arney Catchment and its environs (see the Figure in the Bedrock section, and Figure below for legends) (Data source: GSI and GSNI) (from GSI Groundwater viewer)

Existing dye tracing studies have determined the catchments to other large springs in the area such as Barran Springs, Ture risings, Hanging Rock springs and Tullyhone Rising. The tracing proves that the groundwater catchment extends further south than the surface catchment, which is often used as the overall Arney Catchment boundary. For example, the Barran springs have been traced from Pollnagosson and Pollnaskeoge sinking streams, both of which originate south and outside of the catchment boundary. The traces are shown in Figure 9.

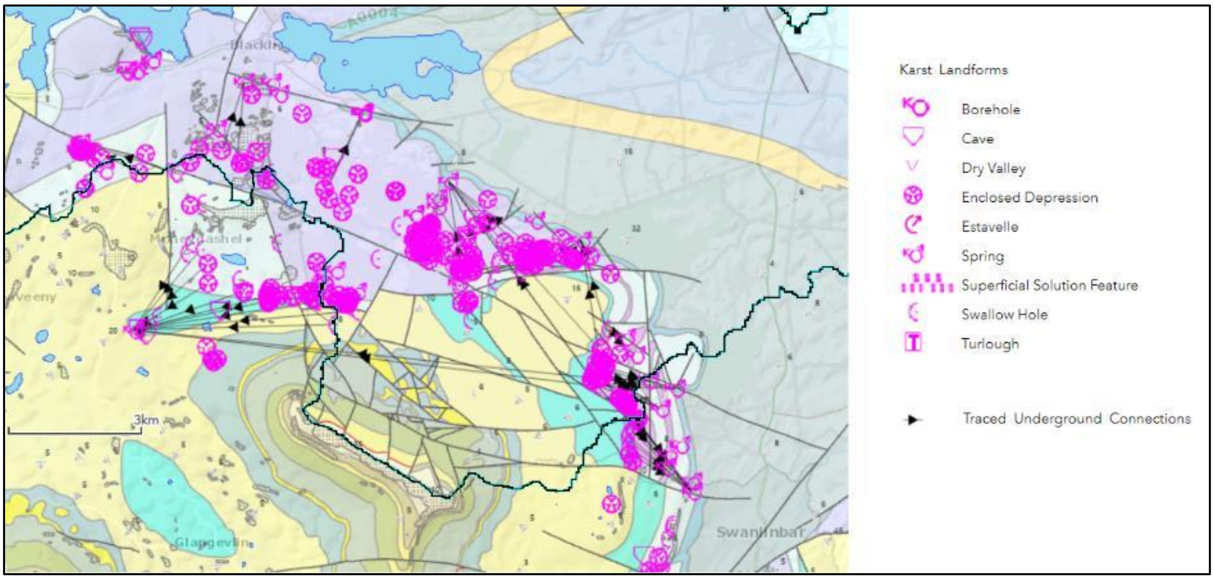


Figure 9 Karst features and proven underground connections across the southern surface water catchment of the River Arney Catchment (see the Figure in the Bedrock section for legend) (Data source: GSI and GSNI) (from GSI GW viewer)

The average minimum groundwater velocities in the limestones as shown by groundwater tracing studies is 95 m/h or 2.3 km/d and the longest proven underground connections are from sinking stream over 10 km away. As part of the CatchmentCARE project Community Incentive Schemes (CIS) a groundwater tracing programme was carried out by members of the Speleological Union of Ireland. The purpose of this was to help define the true catchment of the Arney and better understand the groundwater pathways. Connection between stream sinks and springs is well known around Cuilcagh Mountain, but there is little known about of the streams coming off Belmore Mountain.

Limestone aquifer catchment mapping in the Cuilcagh Karst (Figure 10) was first undertaken by Gunn (1982). Subsequent tracer experiments by Gunn during the 1980s, Gunn and Brown in the 1990s and then by Gunn, Brown (2005), and Kelly since 2000 has refined these catchment boundaries and identified the complexity associated with the divergent flows, including bifurcation of flow (Figure 11).

The water tracing experiments undertaken as part of water tracing since the 1990s have been intended to assist the understanding of these divergent flows and to further refine the catchment boundaries. Sinks on the East Cuilcagh limestone escarpment have been proven by Gunn and Brown to form part of a complex karst drainage system. In particular, the stream sinking at Pigeon Pot II drains to multiple risings in the River Erne drainage basin as well as Shannon Cave, which is part of the karst drainage to Shannon Pot rising, the source of the River Shannon (Figure 12).

A second bifurcation of flow has been proven by Brown and Kelly at Pollnagossan Cave in the western part of Marlbank. Under flood conditions flow diverges with one flow path to Barran Rising (River Erne) and one flow path to Shannon Pot, the source of the Shannon (Figure 13 and Figure 14).

Those risings in the Erne drainage basin that receive water from Pigeon Pot II including Cascades Rising in the Cladagh Glen, Tullyhona Rising in Florencecourt forest as well as Sumera and Gortalughany risings, at the foot of the East Cuilcagh limestone escarpment.

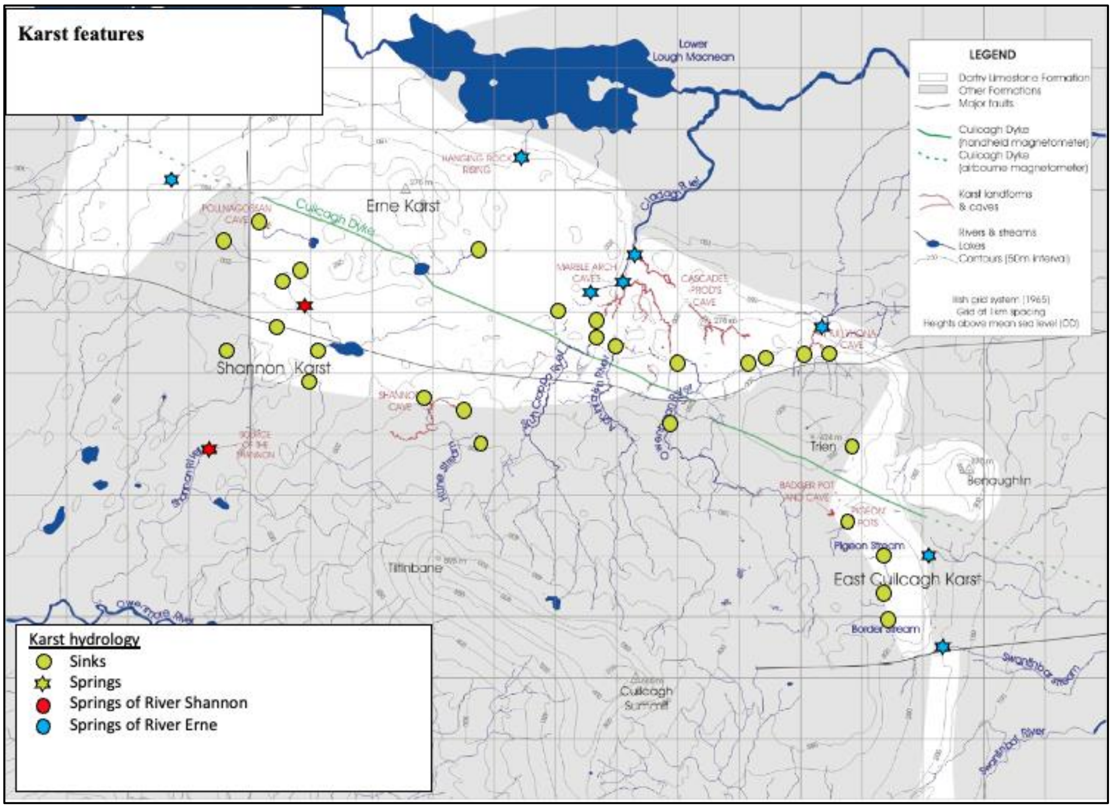


Figure 10 Karst features in the Cuilcagh karst (from Les Brown)

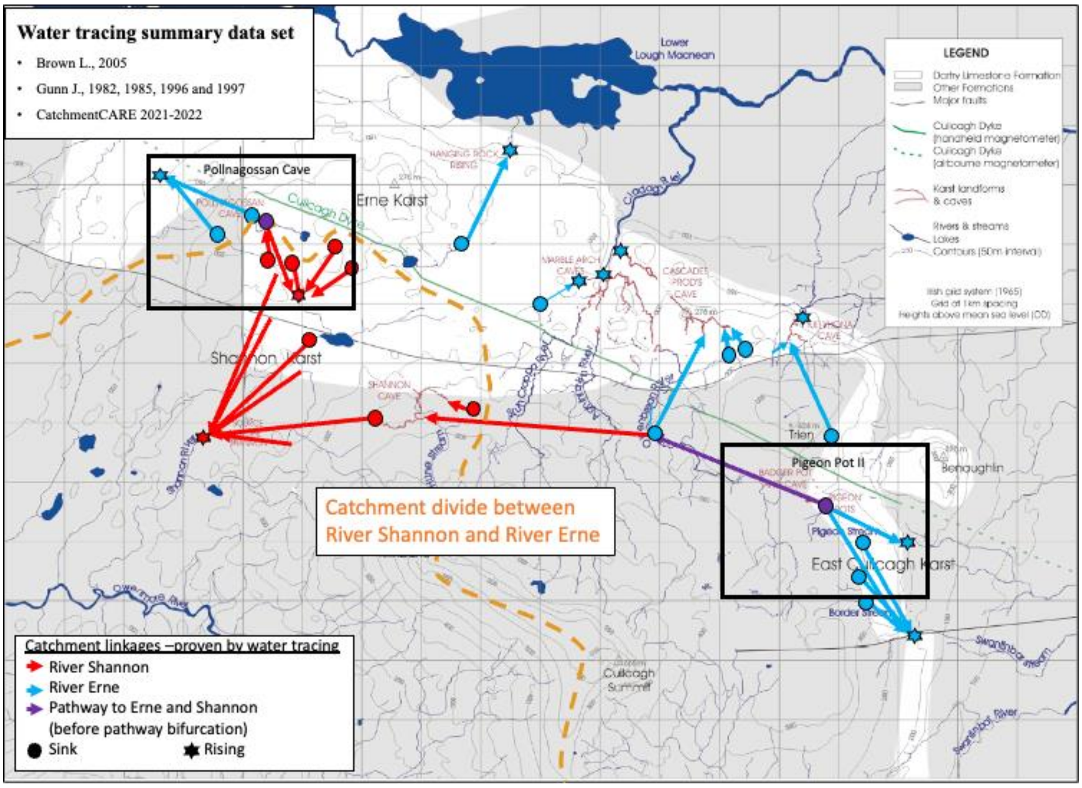


Figure 11 Water tracing tests in the Cuilcagh karst (highlighting were bifurcating flows are proven) (from Les Brown)

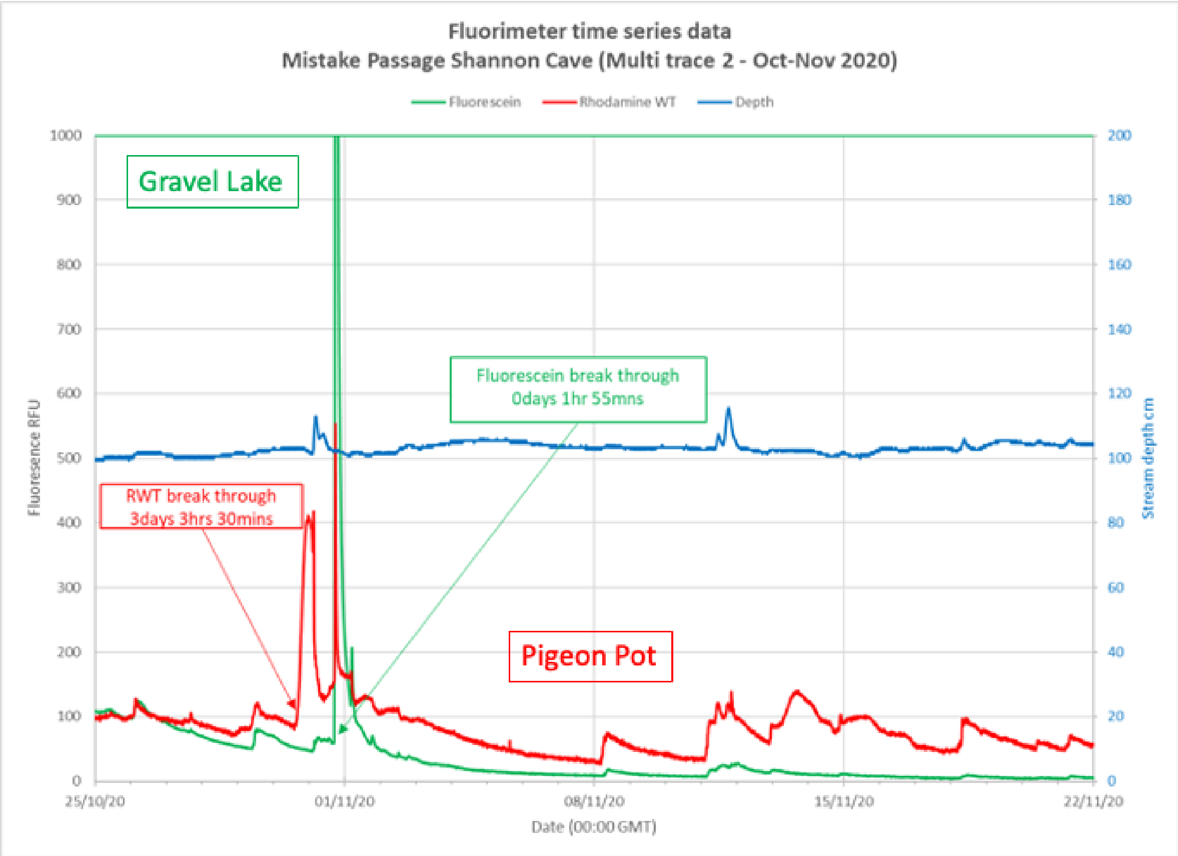


Figure 12 Tracer hydrograph from Pigeon Pot II (red) and Gravel Lake (Green) to Shannon Cave. (from Les Brown)

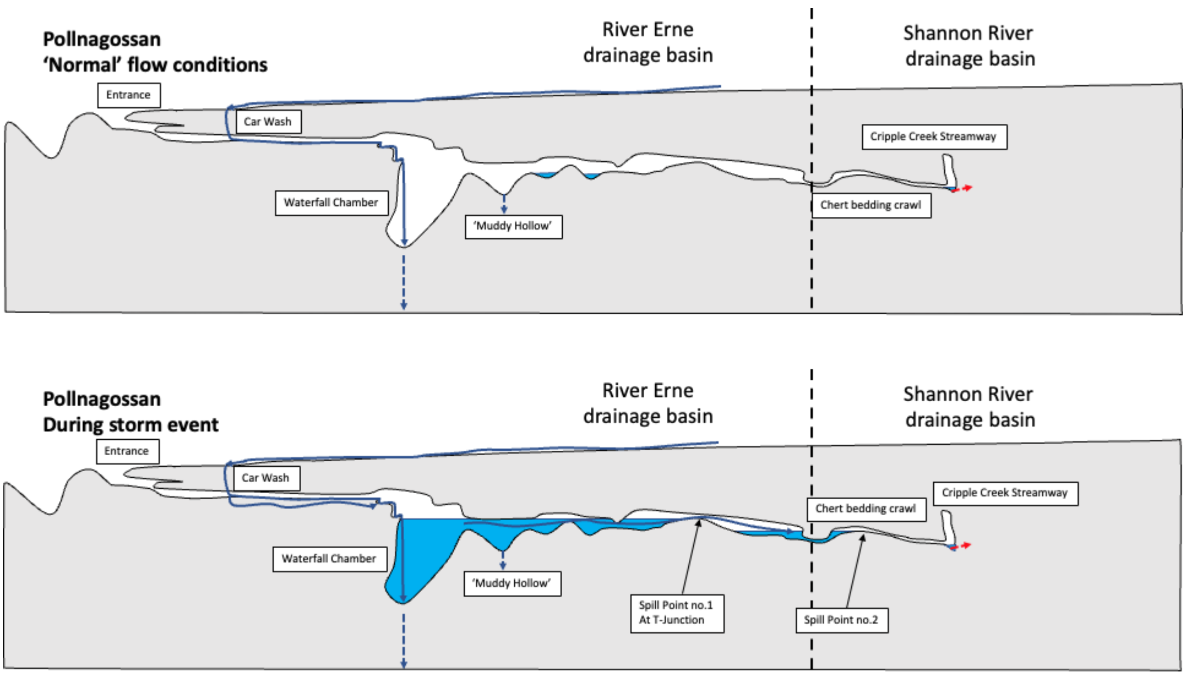


Figure 13 Stages of flow bifurcation in Pollnagossan Cave during a flood event (from Les Brown)

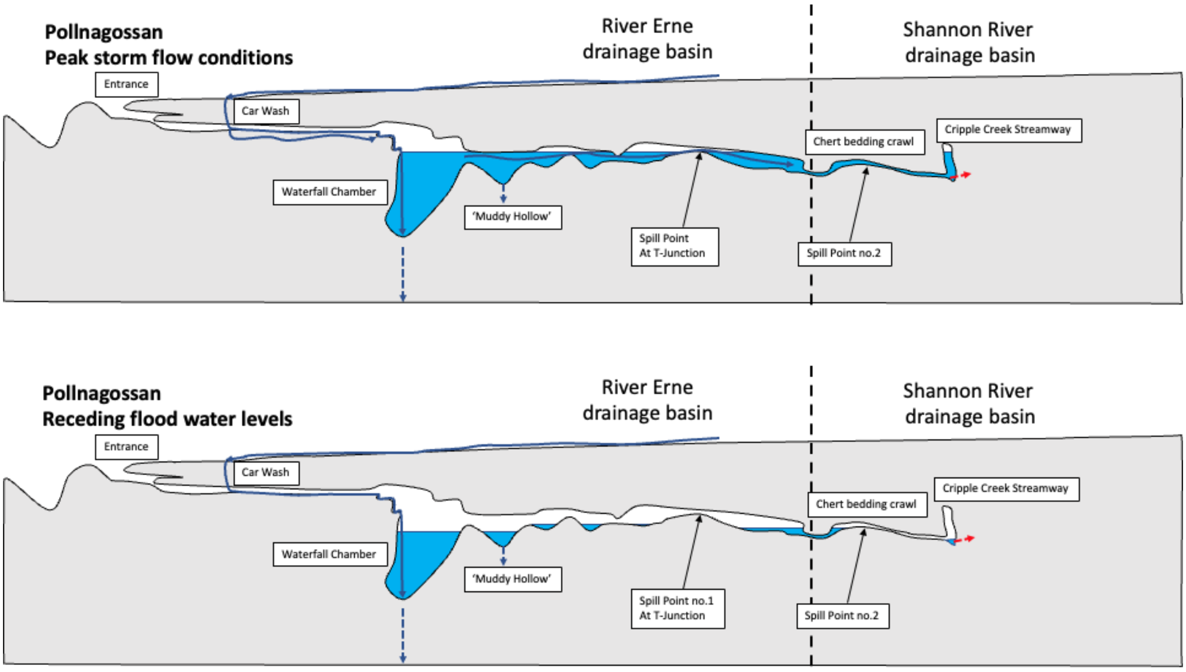


Figure 14 Stages of flow bifurcation in Pollnagossan Cave during a flood event (from Les Brown)

The Marble Arch and Prod's-Cascade cave system has the largest surface water catchment in the Cuilcagh Karst at 35km2. Shannon Pot Rising is the second largest with a catchment of 15.2km2.

From east to west, the Dartry Limestone Formation thickens but also gently dips south-westward. In the east the formation is 120m thick and up to 80m above the valley floor. At Shannon Pot Rising formation is over 300m thick, with the formation top approximately 30m below the valley floor.

Conduit systems extensively drain the limestone aquifer and form pathways that are partially explorable as networks of cave passages. Where the base of the limestone is exposed above the valley floor then the major risings occur near the base of the Dartry Limestone Formation. However, in the west where the formation lies below the valley floor then the risings occur in stratigraphy above the Dartry Limestone Formation. These rising in the west part of Cuilcagh Mountain are flooded and have upwelling waters

The chemical signatures of the emergent waters provide information on the hydrology of the karst systems. The emergent water from risings that have extensive cave passages tend to have lower electronic conductivities and lower ionic concentrations, reflecting the more rapid flow though times and relatively short contact time with the bedrock. However, those systems in the west have higher conductivities and higher ionic concentrations reflecting dispersed recharge, slower flow through times and greater contact with the bedrock. The lowest conductivity (63uS/cm) was recorded at Marble Arch Rising during high flow and the highest conductivity (710µS/cm) was recorded at Barran Rising 3 during low flow. The conductivity of emergent waters generally increases westwards.

The cave systems are all single tier branching cave systems. From stream sink to rising, the hydraulic gradients through the cave systems are moderate at c.40-60m/km, with average linear velocities up to 400m/h.

The shales and sandstones underlying the catchment are generally poorer aquifers, have low transmissivity, and contain limited groundwater resources. The aquifer types are shown on Figure 15. Most of the groundwater flow is likely to be in the uppermost part of the aquifer comprising a broken and weathered zone and a zone of interconnected fissuring. Isolated fissures can be encountered at greater depths. Recharge occurs diffusely through the subsoil and rock outcrops, although is limited by any thicker low permeability subsoil and inability of the aquifer to accept the rainfall. Most of the effective rainfall will discharge quickly to springs, seeps and surface waters. Flow paths are likely to be short (<500 m). These aquifers are considered to be Poor (Pl and Pu aquifer classifications in Ireland), or Locally important (Ll in Ireland and Bl(f) in Northern Ireland).

The well-fractured Glenade Sandstone Formation has a greater groundwater resource value (Locally Important Aquifer which is Generally Moderately Productive (Lm)/ Moderate Productivity Fracture Flow (Bm(f)). Groundwater to flow through them, but not in such significant quantities as the karstified limestones. Higher transmissivity values are expected in the sandstones, resulting in longer flow paths (up to 2,000 m).

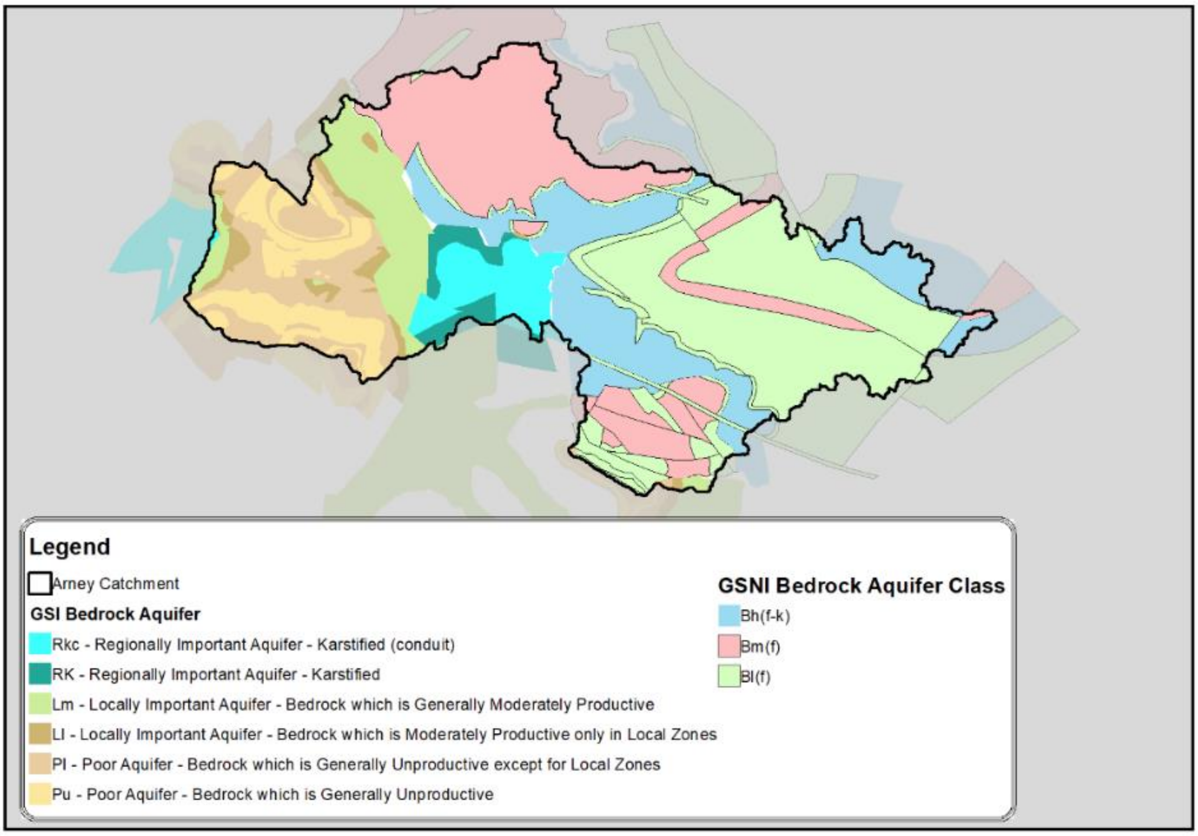


Figure 15 Aquifers in the Arney catchment. The legend keys for Irish and Northern Irish maps are arranged in order of greatest to least groundwater resource value (Data source: GSI/GSNI) (from catchmentcare.eu)

Groundwater is most vulnerable where the subsoils are absent or thin, or in areas of karstic limestone where surface streams sink underground at swallow holes (see Figure 16). Areas of the greatest vulnerability associated with shallow or exposed bedrock are mainly found in upland areas such as Thur Mountain and parts of the Cuilcagh Mountain, around the edges of the catchment. The blanket peat here is thin, with rock not far from the surface. There are also areas of exposed limestone pavement, especially in the south of the catchment. Greatest vulnerabilities are also related to karst features such as swallow holes and enclosed depressions that puncture the thick, protective subsoil layers overlying the karst limestone aquifers. In the valleys, sediments are thicker and the groundwater beneath is better protected.

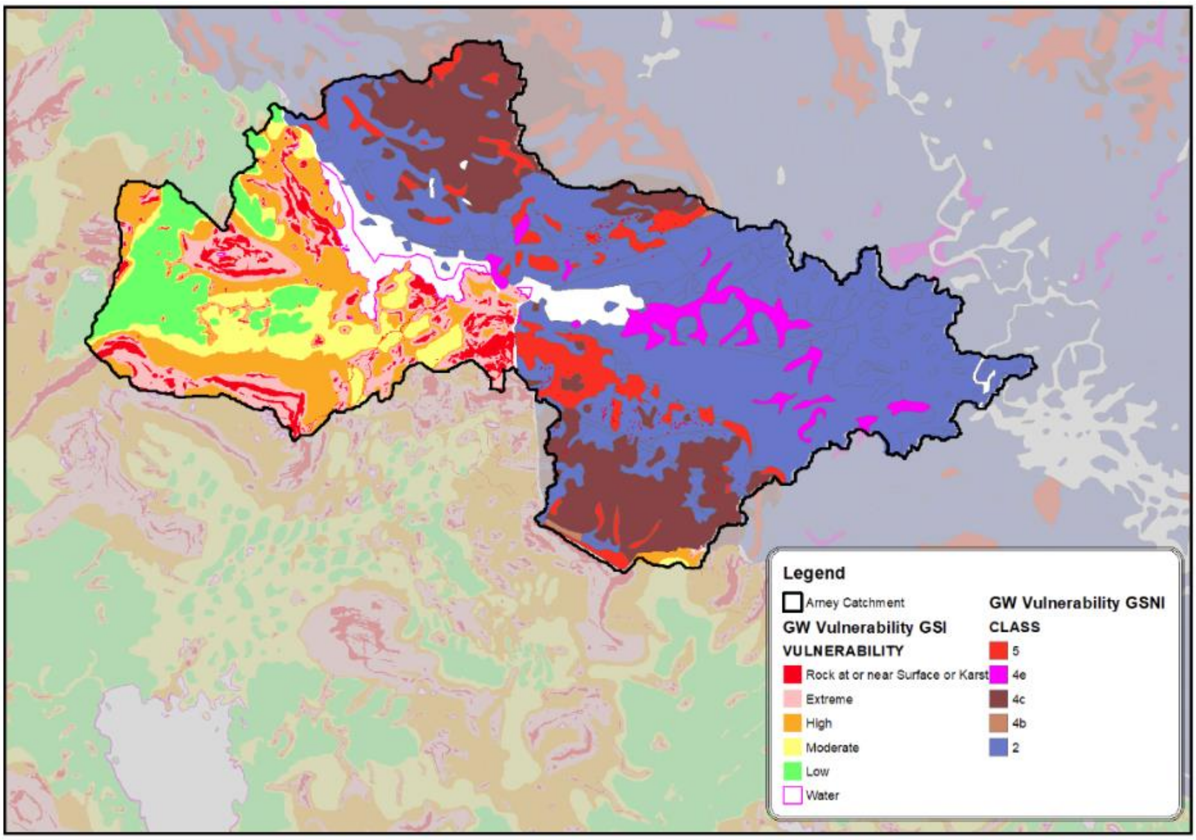


Figure 16 Groundwater vulnerability in the Arney catchment. The legend keys for Irish and Northern Irish maps are arranged in order of greatest to least groundwater vulnerability. (Data source: GSI/GSNI) (from catchmentcare.eu)

Population, land use and significant pressures

The population of the Arney catchment is approximately 9,800. This is equivalent to a density of about 32/km^2. The biggest settlements in the catchment are Blacklion in County Cavan (population 194 in the 2016 census), and Belcoo/Holywell in Fermanagh (population 540 in the 2011 census). Therefore some 85% of the population distribution in the catchment is dispersed rural, often as ribbon development.

The majority of the land use (Figure 17 and Figure 18) in the catchment is agricultural (54%) with 36% used as pasture for grazing. There is also extensive peatland (23%) especially on high elevations such as the Cuilcagh Mountains, which is one of the largest expanses of blanket bog in Northern Ireland. Peat extraction occurs in a number of areas. On drier slopes the peats are replaced by moors and heathlands. Montane heath is found on the summit of Cuilcagh Mountain.

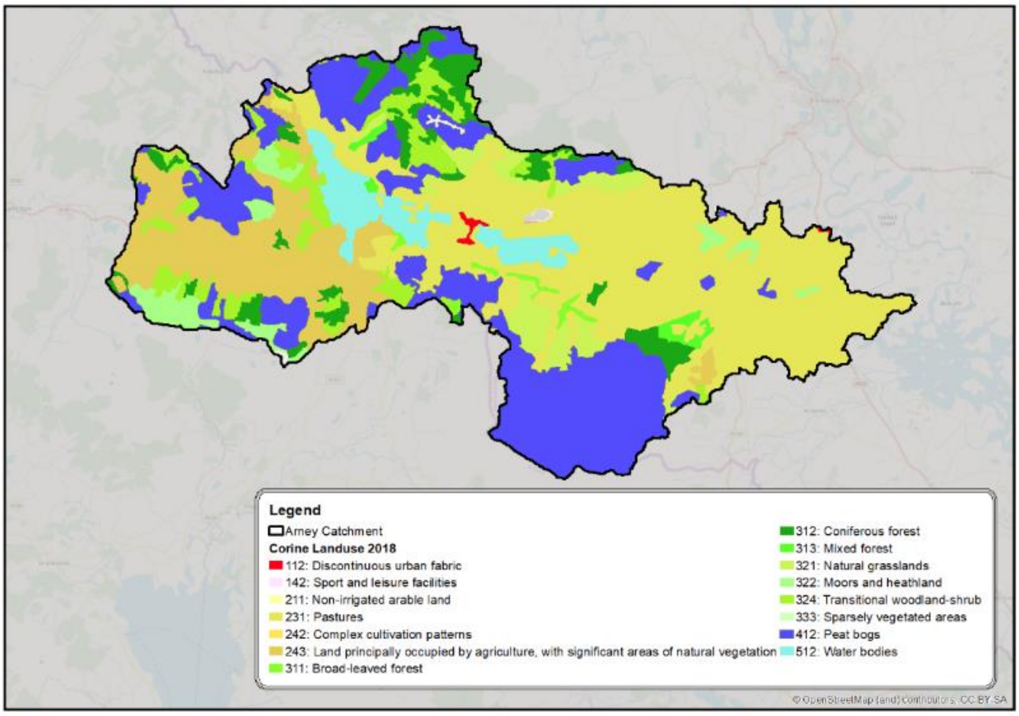


Figure 17 River Arney Catchment Land Classifications Map. (Data source: CORINE Land Cover 2018, EEA) (from catchmentcare.eu)

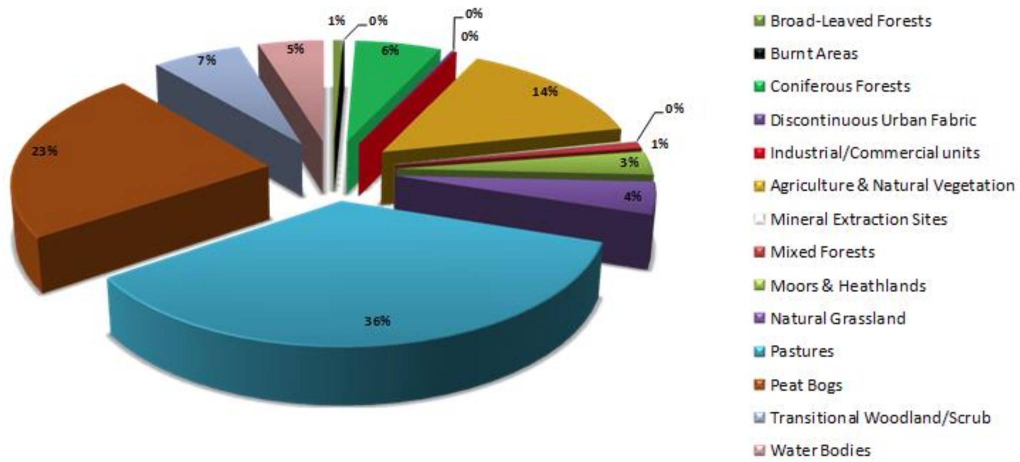
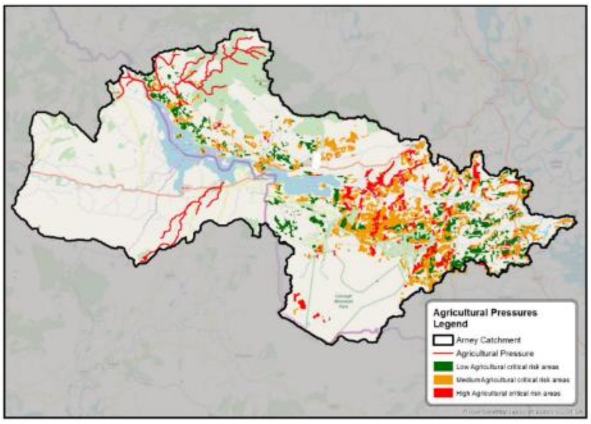


Figure 18 Land use and land cover in the Arney catchment. (Data source: CORINE Land Cover 2018, EEA) (from catchmentcare.eu)

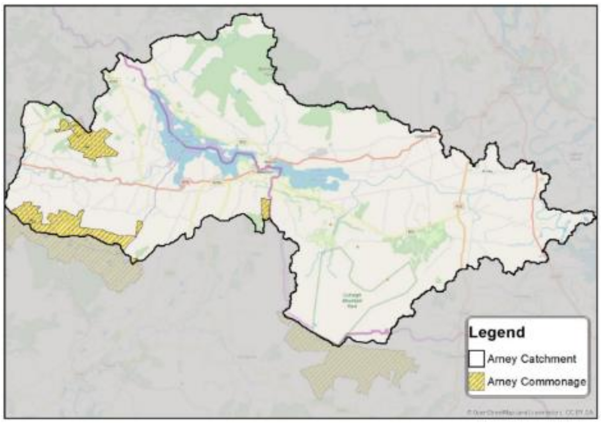
Parcels of coniferous forestry occur throughout, particularly in the upland areas. The most significant area is Ballintempo forest in the northern catchment. Transitional woodland and scrub is also widespread in the uplands and on the slopes, but broadleaved woodland is restricted to small areas. The valleys of the western catchment, in particular the Cornavanogue valley, support agriculture but with an admixture of significant areas of natural vegetation. The eastern lowland catchment is dominated by pastures.

Significant pressures impacting on water quality in the Arney catchment include agriculture and forestry, urban wastewater treatment effluent, domestic wastewater discharges, and anthropogenic pressures.

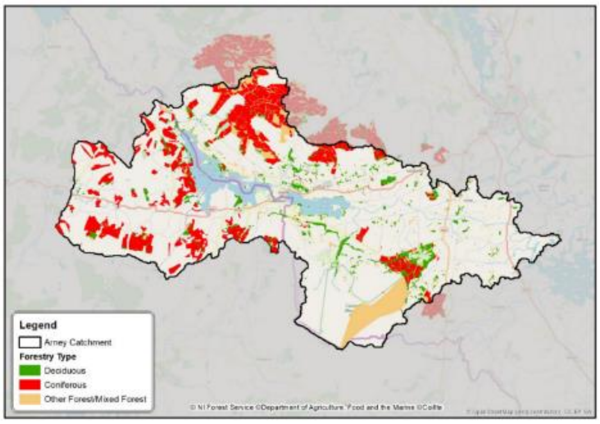
Agriculture: The extent of significant agricultural pressures (amber and red areas) in the eastern catchment is clear (see Figure 19). Sheep grazing on commonages in the western upland portion is not identified as a significant pressure. More intensive farming is confined to the river valleys in the uplands such as the Black River and Roo stream. In the Arney lowlands, farms typically consist of small fields that are grouped on low hills above surrounding damp soils, but the holdings also include intensive grassland on large, improved fields. The main types of farming in these areas are beef, dairy, and sheep. Most of the agricultural land is used as grassland for grazing and silage or hay rather than for other crops. The main impact of agriculture in the catchment is diffuse nutrient enrichment.



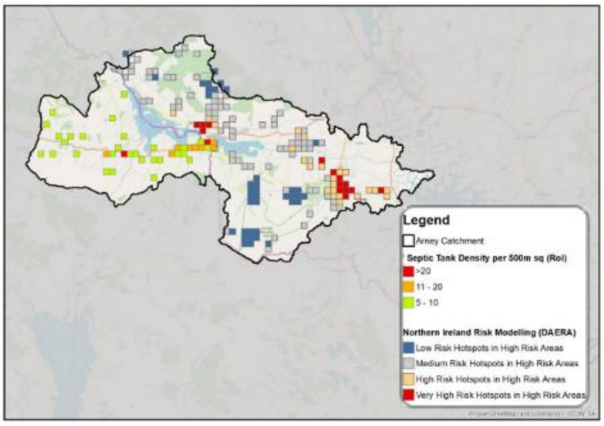
Agricultural Pressures



Commonage Areas



Forestry Pressures



Domestic Onsite Wastewater Treatment System Density

Figure 19 Selected land use pressures in the Arney catchment. (Data sources: various) (from catchmentcare.eu)

Forestry and peat extraction: Many commercial conifer plantations have been planted on upland blanket peats (see Figure 19). Forestry has been identified as a significant pressure in the Lough Macnean Upper catchment. Greatest impacts are often associated with clear felling and subsequent forest re-establishment. Impacts include sediment and phosphorus release, the latter particularly where forests are growing on peats. Peat extraction is also ongoing in many areas, often the same areas as forestry, and is obvious in the upper Roo valley and around the margins of the lowland raised bogs in the Arney valley. Extensive areas of upland blanket peats have been cut mechanically. Drainage and exposure of bare peat can give rise to sediment and nutrient release, and changes in hydrology. Peat extraction has not been identified as a significant pressure in the Arney catchment to date, although this may need to be revisited.

Urban Waste Water Treatment, On-site Wastewater Systems and Licensed Discharges: There are seven waste water treatment plants (WWTPs) in the Arney catchment (see Figure 19). The EPA consider that the wastewater discharge from Blacklion UWWT plant is the sole significant pressure on the Macnean water body at risk of not meeting its environmental objectives. The remaining WWTPs in the Arney catchment were assessed as compliant in 2018. NI Water has a number of smaller treatment works in the Arney catchment. The Arney catchment is largely rural in character and population is dispersed. The majority of systems are septic tanks with solids removal and effluent disposal to percolation areas. One-off housing and hot spots occur in almost all parts of the catchment except the most remote mountainous areas. Recent settlement has included many houses in ribbon developments along roadways. The Roo valley has been specifically identified as an area with significant pressures from domestic wastewater systems. Licensed discharges are not identified by the EPA as a significant pressure in any waterbody in the Arney catchment.

Protected areas

Four Natura 2000 sites occur wholly or partly within the Arney catchment:

- Boleybrack Mountain SAC 002032
- Corratirrim SAC 000979
- Cuilcagh Mountain SAC UK0016603
- West Fermanagh Scarplands SAC UK0030300

The spatial distribution of the protected sites are shown in Figure 20.

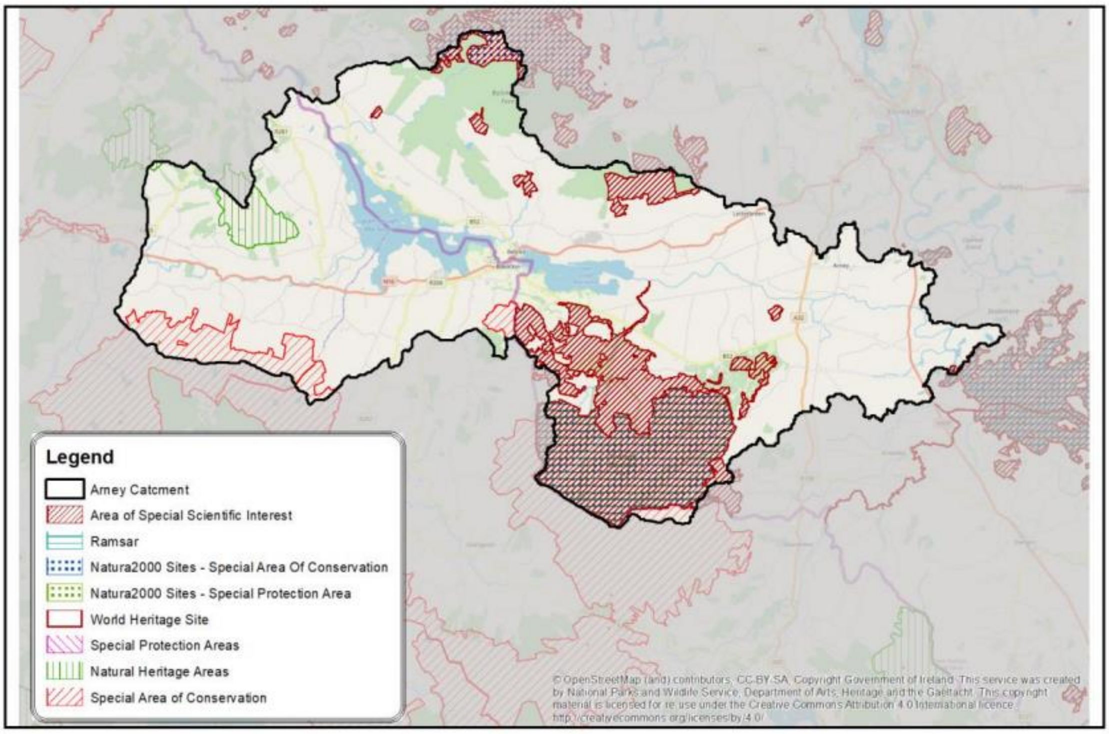


Figure 20 Biodiversity and Landscape Protected Areas in the River Arney Catchment. (Data sources: NPWS and NIEA) (from catchmentcare.eu)

Water Framework Directive Status

The Arney catchment is divided into 11 River Water Bodies (RWBs) and two Lake Water Bodies. It is associated with 11 groundwater bodies (GWBs). The WFD status of waterbodies in the Arney is detailed in Table 1.

Table 1 Evolution in WFD Status of water bodies in the Arney catchment (Data sources: EPA and NIEA)

River Water Bodies	**Status 2015**	**Status 2018 (2020)**	**Status 2021**
Cornavannogue_010	GOOD	GOOD	HIGH
Cornavannogue_020	GOOD	HIGH	HIGH
Roo_010	POOR	MODERATE	GOOD
Black River	MODERATE	MODERATE	MODERATE
Cladagh River	GOOD	GOOD	GOOD
Belcoo river	GOOD	GOOD	GOOD
Drumharriff Burn	MODERATE	MODERATE	GOOD
Lurgan River	MODERATE	GOOD	GOOD
Florence Court River	HIGH	GOOD	GOOD
Upper Lough Erne	MODERATE	MODERATE	POOR
Arney River	MODERATE	MODERATE	BAD
Lake Water Bodies			
Lough Macnean Upper	MODERATE	POOR	POOR
Lough Macnean Lower	BAD	BAD	BAD
Groundwater Bodies			
Belcoo Boho (KA)	GOOD	POOR	GOOD
Florence Court-Drumgormley (PP)	GOOD	GOOD	GOOD
Glenfarne (PP)	GOOD	GOOD	GOOD
Ballintempo (FI)	GOOD	GOOD	GOOD
Marble Arch (KA)	GOOD	GOOD	GOOD
Shannon Pot (KA)	GOOD	GOOD	GOOD
Enniskillen (KA)	POOR	GOOD	POOR
Anierin-Cuilcagh East (PP)	GOOD	GOOD	GOOD
Claddagh-Swanlinbar (FI)	GOOD	GOOD	GOOD
Derrygonnelly (FI)	GOOD	GOOD	GOOD
Tempo (PP)	GOOD	GOOD	POOR

The High and Good status water bodies are in the upland headwater reaches where significant pressures are largely absent. However, one headwater river, the Black River, is at Moderate status and agriculture remains a significant pressure in this area of the catchment. The element driving status in this case is fish, and all other status elements are High or Good.

Three RWBs have improved in status since 2015. The Roo_010, improved from Poor to Good. Septic tanks, agriculture and forestry had all been identified as significant pressures in Roo_010, but recent trends have shown a decrease in total ammonia and in ortho-phosphate. Cornavanogue_020 improved to High status by 2018. The Florence Court River dropped from High to Good status. The Arney River has notably dropped from Moderate to Bad. Over the same time period, Lough Macnean Upper dropped to Poor status from Moderate. Lough Macnean Lower remains at Bad status. The Arney catchment is associated with 11 GWBs. Nine of them are at good status.

WFD Priority Area for Action

The 2nd Cycle River Basin Management Plan for Ireland 2018 - 2021 identified 'Priority Areas for Action'. These consist of waterbodies where actions will be prioritised to achieve WFD objectives. In the Arney Catchment, the Roo river (Figure 21) was selected by the Local Authority Waters Programme (LAWPRO) for Local Authority catchment assessment teams to drive the implementation of mitigation measures, with particular emphasis on driving collaborative and cross-sectoral actions to deliver water-quality improvements. Because of this, and because it is in karst catchment, it also became a focus for the Groundwater team and a focus of Community Incentive Scheme actions within CatchmentCARE.

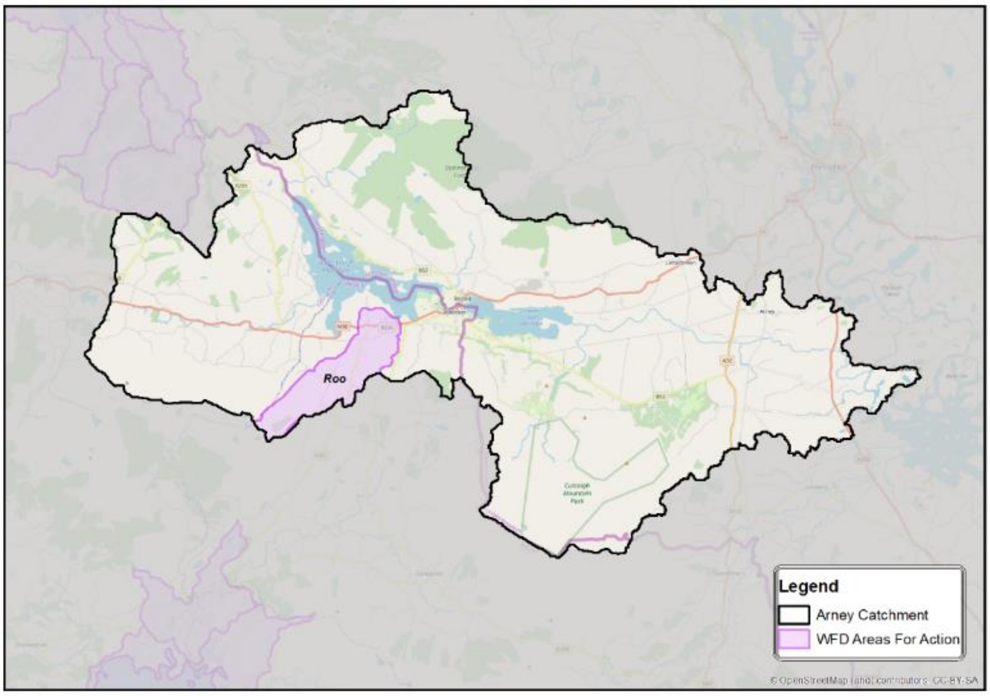
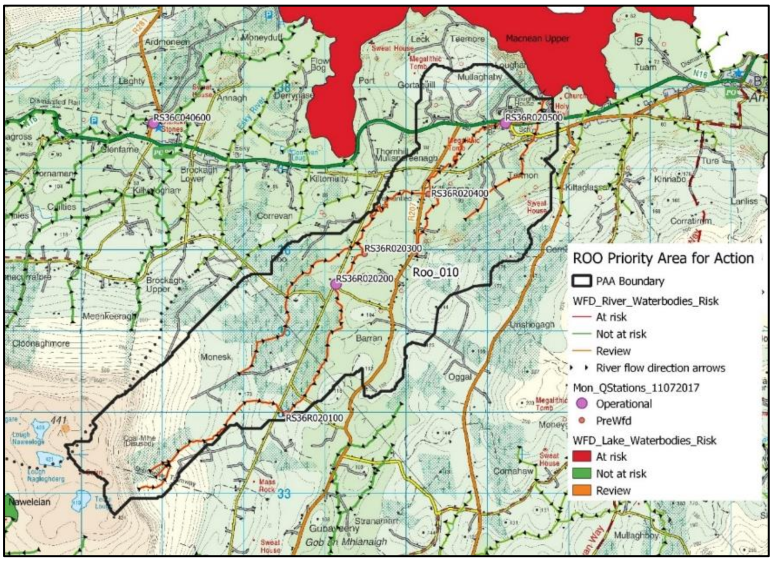
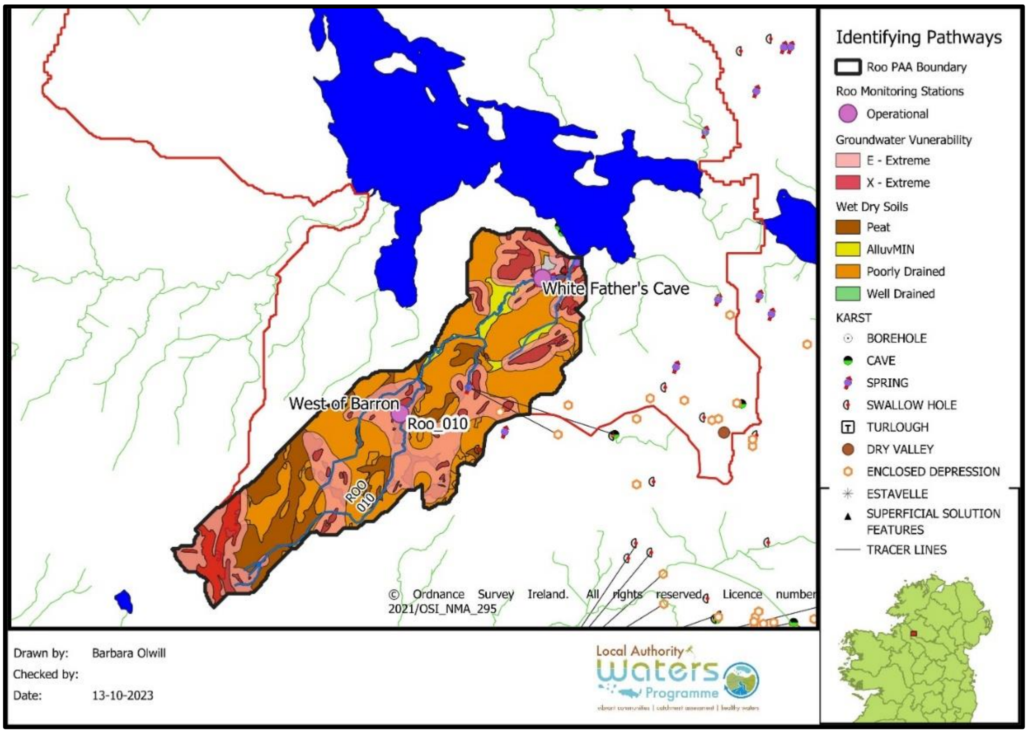


Figure 21 Priority Area for Action in the Arney catchment. (Data sources: EPA) (from catchmentcare.eu)

Below are some figures which Barbara Olwill will discuss on site:

Roo River Identifying the Catchment





Deskstudy Assessment – Current Status

Summary of Roo_10 waterbody from desk study in 2019

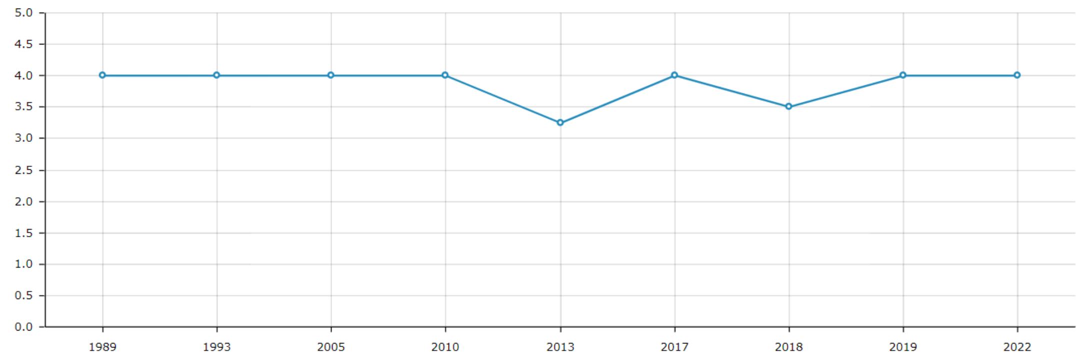
WB Code	WB Name	WFD Risk	Status Obj.	Status 07-09	Status 10-12	Status 12-15	Status 13-18	Q 17	Q 18	Pressure Category	Pressure Subcategory	Sig. Pressure
IE_NW_36 R020200	ROO_010	*At Risk*	Good 2021	H	G	P	M	St. 200 **Q4** St. 500 **Q4**	St. 200 **Q4** St. 500 **Q3-4**	Agri.	Pasture (Nutrient pollution)	Yes
										Domestic Wastewater treatment systems	Single house discharge (Nutrient pollution)	Yes
										Forestry	Forestry	No

Monitoring Stations

Two Monitoring Stations with Data under the National Monitoring Programme

1. **Monitoring Station RS36R020500 White Father's Cave Good Status Objective**

Q Value - Chart

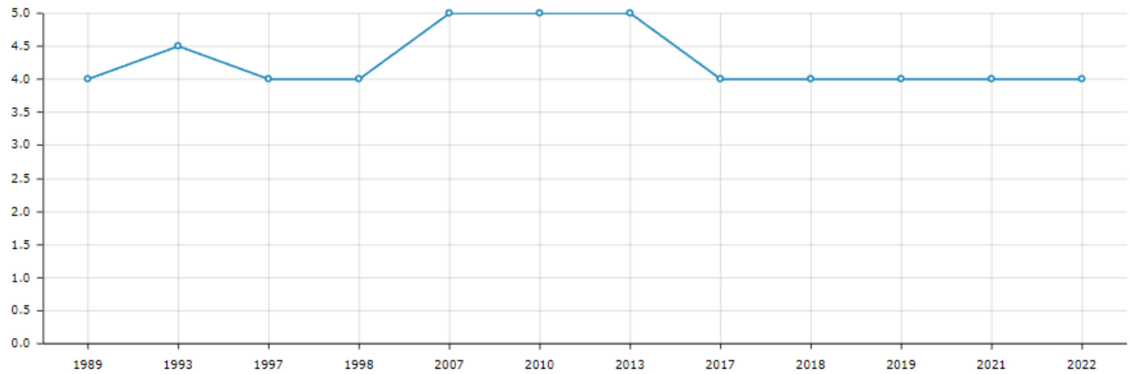


	1989	1993	2005	2010	2013	2017	2018	2019	2022
Result	4	4	4	4	3.25	4	3.5	4	4
Classification	Good	Good	Good	Good	Poor	Good	Moderate	Good	Good
Q-Value	4	4	4	4	3/0	4	3-4	4	4

Not on the Chemistry Monitoring Programme, Good Status Objective

2. **Monitoring Station RS36R020200 West of Barron High Status Objective**

Q Value - Chart

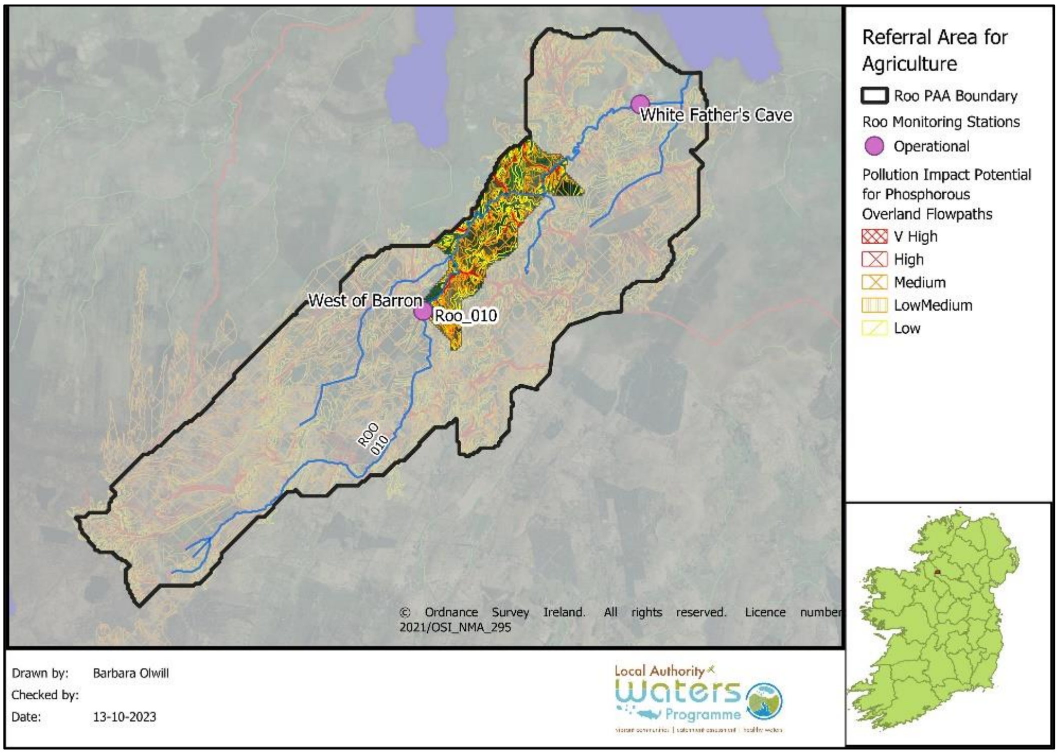


	1989	1993	1997	1998	2007	2010	2013	2017	2018	2019	2021	2022
Result	4	4.5	4	4	5	5	5	4	4	4	4	4
Classification	Good	High	Good	Good	High	High	High	Good	Good	Good	Good	Good
Q-Value	4	4-5	4	4	5	5	5	4	4	4	4	4

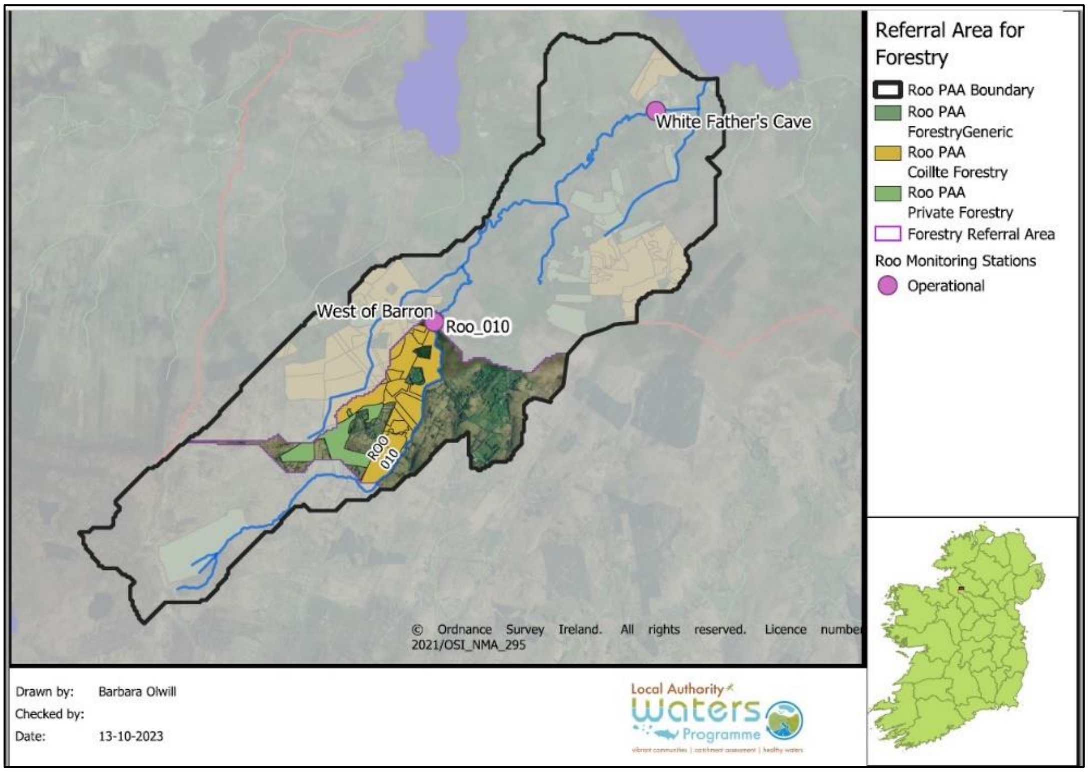
To view EPA River Quality Surveys please click on *View EPA River Quality Surveys*

Local Catchment Assessment Outcomes

Agriculture was identified as a pressure on the waterbody at the lower monitoring point at White Fathers Cave. An area of more intensive agriculture was identified and point sources and overland flows identified as pathways for nutrient and sediment loss to the river.



Forestry was identified as impacting on the upper stretch of the Roo upstream of the *High-Status Objective* Monitoring Station West of Barron. Sediment is the significant issue as a result of forestry felling.



The Roo river achieved *Good Status* in 2020 and the recent Q sample in 2022 remained at *Good Status*. It is currently considered ***Not at Risk***. Nutrient levels have fallen at White Father's cave but there is still further opportunity to reduce nutrients and improve the nutrient loading entering Lough MacNean lake by focusing measures in the Agricultural Referral Area. The ***Blue Dot*** High Status Objective monitoring point at West of Barron is still only achieving *Good Status.* Sediment continues to be a significant issue at this monitoring point.

Establishment of Groundwater Monitoring Stations in the Arney catchment

Due to the karstified nature of much of the Arney catchment, there is an abundance of karst springs in the catchment, transmitting large volumes of groundwater to the surface. Therefore, in the Arney Catchment most of the CatchmentCARE Groundwater Monitoring Stations (GWMSs) were established at springs rather than constructing new monitoring boreholes. Two pre-existing boreholes in the karst aquifer were also monitored (Figure 22)

Figure 22 Holywell and Cascades springs in the Arney catchment. (Data source: GSI)

A subset of about 30 springs (of 54 in the all-island karst database within the Arney catchment) was chosen for a field-based assessment. Each spring was visited and preliminary assessments including spot discharge and field physico-chemical parameter measurements were made. From this, 20 sites were chosen for monitoring of some type. They were chosen on the basis of spring volume, spring type, geology and aquifer type, location in the catchment, importance of spring and accessibility (see Figure 23).

Given the large outflow volumes of some of the karst springs, the karst aquifers have by far the greatest influence on surface waters. Therefore, most of the monitoring sites were focused on karst springs. However, to gain a contrasting groundwater signature, groundwater emergences from sandstones and shales were also monitored. Two pre-existing boreholes and three rivers in the catchment were also monitored. The details of the monitoring sites are listed in Table 2.

Continuous data loggers: The first stage of the monitoring was the installation of continuous data loggers at 19 sites, which in the majority of cases recorded electrical conductivity, temperature and water level.

Hydrochemical sampling: Sixteen of the springs were chosen for hydrochemistry monitoring. Six rounds were carried out in total. The same sites were not always sampled in each round due to seasonality of some of the springs. This resulted in 81 samples in total collected over a two year monitoring period.

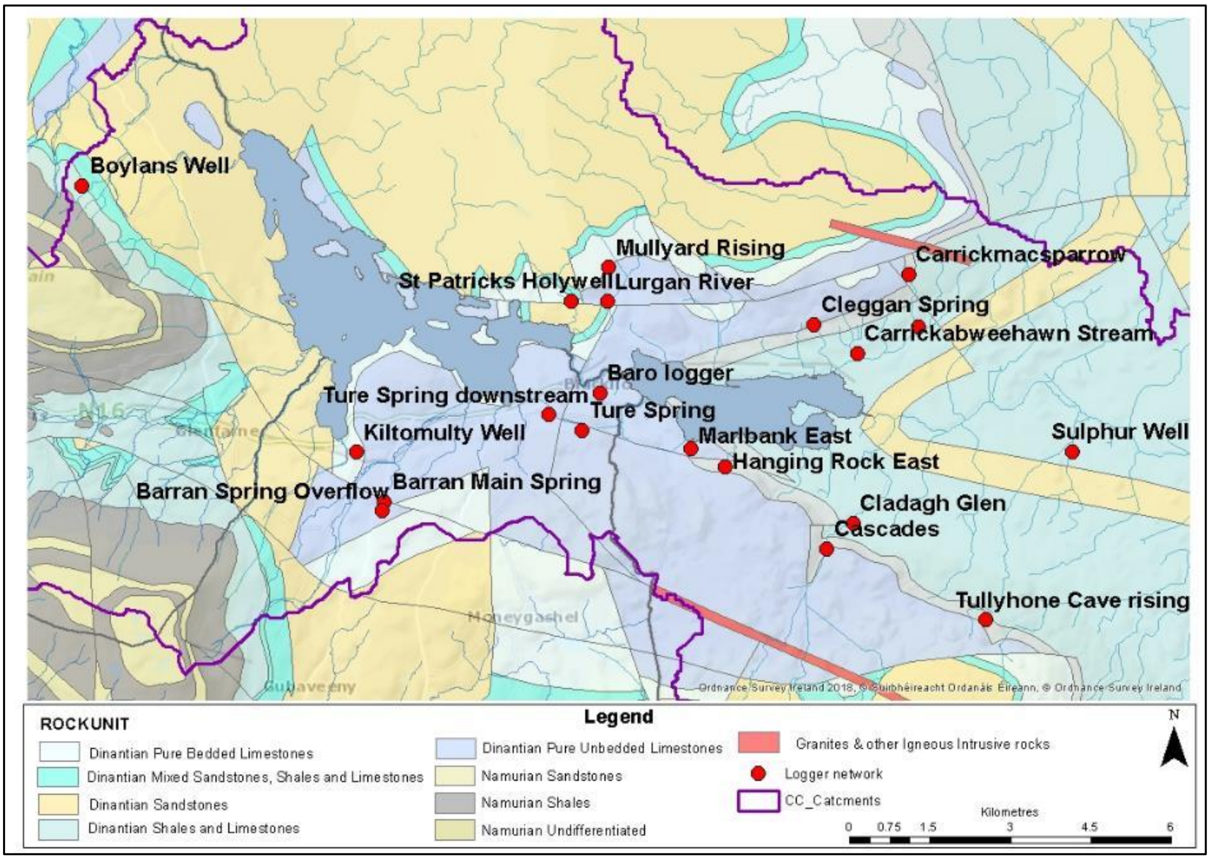


Figure 23 Locations of springs monitored in the Arney catchment. (Data source: GSI)

Spring discharge: A total of 15 different sites were measured for discharge as one of the 16 sites measured for hydrochemistry is a borehole and does not have an overflow. Several methods were used for calculating discharge. The most common method used was the area-velocity method. This involves measurement of the depth, width and velocity of the stream. The discharge is then calculated as: Discharge (Q) = area (A) x velocity (V), where area is the depth of water x width of channel or section, and velocity is length of travel per until of time. A bucket and stopwatch was used at some sites that were not suitable for the area-velocity method. As some springs were dry or didn't have a measurable flow during low flow periods, not all the same sites were monitored in each round. Seven rounds of spot discharge measurements were made over the course of one year. Further measurements are required to complete the ratings curves.

Table 2 Summary of the 19 Groundwater Monitoring Stations in the Arney Catchment

Spring	Grid Reference ITM	Reason for Monitoring	Logger in	Hydro-chemistry	Spot Discharge
Boylans well	598440 841926	In Dinantian shales at Pl/ Ll aquifer boundary	√	√	√
Kiltomulty BH	603545 836887	BH will give access to deeper aquifer possibly non conduit flow	√	√	
Barran Spring main	604082 835940	Large cave fed karst spring with tracing	√	√	√
Barran spring overflow	604020 835797	Connection with Barran spring?	√	√	√
Tuam spring	606060 837857	Possible epikarst / autogenic spring		√	√

Ture rising	607744 837250	Variable cave fed karst spring with tracing	√	√	√
Hanging rock spring	610337 836645	Large cave spring	√	√	√
Cladagh River	612775 834983	Large river made up of three resurgences including marble Arch Cave	√	√	√
Tullyhone Rising	615282 833761	Flashy cave rising with tracing	√	√	√
Sulphur Well	616927 836886	Sulphur well from the shales	√	√	√
Carrickmacsparrow Spring	613665 840278	From Belmore Mountain. Made up of at least 3 smaller springs. Signature from Belmore aquifers	√	√	√
Cleggan Spring	613354 839441	Lovely small spring. Possibly autogenic flow	√	√	√
Mullyard Rising in to Lurgan River	608304 840300	Fast flowing karst spring on north side of catchment	√	√	√
St Patrick's Holy Well	607555 839703	Biggest resurgence on the north side. Hydrogeology not fully understood	√	√	√
Mullaghdun	614362 839590	At least 3 small springs from Belmore Mountain, north side of catchment	√	√	√
Carrickabweehan	612723 838761	Made up of a few smaller springs on north side plus some overland flow	√		
Lurgan River	608224 839695	Large river on north side of catchment	√		
Marlbank East	609789 836952	Small stready spring emerging from Marlbank	√		
Marlbank West	608487 837218	Small stready spring emerging from Marlbank	√		√
Rahallan Stream	614056 839172	Made up of smaller springs on sandstone	√		

Groundwater hydrochemistry in the Arney catchment

The hydrochemistry sampling and preliminary analyses in the Arney was carried out by CDM Smith Ireland Ltd on behalf of the project and much of the following is taken from CDM Smith's hydrochemistry report for the Arney (Papageorgiou et all, 2023). The sites were monitored for the parameters which fall into three main groups:

1. Inorganic parameters: 52 parameters, including metals, major anions and cations, macronutrients (nitrogen and phosphorus species), physicochemical parameters;
2. Organic parameters: 103 parameters, including pesticides, and insecticides; and
3. Microbial parameters: *E. coli*, total coliforms and *Clostridium Perfringens*.

Overall, the groundwater sampled in the Arney catchment is calcium-magnesium bicarbonate (Ca-Mg-HCO_3) and mostly Ca-bicarbonate type, with the two non-karst sampling sites plotting in mixed type of groundwater (Boylans Well) and on the Na-K-HCO_3 type (Sulphur Well) (see Figure 24). This shows the dominance of the karst limestone aquifers on the monitoring stations.

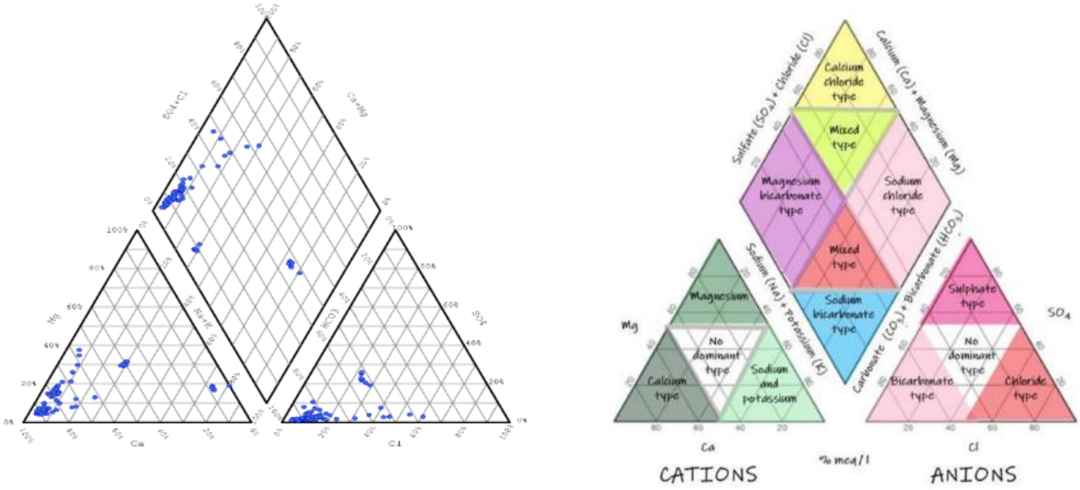


Figure 24 Piper diagram of all samples in the Arney (source CDM Smith, 2023)

The results indicate that the water quality in the Arney Catchment is mixed with some exceedances of Water quality Standard (WQS) present throughout the sampling rounds. Table 3 shows the location of these exceedances and is coloured according to the frequency of exceedance, with yellow fill indicating relatively few exceedances of the relative threshold (1 exceedance only) and orange fill indicating higher numbers of exceedances (2 of more exceedances).

Some of these elevated concentrations, such as sodium, potassium, barium and iron bearing minerals, may be due to the naturally occurring aquifer hydrochemistry. For example, Sulphur Well, which is found in the Bundoran Shale Formation, has consistently high values for sodium, chloride, fluoride, sulphate and low calcium.

Table 3 Water quality exceedances in the Arney Catchment by frequency (source CDM Smith, 2023).

Parameter	Manganese	Specific Electrical Conductivity	Ammonia	Fluoride	Sodium	Ortho-P	Chloride	Potassium	Iron	Barium	Arsenic	
Barran Spring												
Barran Spring 2												
Boylans Well												
Cladagh River												
Hanging Rock												
Kiltomulty Borehole												
Marlbank West												
Mullyard Spring												
Mullaghdun Spring												
Sulphur Well												

However, some exceedances are likely to be related to land use practices occurring near the spring or within its catchment. Fluoride is relatively rare naturally and can be associated with domestic waste-water treatment systems. However, it is known to be naturally elevated in groundwaters across a swathe of Monaghan and Cavan. It was found in high concentrations throughout the catchment but especially at Sulphur well, Boylans well and Clagadh River (up to over 10,000 times the EQS in Sulphur well). Elevated ammonia, ortho-phosphate and potassium may be associated with fertiliser use. Elevated ammonia was found in every sample taken from Boylans well, which is found up in forestry land, and sulphur well, which is found in agricultural land. Kiltomulty borehole, which has elevated ammonia in 5 out of the 6 samples is located beside a large farmyard and agricultural sheds.

Microbial parameters *E. coli*, total coliforms and *Clostridium Perfringens* were monitored at all spring locations during the last four monitoring events (i.e. monitoring event 3 through 6).

There were detections of microbial parameters of microbial parameters at all locations during all monitoring events (Table 4). This is to be expected in karst springs as they are highly vulnerable. Total coliforms are naturally present in soils and do not in themselves indicate an anthropogenic input. *E. coli* and *Clostridium perfringens,* however, indicate contamination with human/animal waste.

Table 4 Summary of exceedances of microbial parameters at each spring

	Total coliforms		*E. coli*		*Clostridium perfringens*	
Spring name	No detections	% detections	No detections	% detections	No detections	% detections
Barran Spring	4	100%	4	100%	4	100%
Barran Spring 2	4	100%	3	75%	3	75%
Boylans Well	4	100%	1	25%	0	0%
Carrickmacsparrow	2	50%	2	50%	2	50%
Cladagh River	4	100%	4	100%	4	100%
Cleggan Spring	1	25%	1	25%	1	25%
Hanging Rock	4	100%	4	100%	3	75%
Holywell Rising	4	100%	2	50%	2	50%
Kiltomulty Spring	3	75%	1	25%	2	50%
Marlbank West	3	75%	3	75%	2	50%
Mullaghdun Spring	4	100%	4	100%	4	100%
Mullyard Rising	2	50%	2	50%	2	50%
Sulphur Well	3	75%	2	50%	1	25%
Tuam Spring	4	100%	4	100%	4	100%
Tullyhone Rising	4	100%	4	100%	3	75%
Ture Rising	3	75%	3	75%	3	75%

There were no detections of MCPA or any other organic parameter monitored.

In summary, the data indicate that groundwater in the Arney catchment is affected by anthropogenic practices and that the main pollution sources appear to be coming from agriculture and domestic waste water treatment. Cladagh River and Kiltomulty borehole have the most exceedances of water quality.

Continuous hydrochemical monitoring:

As previously stated, data loggers were deployed at 19 out of the 20 locations (Figure 23 and table 3) as Tuam spring was not suitable for a datalogger. 18 of these were CTD loggers which record electrical conductivity, temperature and level at specific intervals. A barometric logger was also placed in the centre of the catchment. To reduce the number of monitoring sites, springs were grouped, where possible, with a logger installed downstream where the springs converged. (For example, the loggers for Carrickabweehan, Carrickmacsparrow and Cladagh Glen were monitoring the flow from a cluster of springs upstream.) The continuous loggers were installed at each site in February and March 2020, with the exception of three locations that were monitored subsequently. Some loggers were placed in the spring by the use of a specially made weighted logger housing which secured the logger in the resurgence.

Classically, due to their high degree of heterogeneity, the understanding of the hydrogeology of karst aquifers relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterise the karst as a whole entity. Discharge time series analysis, using several tools (spectral analysis, recession curve analysis) as well as additional hydrochemical parameters, such as temperature, electrical conductivity (EC), and others, provide information about the karst hydrodynamics and vulnerability and can be used classify karst aquifers.

Water that passes quickly through the limestone (conduit water) is characterised by a relatively low calcium carbonate content, but has relatively high variations in its chemistry and temperature. Water that percolates slowly through diffuse pathways in the limestone mass contains a relatively high calcium carbonate content and has little variation in calcium carbonate content or in temperature.

Figure 25 shows the response of the Cladagh River to an isolated rainfall event. The Cladagh River, which is fed by a combination of springs discharging from caves such as Marble Arch, is extremely flashy with little storage. The main spring emerging is fed from three sinking rivers: the Sruh Croppa, the Aghinrawn and the Owenbrean, all of which sink into limestone on the Cuilcagh Mountain and join up underground in the Marble Arch Cave system. In this event the system starts to respond within 10 hours, with the time from the peak rainfall to the lowest point in EC being 14 hours. The time for the system to recover from this rainfall event is estimated as five days. This contrasts some of the other springs, such as Boylans well, in the sandstone aquifer, which do not show any response to individual rainfall events.

The results of different analyses demonstrate the dominance of karst processes in the springs of the Arney catchment, with exception of the non-karst wells. Shuster and White (1971) argued that springs showing a high coefficient of variation of water hardness, usually described as CV of EC, (>10%) drained aquifers dominated by conduit flow, whereas those with low variation (<5%) drained aquifers characterised mainly by diffuse flow. All the karst springs monitored in the Arney catchment have CV of EC values in excess of 10%, many much higher (Figure 26)

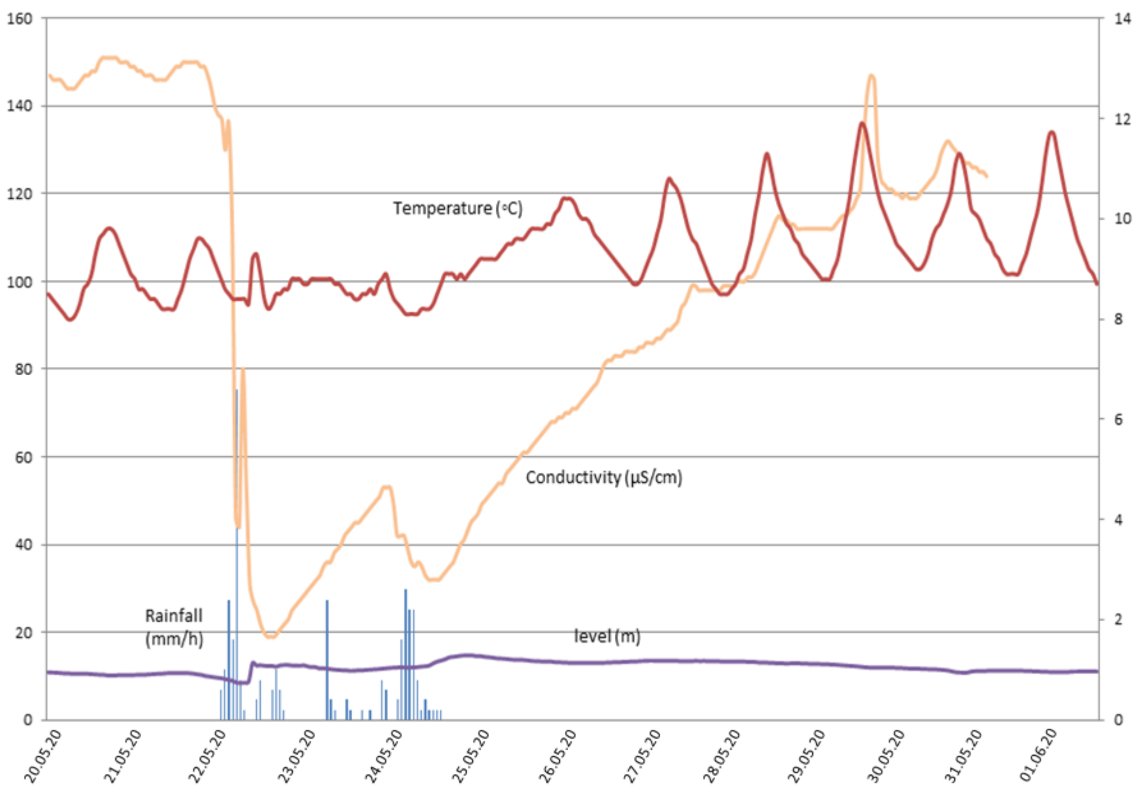


Figure 25 Cladagh River hydrograph and chemograph showing a rapid response to hourly rainfall (hourly rainfall data provided by AFBI from their dedicated rainfall station established in the Arney Catchment).

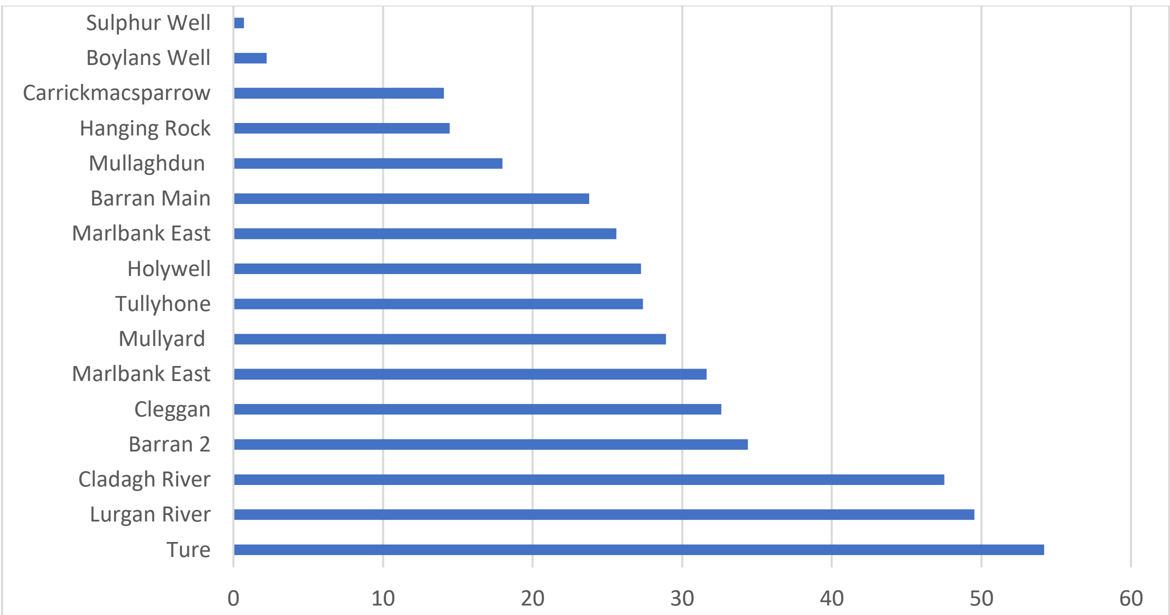


Figure 26 Coefficient of variation of specific conductivity for monitoring sites in the Arney catchment

The statistical spread of hydrochemical parameters of the time series was found to be a more useful tool in classifying the karst springs in the Arney catchment. The range and variability in temperature and water level were both useful methods to understand the hydrodynamic functioning of the karst springs. However, analysis of electrical conductivity (EC) values was found to be the most insightful. Figure 27 shows a box and whisker plot of EC values for the monitoring sites in the Arney catchment.

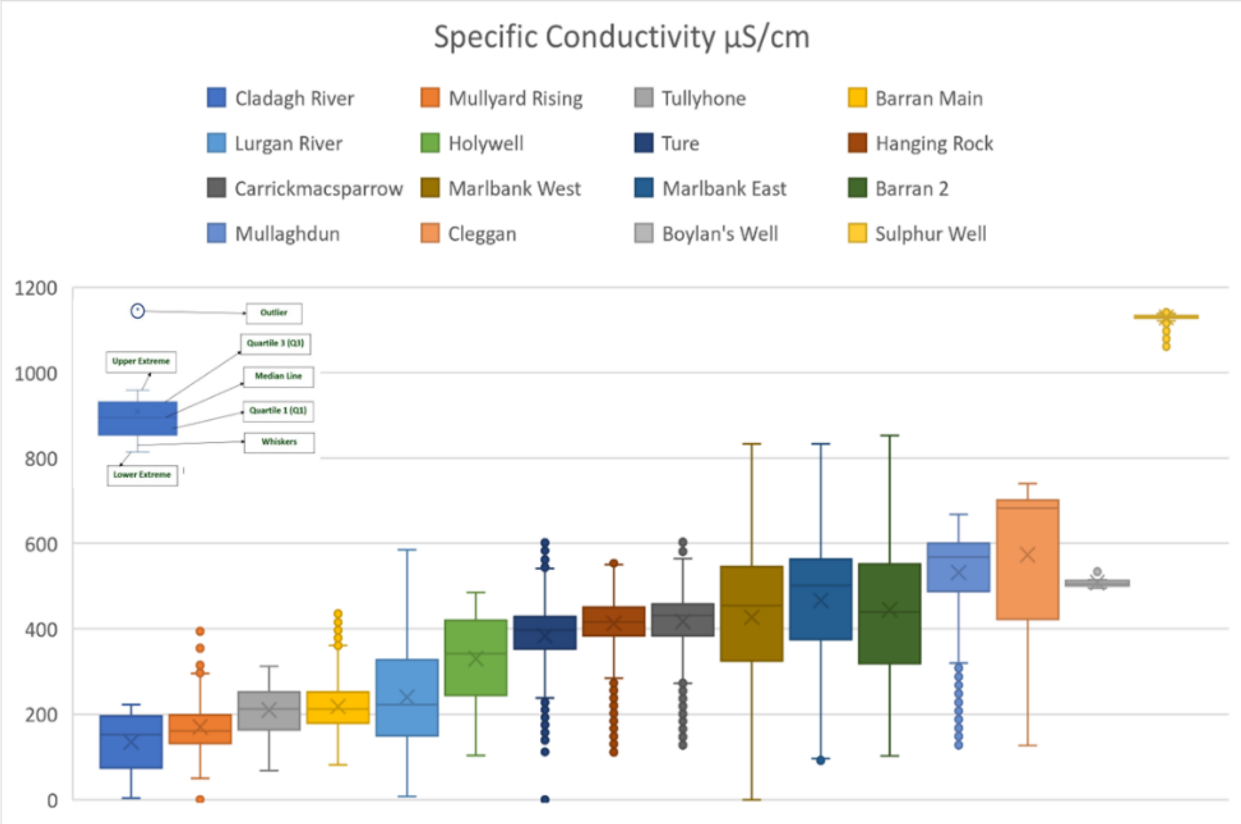


Figure 27 box and whisker plot of electrical conductivity values of selected springs in the Arney catchment

The springs are ordered in terms of their mean and range in values of EC. The two non karst springs, Boylans well and Sulphur well are plotted at the end for comparison. The influence of the composition of recharging water to each spring is seen to have a great influence on their distribution of EC values. The springs to the left of the plot are most influenced by allogenic recharging waters – such as Cladagh River. Here the dominance of relatively low EC values can be seen. This is considered the dominant source of recharging waters up to and including Barran Main spring. This group includes the Lurgan River.

The next group ranges from Holywell up to Carrickmacsparrow and indicates a more mixed recharging regime. The mean values are slightly higher than the more allogenically fed springs. The last group in general, have much higher EC values and this indicates that they are generally fed by autogenic / epikarst or more local waters. Figure 28 shows some of the water tracing experiments to some of these monitoring sites. The water tracing backs up the classification based on statistical analysis of EC values.

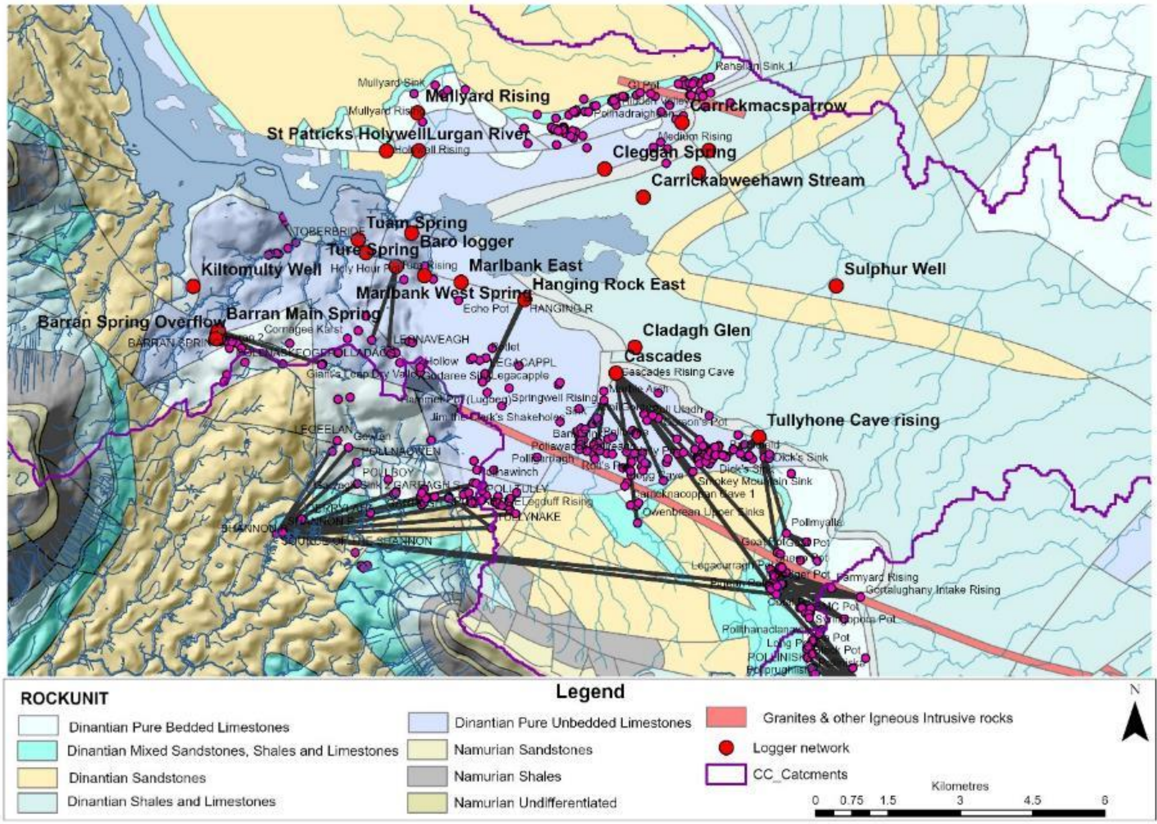
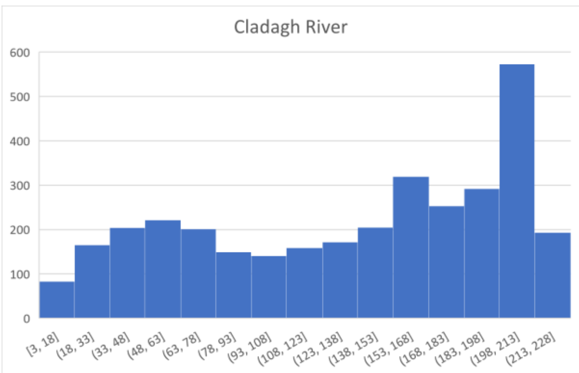
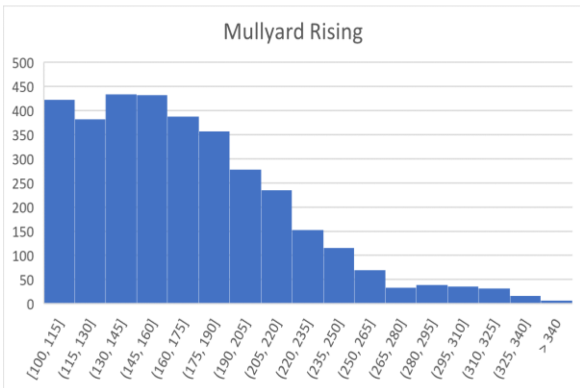
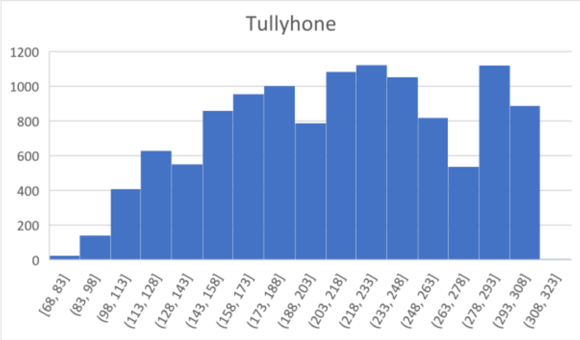


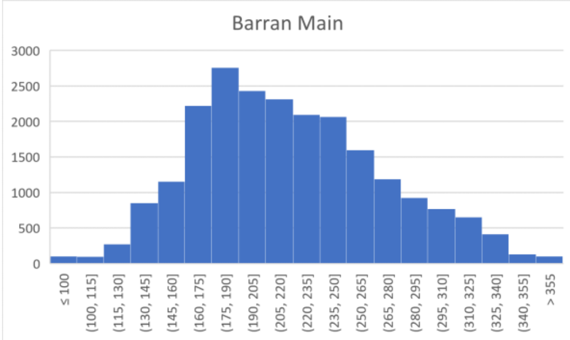
Figure 28 Water tracing experiments to monitoring site

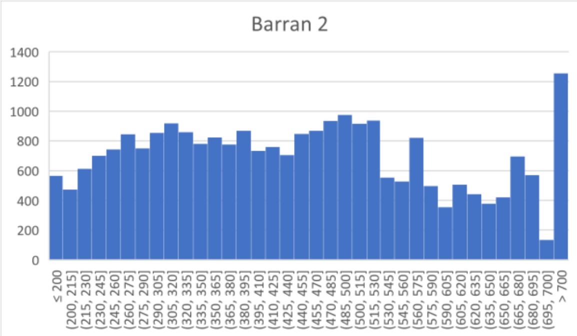
Another commonly used method of analysis of karst spring flow data is the study of frequency distribution of various hydrochemical parameters, in particular electrical conductivity. Figure x shows the frequency distribution of electrical conductivity of the karst springs in the Arney catchment. The shape of the histogram shows the distribution of frequencies of EC values in various groups or 'bins'. The series of histograms in the following pages show different ranges in EC values but each have the same bin width for comparison.

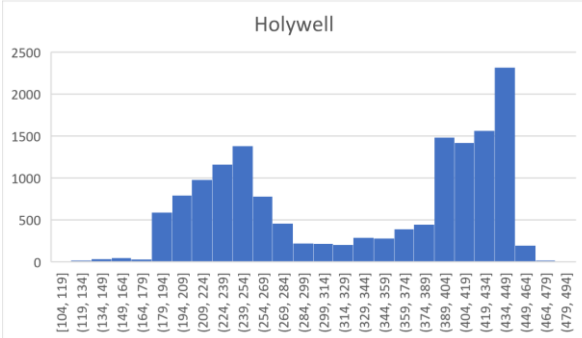


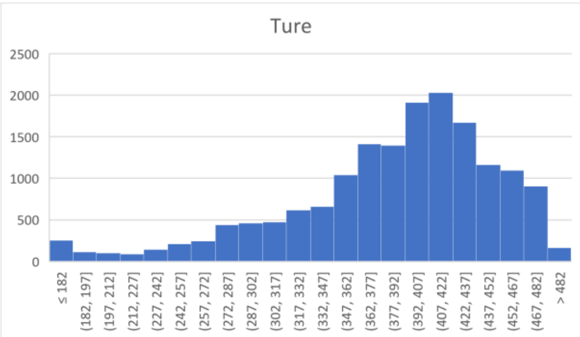


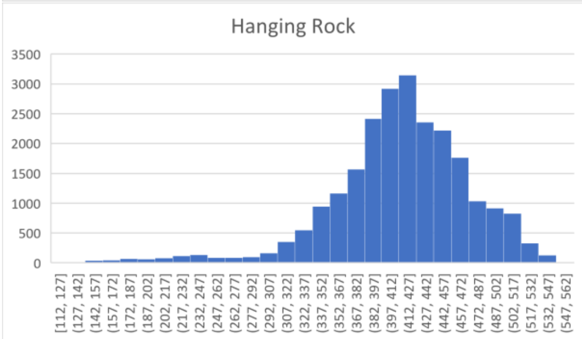

Tullyhone

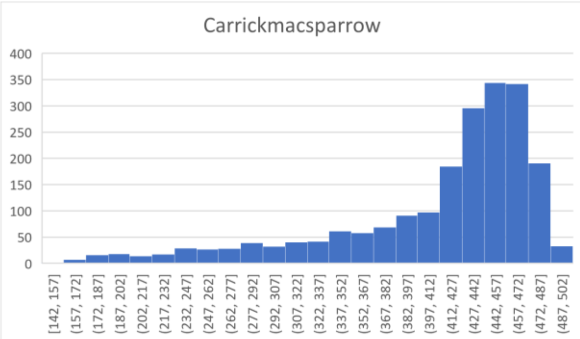

Barran Main

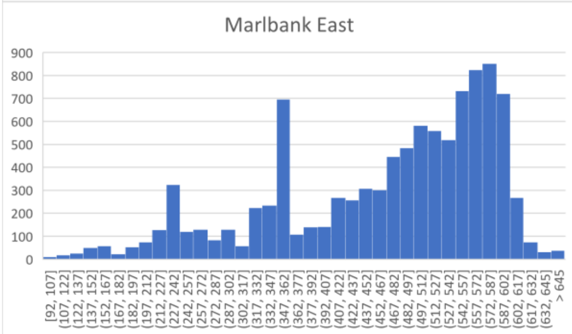

Barran 2

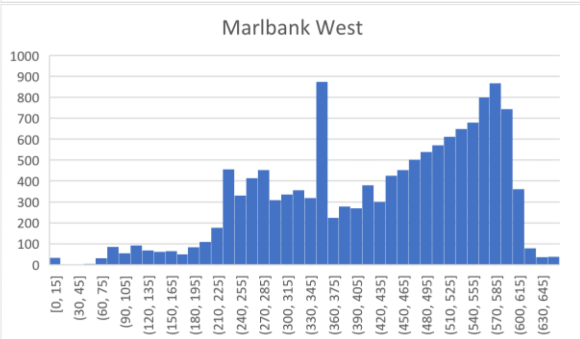

Holywell

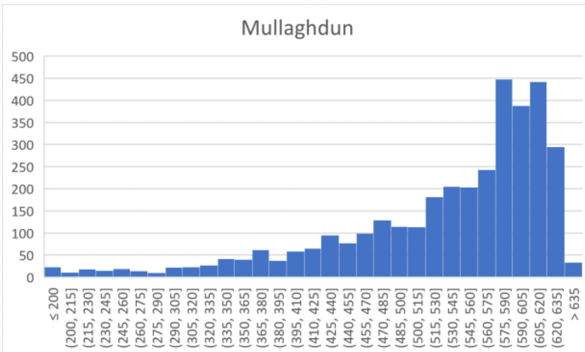

Ture

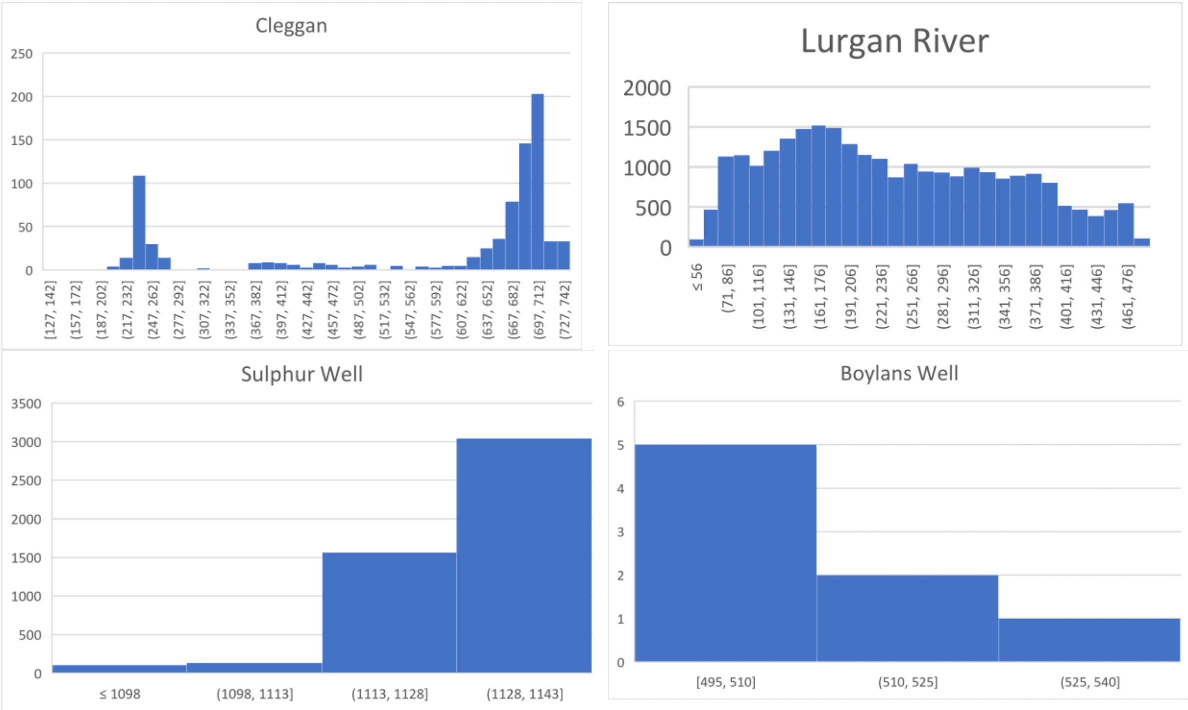

Hanging Rock


Carrickmacsparrow


Marlbank East


Marlbank West


Mullaghdun



The dominance of the low EC values for Cladagh River, Mullyard Rising can be clearly seen. Interestingly, the Cladagh River shows a bimodal distribution, indicating the influence of sporadic and very low mineralised flow. The dominance of the higher EC values for sites like Hanging rock and Ture may initially seem somewhat surprising as these are springs emerging from large caves and they have been traced, to indicating rapid flow. However, Figure 29 shows that the sinking streams are mostly and autogenic, therefore, it is suggested that do not greatly influence the chemical composition of the springs. It may also be that they make up a smaller proportion of the water emerging at the spring.

The hydrodynamic functioning of some poorly understood sites is also revealed by frequency distribution analysis. For example, the hydrogeology of Holywell was not well understood, and it was not clear whether this functioned as a 'true' karst spring. Looking at the frequency distribution of EC it can be seen that there is a clear bimodal distribution, indicating a mix of origin of recharging waters, with a fast and slow flow element. This is also seen in Cleggan spring, which was suspected as being solely an epikarst spring. However, it can be seen that there is some element of faster flow recharging this spring at times.

Both the box and whisker plots and the frequency distribution for Marlbank East and Marlbank West are very similar, indicating similar hydrodynamic properties. This was suspected but never actually demonstrated before now.

Another spring duo that was not fully understood before this project was the Barran springs (see Figure 3). The main spring, referred to as 'Barran main' is a medium to large karst spring. Nearby is a much smaller spring, referred to as 'Barran 2'. It was thought that this smaller spring may function as an overflow spring to the main spring, as is quite common in karst aquifers.

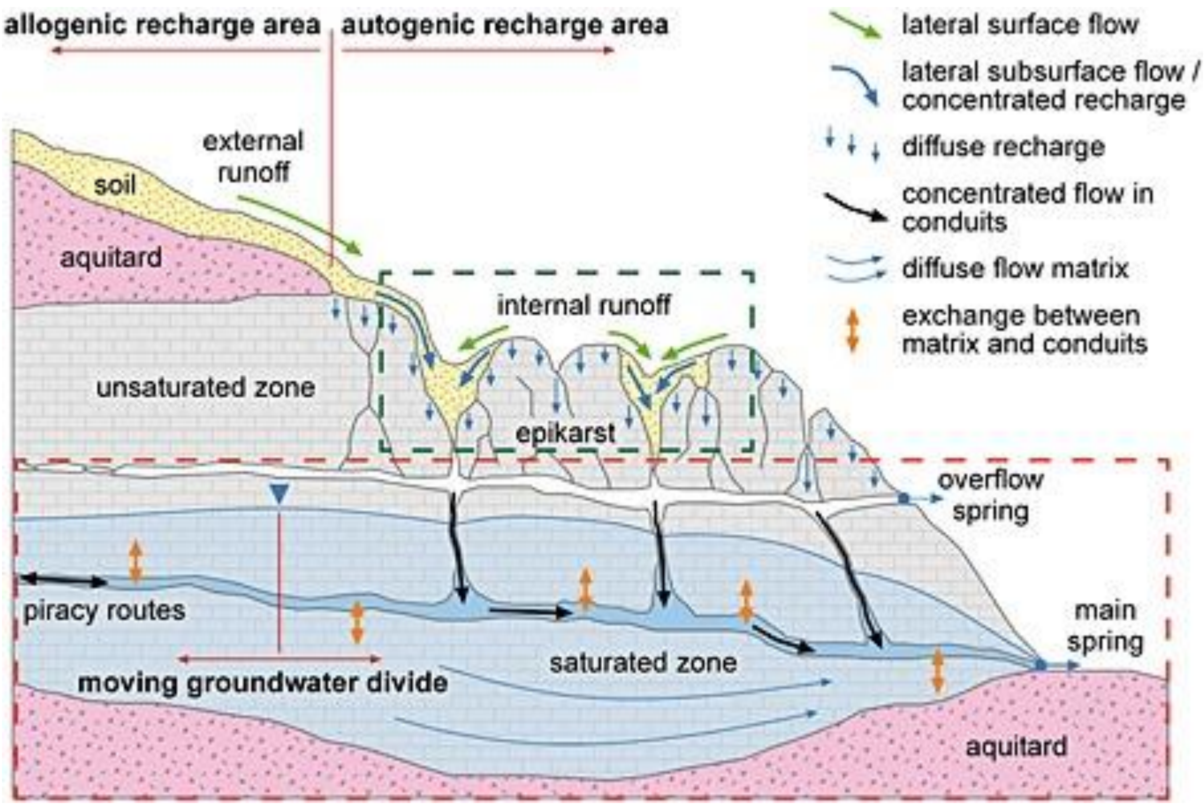


Figure 29 A conceptual model for an underflow and an overflow spring, modified from Hartmann et al, 2016

Figure 30 Location of Barran Main (~78 mOD) and Barran 2 (~82 mOD).

The Barran springs emerge in two nearby fields (see Figure 31). The fields around the spring are used for agricultural activities, predominately grassland with some areas of scrub that appear quite poorly drained. Karst landforms such as dolines, sinkholes and sinking streams are common the surrounding fields and help with the land drainage. A large forested area is planted on the poorer higher ground some 200 m to the east.

The main spring gives rise to a stream which flows in a northerly direction and is one of the tributaries of the Roo River. Approximately 900 m downstream the Barran Stream joins the Roo River and continues northeast until it eventually flows into Upper Lough Macnean. The Roo River flows underground in White Fathers Cave for a few hundred meters before surfacing again and flowing into Upper Lough Macnean.

The spring is fed from the east and numerous sinking streams flowing from the western flank of the Burren and Giant's leap have been dye traced to the spring. The water from Barran 2 sinks just under the surface and also emerges at this spring (Barran Main).

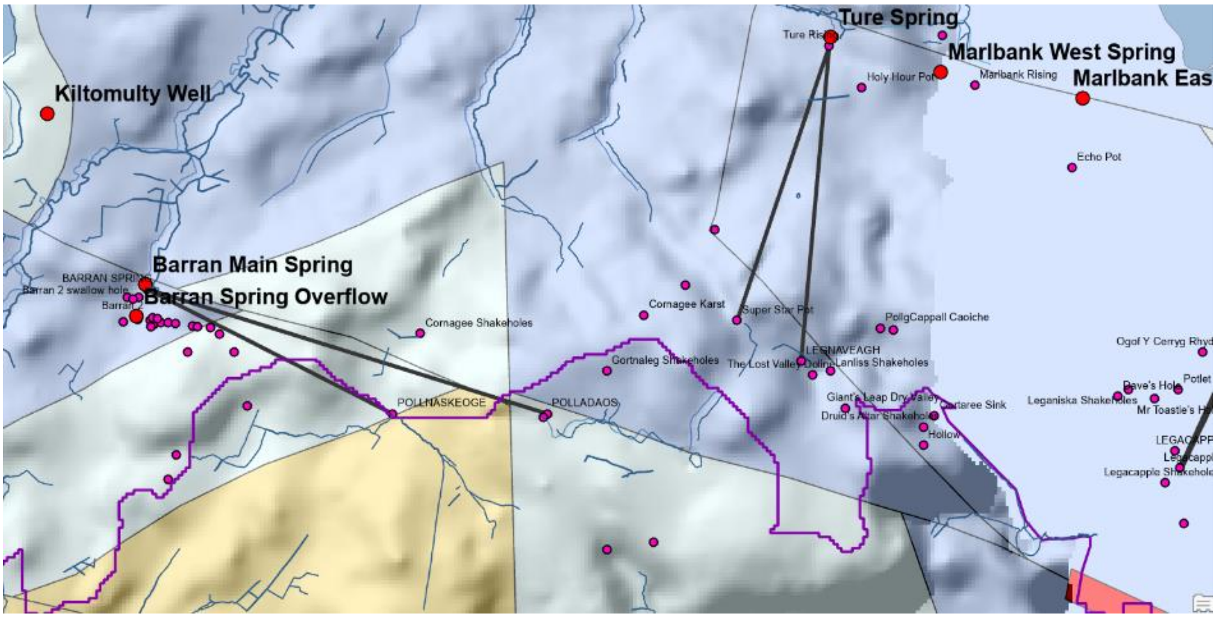


Figure 31 tracing and karst landforms around the Barran spring complex

Analysis of the box and whisker plots for these two springs demonstrates that they are quite different in terms of their make-up. The frequency distribution of EC for the two springs is plotted in figure 32 below and clearly shows the differences in the EC values at the two springs. The EC values for Barran Main rarely rise past 350 µS/cm. In contrast, Barran 2 has much higher EC values and may indicate that this is predominantly an epikarst spring.

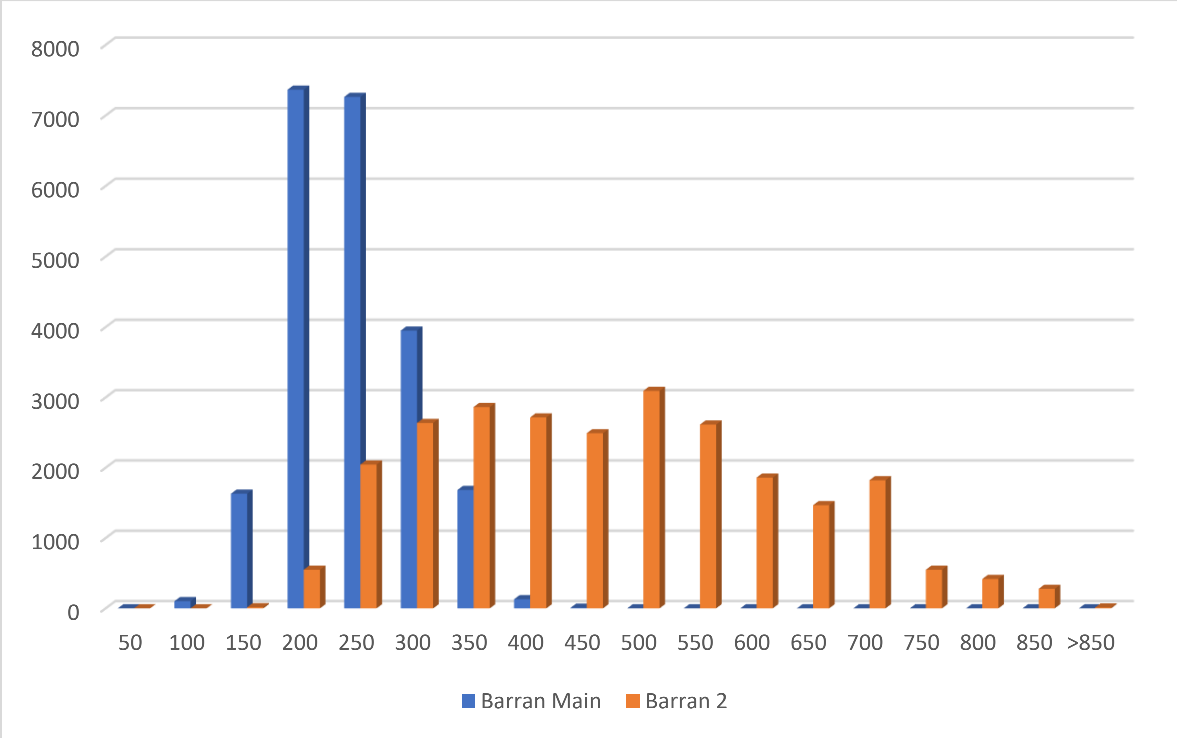


Figure 32 Histogram of frequency distribution of EC at Barran Main and Barran 2

Analysis of the spring hydrographs show that there are some rapid drops in EC values, in both springs as water levels rise due to rainfall. Figure 33 shows an immediate drop from the normally high EC values found at Barran 2. This indicates that there are elements of rapid recharge entering the spring at Barran 2 but these episodes are sporadic and short lived.

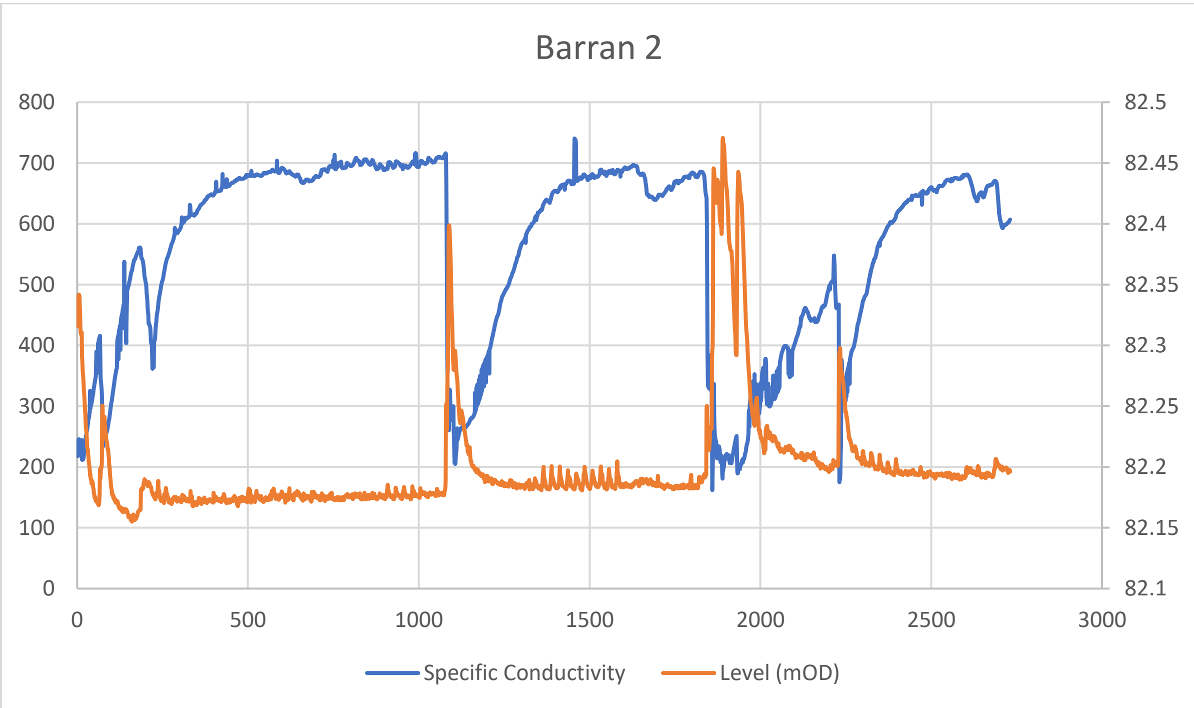


Figure 33 Spring hydrograph and chemograph for Barran 2 showing rapid response to rainfall events

Figure 34 shows both these spring hydrographs plotted in response to rainfall. It can be seen that Barran 2 reacts slightly faster to the rainfall events that Barran Main. This may suggest that the freshwater pulse at Barran Main has further to travel than at Barran 2 and may indicate a more local source of recharge at Barran 2. This may be from the nearby karst features, whereas, Barran Main has been traced to from sinking streams several kilometres away.

From looking at the hydrographs we can also ascertain lag or response times to rainfall events, as well as recession. Looking at how long it takes for EC to recover is a better gauge of the response of the system than just looking at level alone (see Figure 34).

Table 5 shows the lag and recession times for Barran Main and Barran 2 and these further reinforces the different recharge mechanisms for the two springs.

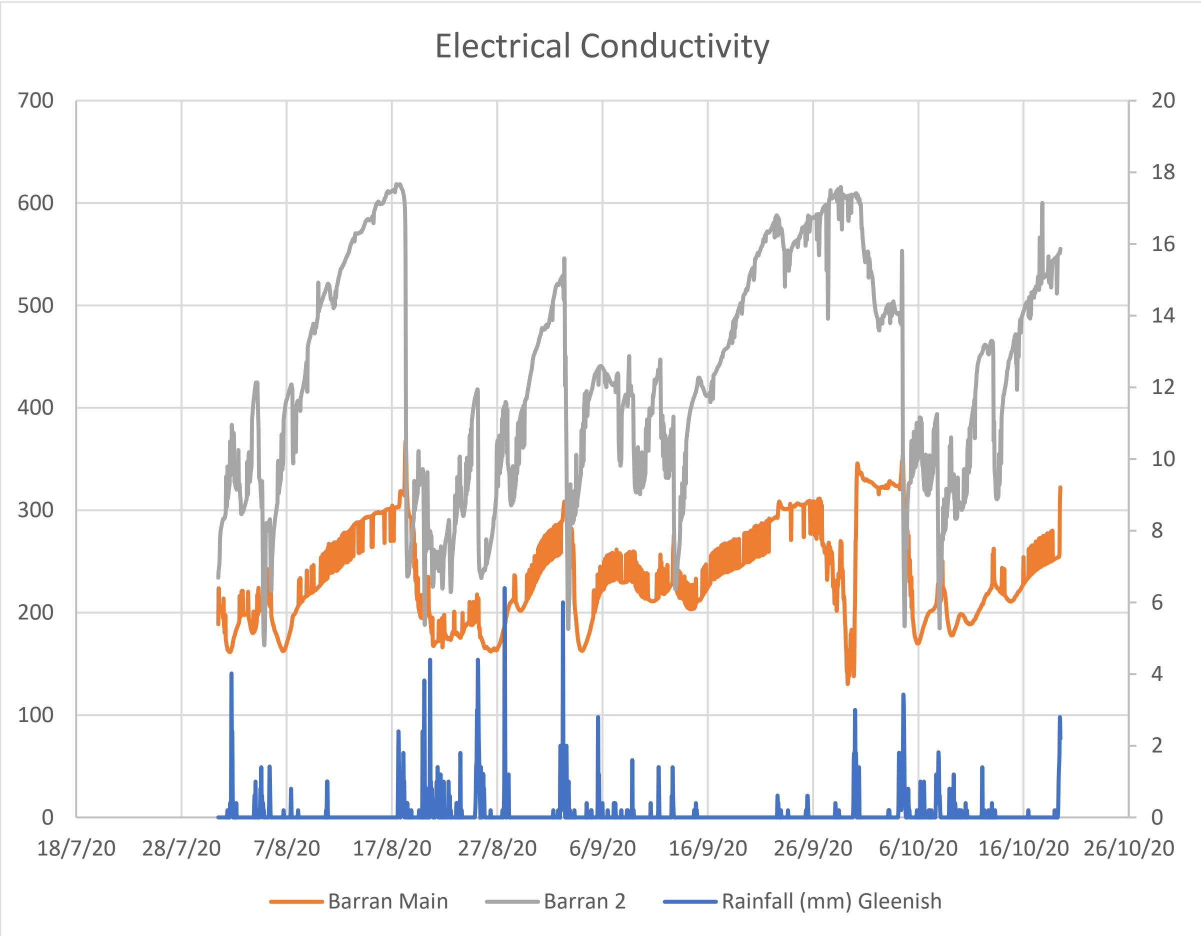


Figure 34 Barran Main and Barran 2 electrical conductivity chemographs

Table 5 Lag and recession times for Barran Main and Barran 2

Spring	Average response to rainfall event	Average total recession time
Barran Main	30-33 hrs	16 – 17 days
Barran 2	9-12 hrs	16 – 17 days

Spring discharge analysis

Several methods were used for calculating discharge. The most common method used was the area-velocity method. This involves measurement of the depth, width and velocity of the stream (see Figure 35). The discharge is then calculated as: Discharge (Q) = area (A) x velocity (V), where area is the depth of water x width of channel or section, and velocity is length of travel per until of time.

A bucket and stopwatch were used at some sites that were not suitable for the area-velocity method. As some springs were dry or did not have a measurable flow during low flow periods, not all the same sites were monitored in each round. Seven rounds of spot discharge measurements were made over the course of one year. Further measurements are required to complete the rating curves.

Figure 35 CDM Smith measuring discharge at Cladagh Bridge by dividing the channel up into sections.

Karst springs are the most 'flashy' springs, varying in size often by orders of magnitude in a single recharge event. Analysis of karst springs discharges can indicate how variable a system is. It can also reveal underflow and overflow springs. Figure 36 shows the coefficient of variation of discharge of the springs in the Arney catchment, ranked from high to low. Somewhat surprisingly, the most variable in terms of discharge is Barran 2 spring. However, as this spring dries up frequently this unduly influences the coefficient of variation. However, the relatively high variation in discharge fits with the theory that this spring acts an epikarst spring, which normally discharges small amounts of epikarst flow but which gets inundated by rapid flow from time to time.

The next highest variability of discharge are all springs which are known to be fed from sinking streams, with the exception of Cleggan. This is also thought to be an epikarst or generally more diffuse fed spring so may function similarly to Barran 2.

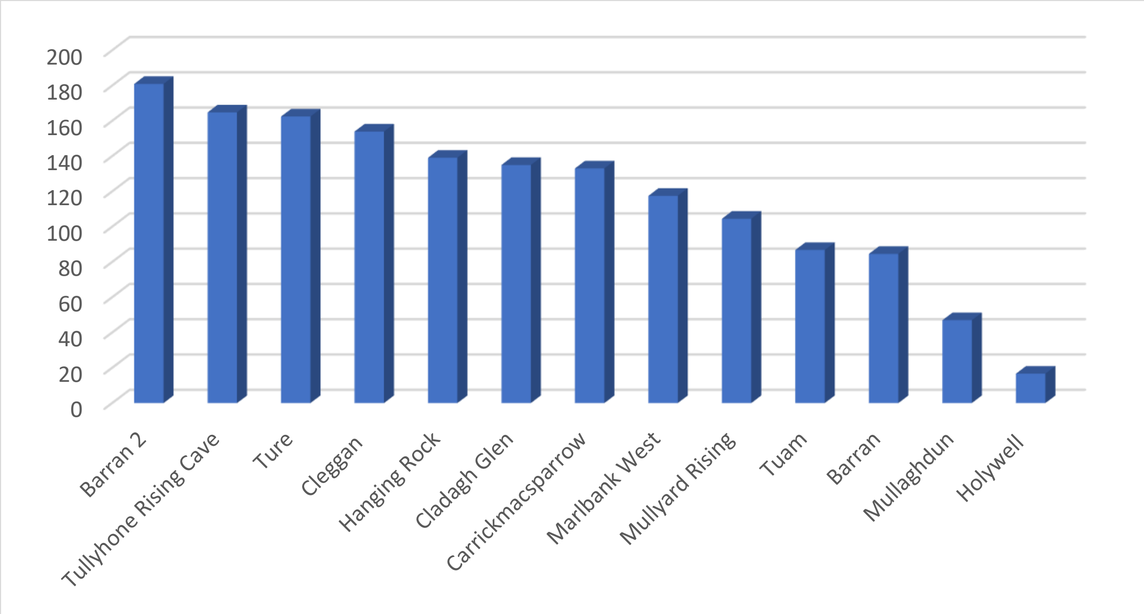


Figure 36 Coefficient of variation of discharge of springs in the Arney catchment.

Box and whisker plots summarising the statistical analysis of discharge are thought to be a more useful way to demonstrate the size and variability of the discharges of the springs. The size and range of discharge at Cladagh Glen dwarfs the other springs, and indeed much of the catchment area around it. Figure 37 shows the same information but with Cladagh Glen removed. Similar to that observed at Cladagh Glen, the large discharges and discharge ranges of the springs fed by sinking streams are obvious; Ture, Barran Main, Hanging Rock, Tullyone and Mullyard Rising. The more diffuse or epikarst springs are much smaller in terms of size and variability of discharge.

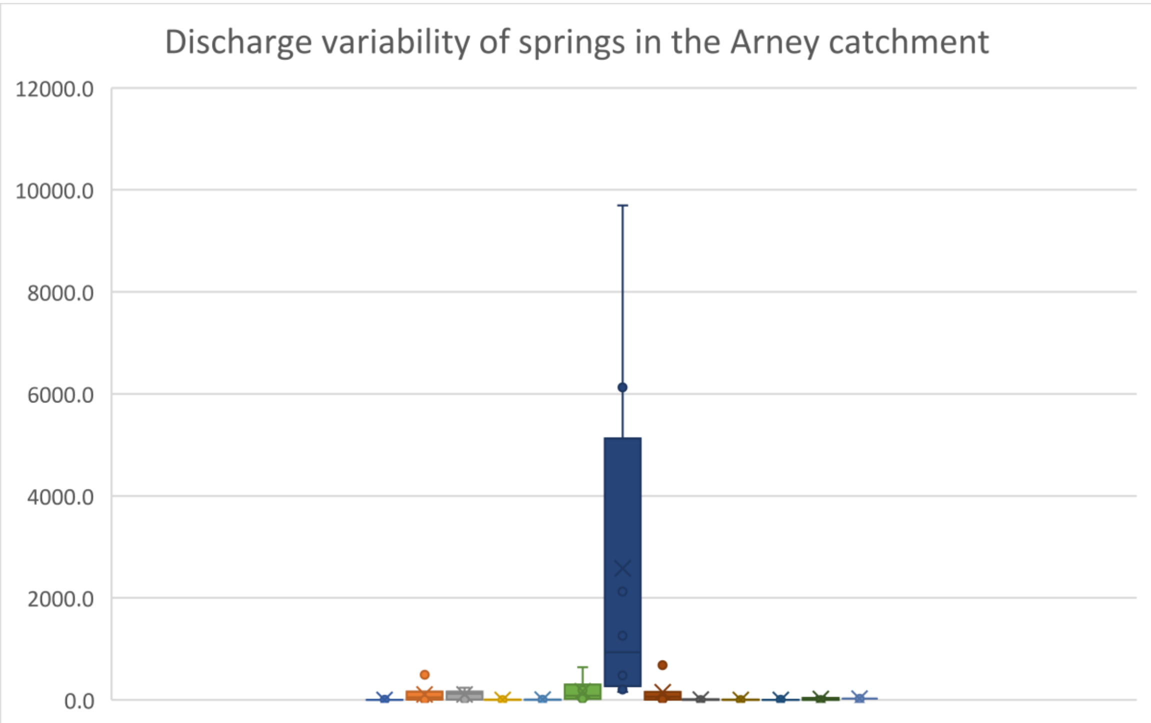


Figure 37 Box and whisker plot showing statistical summary for the springs in the Arney catchment. Note the dominance of the Cladagh Glen in terms of discharge

Box and whisker plots summarising the statistical analysis of discharge are thought to be a more useful way to demonstrate the size and variability of the discharges of the springs. The size and range of discharge at Cladagh Glen dwarfs the other springs, and indeed much of the catchment area around it. Figure 38 shows the same information but with Cladagh Glen removed. Similar to that observed at Cladagh Glen, the large discharges and discharge ranges of the springs fed by sinking streams are obvious; Ture, Barran Main, Hanging Rock, Tullyone and Mullyard Rising. The more diffuse or epikarst springs are much smaller in terms of size and variability of discharge.

Interestingly, Holywell spring, with a relatively large overall mean discharge has very little variability in discharge. The bimodal distribution of the histogram for Holywell suggests a dual recharge system feeding it but analysis of discharge suggests little variability in terms of flow and response to rainfall of the recharging waters. It could also be due to conditions at the spring, such as a gravel lens, dampen the response to rainfall. There are till deposits mapped around the spring described as having low permeability and being between 3 to 10m thick. Further investigations are required to understand this.

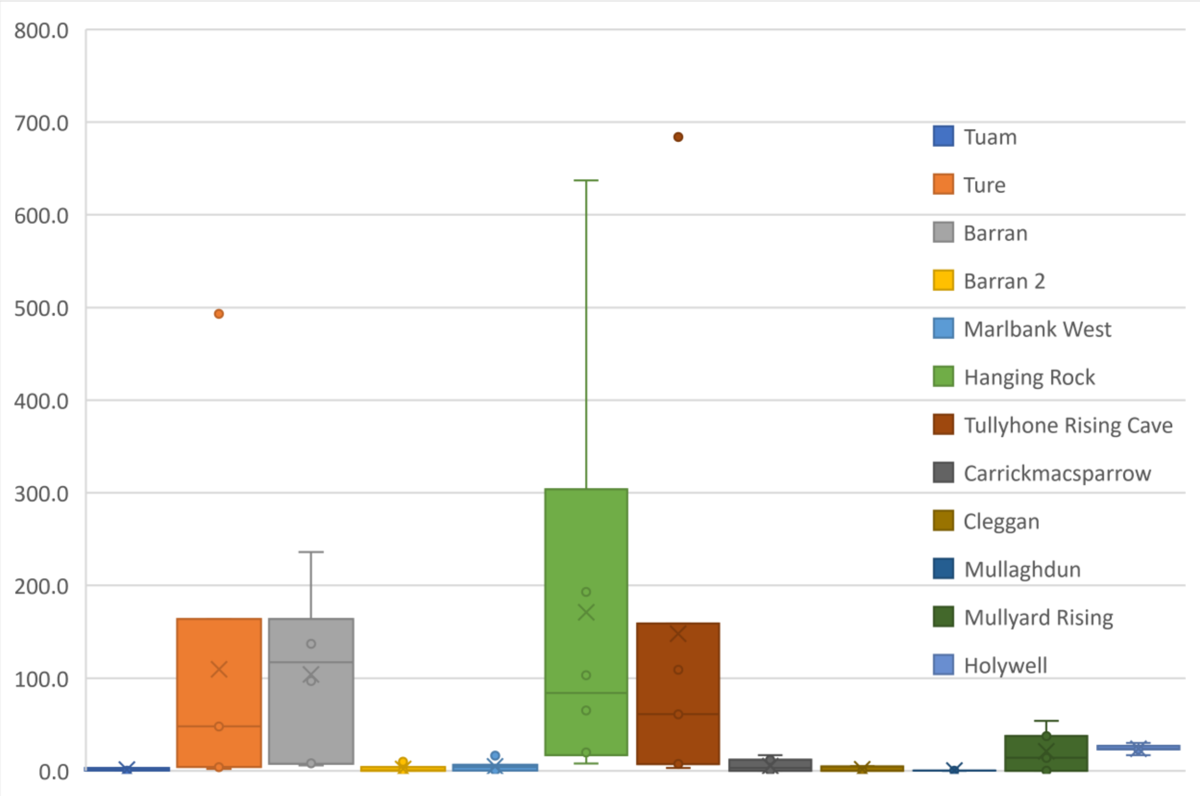


Figure 38 Box and whisker plot showing statistical summary for the springs in the Arney catchment with Cladagh Glen removed.

The combination of continuous water levels and spot flow discharges will allow rating curves to be developed for each site. A rating curve is a graph of discharge (usually obtained periodically) plotted (usually on x-axis) against stage (usually on the y-axis). This establishes the relationship between stage and discharge over a range of stage conditions for a specific site.

Having a continuous record of stream discharge is critical to understanding the function of a stream or river. It can be used to calculate e-flows, understanding and protecting ecosystem processes, estimate loadings for water quality assessments, forecasting floods droughts, designing engineering structures such as bridges, embankments, water storage or treatment facilities, hydrological research and understanding the functioning of a river catchment.

2. Overview of the Blackwater Catchment

Introduction

The Blackwater catchment lies in the Neagh Bann International River Basin District. It includes parts of Counties Armagh, Tyrone and Monaghan. The Blackwater catchment covers an area of 1,491 km^2 of which about three-quarters are in NI and one-quarter within Ireland.

The Blackwater River takes a meandering path south from where it rises in County Tyrone, flowing east and north, where is discharges into the southwestern part of Lough Neagh. The Blackwater forms the boundary between Ireland and Northern Ireland for more than a quarter of its 91 km length. Flows in the Blackwater have been influenced by major arterial drainage schemes that started in 1983 and finished in 1995.

The Blackwater catchment was chosen as one of the three CatchmentCARE study catchments due to the Poor status of many of its surface water bodies under the 2nd Cycle (2015-2021) of the Water Framework Directive (WFD). The WFD assessments by EPA and NIEA had identified nutrient enrichment and hydromorphology as failing elements in this waterbody. The lake to which the Blackwater discharges is struggling, as evidenced by the algal blooms reported on in the media in the early autumn of 2023. Following a comprehensive selection process in 2017, the Mountainwater subcatchment was identified by LAWPRO as a WFD Priority Area for Action in the WFD 2nd Cycle. It has High status headwaters, but the High status middle reach declined to Good in 2015.

Landscape and surface waters

The Blackwater River rises to the north of Fivemiletown in County Tyrone (see Figure 39). The upper Blackwater flows through the broad valley between Slieve Beagh and Brougher Mountain. It is fed by a large number of tributaries, and their meandering routes are influenced by the drumlin topography of the region. The Blackwater discharges to Lough Neagh 91 km after it rises.

The maximum altitude in the catchment is 382 m at Slieve Beagh, and approximately half of the catchment is above 100 m AOD. Much of the catchment is typified by lowland undulating topography with river corridors meandering through an extensive drumlin landscape. The Clogher Valley in the southwest of the catchment is considered to be a fine example of an undisturbed fluvio-glacial landscape. Wet marshy areas, fens, basin peats and lakes are abundant between the drumlins.

Drumlins are separated by pasture and gently rolling mixed farmland. To the south-west, towards Augher and Clogher, much of this area has been drained to produce good agricultural land, and arable fields are interspersed with pastures. Grasslands, almost all improved pasture, account for a high proportion of the catchment land cover. Rough grassland dominated by rushes occurs in inter-drumlin hollows and on higher areas.

Between Fivemiletown and Rosslea there is an extensive area of rolling sandstone uplands, rising to the rounded summit of Slieve Beagh (382m aOD). The Slieve Beagh uplands straddle the borders of Tyrone, Fermanagh and Monaghan. Undulating peatland and moorland dominate this area which has one of the most extensive areas of intact blanket bog in Northern Ireland, although mechanised peat cutting has occurred in the area. Occasional loughs are located in this upland peatland landscape.

Long river valleys dissect the hills, and the upland is bounded by a prominent escarpment on the south. The southern escarpment slopes were historically in agricultural use, with fields extending from the lower valleys up the slopes. However, some of these small farms are now derelict, and fields are rush-dominated. There are also large areas of commercial forestry, and smaller forestry parcels are scattered throughout the catchment with occasional small broadleaf woodlands and copses. The latter are largely associated with demesnes.

In their middle and lower reaches, the Mountainwater River and Blackwater River valleys comprise relatively flat floodplains with large lowland areas of drumlin farmland that extend south to the Monaghan-Clones depression. These areas support wet meadows, pasture and bog.

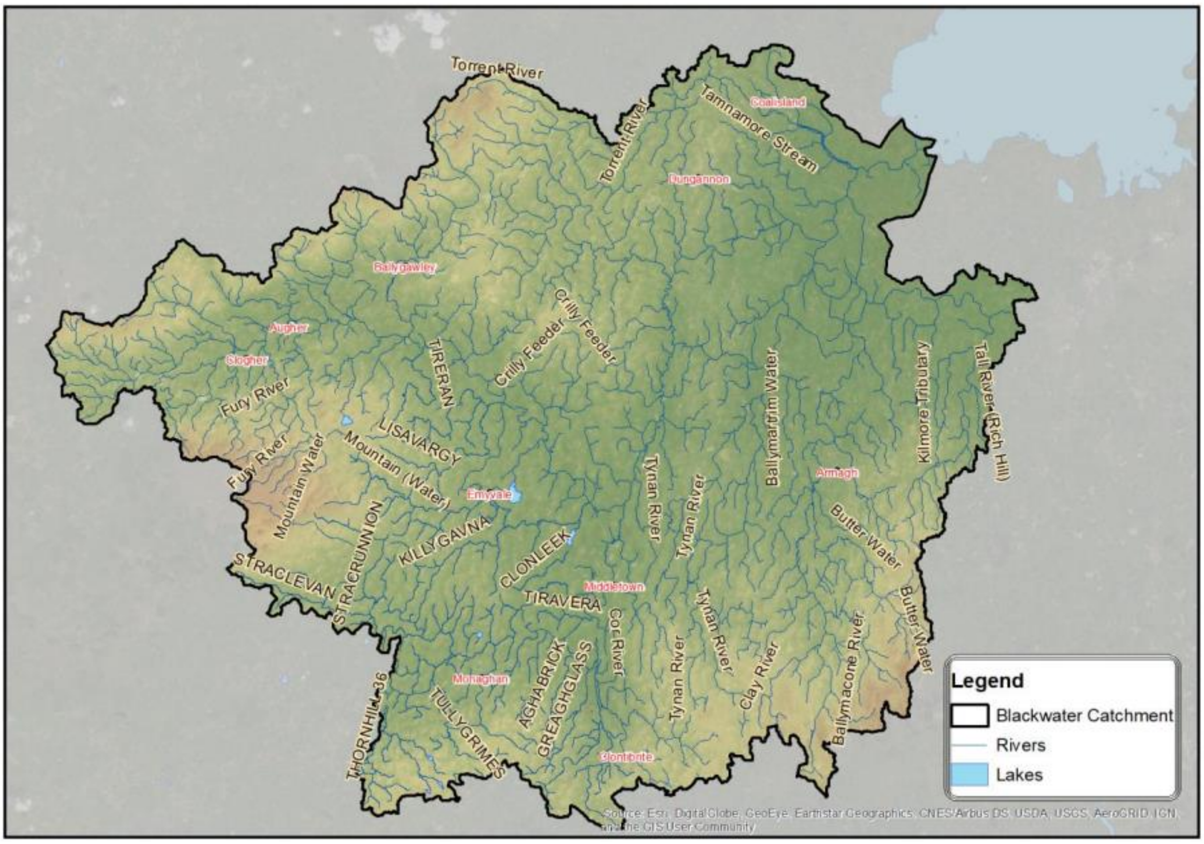


Figure 39 Topography and main surface water bodies in the Blackwater catchment. (from catchmentcare.eu)

Bedrock geology

The Blackwater Catchment is underlain by a wide range of different rock types. Many of the geological features follow a northeast to southwest (Caledonian) trend. The bedrock geology can be seen in Figure 40.

Across the southeast of the catchment, steeply dipping Ordovician-Silurian interbedded shales, mudstone and sandstone metasediments occur in a broad strip. The southwest-northeast orientation of these rock units has influenced the geological trend of younger rocks in the catchment.

Across the centre of the catchment, the shallow dipping late Devonian and Carboniferous Dinantian limestones and sandstones unconformably overlie the older rocks. The western Blackwater catchment is dominated by the rolling Carboniferous sandstone and shale uplands of Slieve Beagh. Underlying the plateau are calcareous shales (Meenymore Formation), which occur in the centre of a U-shaped northeast-southwest fold. Occurring as a thick layer within the shales, there are very coarse-grained to medium-grained sandstones (Carnmore member). These rock units form a prominent escarpment to the south of Slieve Beagh, at the foot of which is the underlying highly fractured and karstified pure Dartry Limestone.

The Monaghan lowlands to the south west of the catchment are mainly underlain by generally laminated, dark-grey calcareous shale (the Bundoran Shale and Benbulben Shale Formations). Parallel narrow bands of fossiliferous dark-grey muddy limestone, calcareous sandstones and siltstones, conglomerate and sandstone, and pale brown-grey flaggy silty mudstone run roughly north east to south west through Monaghan Town (the transitional beds, lower limestone shales and the Ballysteen Formation). There is a thin pure limestone rock unit (Ballyshannon Formation).

A band of shaley limestone and siltstone extends in an arc eastwards from Aughnacloy, through Emyvale to Armagh. This is known as the Maydown Limestone Formation. Mapped as being preserved in synclines above this shaley limestone is a friable red sandstone (Carrickaness Sandstone Formation).

To the north of Slieve Beagh, the Clogher valley is largely underlain by impure limestones containing layers of siltstone (Clogher Valley Formation). Further north again, the uplands bounding the Clogher-Augher valley are composed of Devonian-age conglomerate and red-grey sandstone.

In the north east of the catchment, north of Armagh, red, fine-grained Triassic-age sandstones and siltstones occur. Similar, very heavily faulted Permian-age sandstones are found beneath Armagh itself. These sandstones are known for having high porosities. The lowest section of the catchment, within 5 to 8km of the shores of Lough Neagh, are underlain by Oligocene grey mudstone and lignite of the Lough Neagh Clays Group.

The whole area is structurally complex with several generation of faulting and folding, starting with the Caledonian trends in the Ordovican sediments and basin related faulting in the Carboniferous.

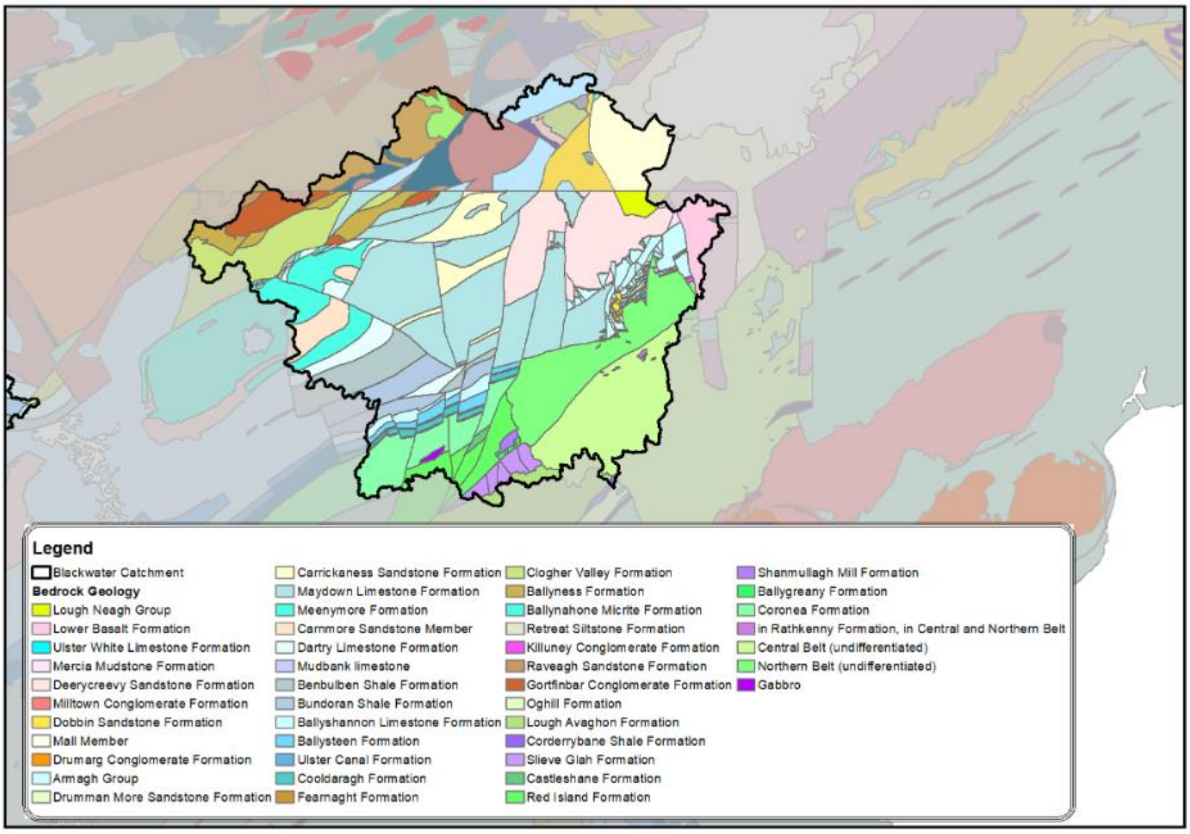


Figure 40 Figure: Bedrock geology underlying the Blackwater catchment. (Data sources: GSI and GSNI) (from catchmentcare.eu)

Subsoil geology and soils

Most of the catchment is covered by glacial tills ('boulder clays') derived relatively locally from the underlying limestones, sandstones and shales. These glacial sediments were sculpted by the passage of the ice-sheet above them, resulting in the drumlin landscape across much of the catchment. In some areas, such as the slopes south of Slieve Beagh, subsoil thicknesses can reach more than 30 m. In general, the drumlins comprise thick glacial sediments, whilst in the interdrumlin areas, the subsoils are a lot thinner. The subsoil geology is shown in Figure 41.

Ribbons of alluvium are prevalent along the rivers that meander through the inter-drumlin areas. The Blackwater River lowland catchment areas reveals an extensive floodplain containing abundant alluvial material, and pockets of glacio-fluvial deposits of silt, sand, gravel and boulders.

The upland catchment areas are largely covered by peat, notably on Slieve Beagh, but also at Slievemore and Cappagh Mountain. Lowland fen and basin peats are widespread between the drumlins, and also on the shores of Lough Neagh.

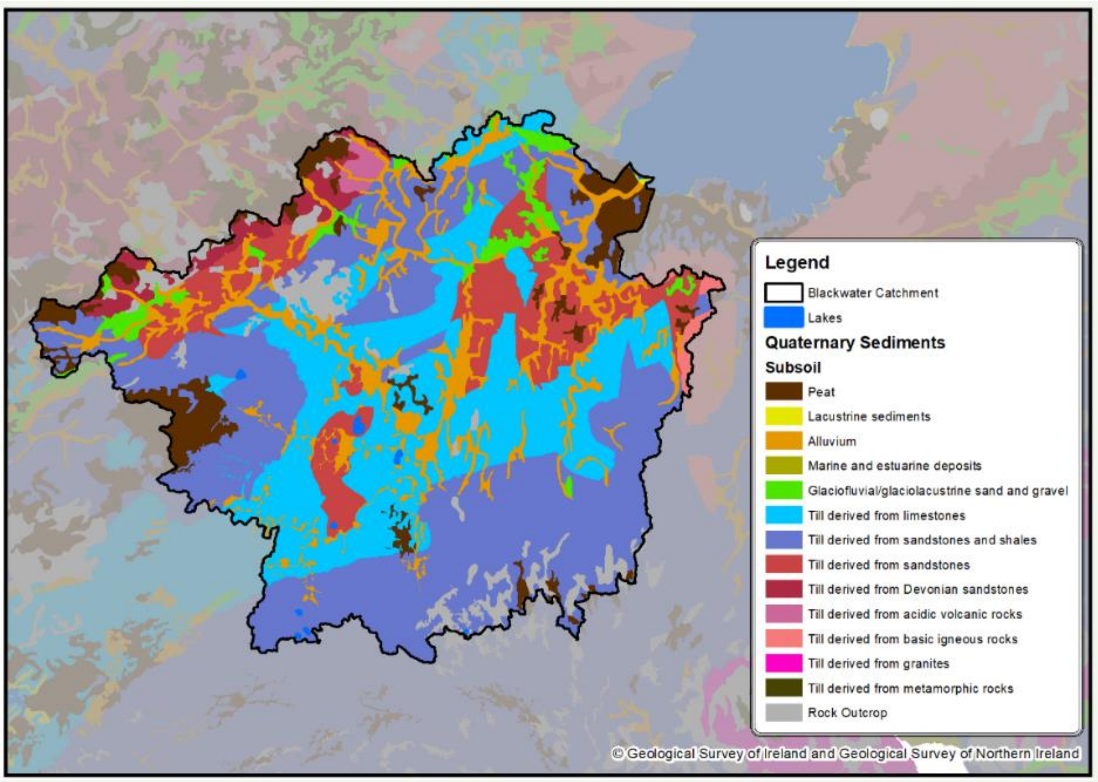


Figure 41 Subsoils geology underlying the Blackwater catchment. (Data sources: GSI and GSNI) (from catchmentcare.eu)

The poorly drained tills of the catchment have given rise to extensive stagnosol/surface water gleys development over most of the catchment (see Figure 42). Fluvisols/alluvium occur in riverine and lacustrine alluvial deposits along the Blackwater River and along the lower reaches of its main tributaries e.g. Mountain Water, Blackwater (Monaghan), Callan River, River Torrent and Oona Water. Peats, particularly cutover or cutaway bogs, occur in the hollows throughout the drumlin landscape. Podzols have developed on the higher ground north of Augher. Significant areas of cambisols occur and support more intensive agriculture, such as in the upper Blackwater valley between Fivemiletown and Clogher. Acid brown earths over shales, sandstone and siliceous material, brown podzolics and lithosols are present in the south east of the catchment. Brown earths over limestone and calcareous material are predominant from the south western catchment boundary, running in a band north eastwards through Monaghan town to Glaslough.

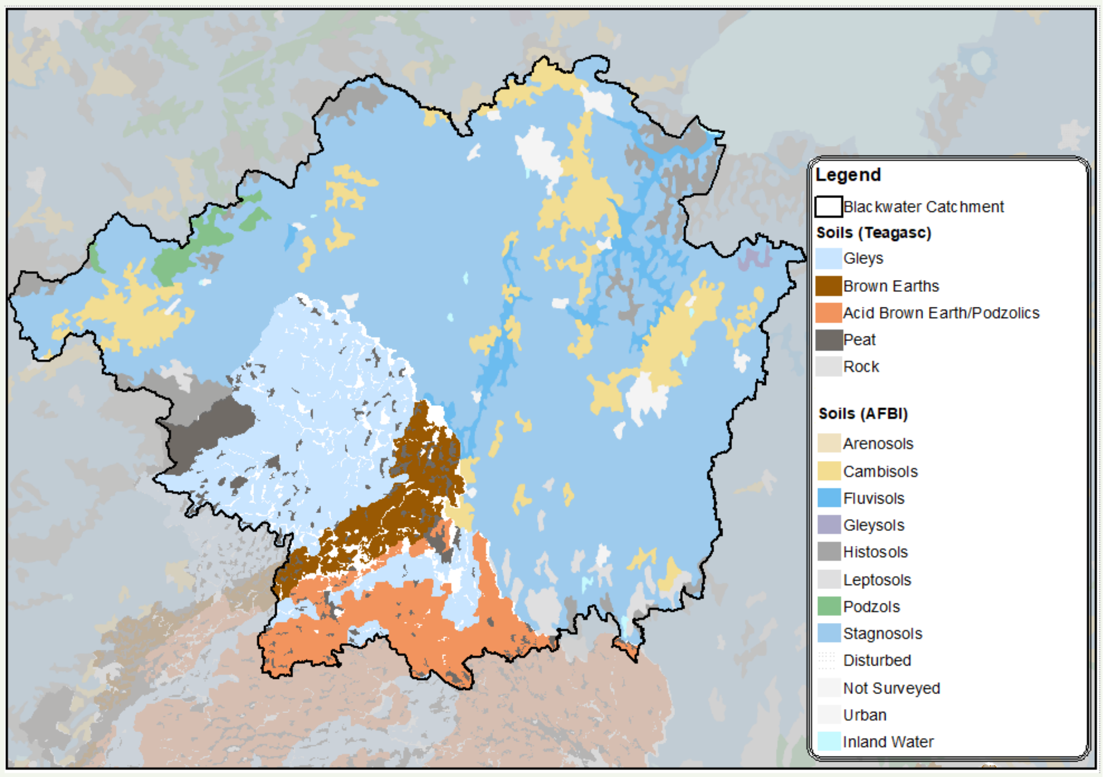


Figure 42 Soils covering the Blackwater catchment. (Data sources: Teagasc and afbi) (from catchmentcare.eu)

Hydrogeology

The Blackwater Catchment is underlain by a wide range of different rock types and therefore many different aquifer types. The aquifer types are shown in Figure 43. Most of the aquifers are fractured bedrock. First and foremost, the nature of the bedrock and the amount of deformation and fracturing the rock has undergone determines how well-fissured the aquifer is, and therefore how productive it is. There are additional factors such as whether the bedrock is a pure limestone and has been karstified (such as the Dartry or Ballyshannon Limestones), or whether the bedrock also has primary porosity (such as the Sherwood Sandstone).

In the southern portion of the catchment, the old and shaley Ordovician and Silurian bedrock is poorly productive, with very limited groundwater resources. They are classified in Ireland as Pl and Pu aquifers, and in Northern Ireland as B(l-f). Similarly, the Devonian sandstones in the northwest of the catchment are relatively poorly fractured, lacking in primary porosity and has limited groundwater flow paths. They are also classified as Bl(f) aquifers.

In the area around Slieve Beagh, the Carboniferous sandstones are more extensively fractured and in Ireland are classified as Lm aquifers, and Northern Ireland as Bm(f). South of Slieve Beagh the rocks are extensively faulted and fractured. This has resulted in even the shaliest rocks being at least locally important aquifers. The Dartry limestone that dips to the north beneath the mountain is highly karstified, which has caused cavities to develop and permeability to be enhanced, but is limited in lateral extent by faulting and in recharge volumes by the overlying thick tills. It is therefore classified as an Lk aquifer in Ireland. The Tydavnet Group Water Scheme takes part of its supply from this aquifer.

In the Monaghan-Scotstown area, the bedrock is mainly fine-grained and shaley, but due to the extensive faulting the aquifers are moderately to highly productive. Several very large abstractions are supported in a well field. Further east, the shaley Maydown Limestone is classified as a Lm aquifer in Ireland and as Bm(f) in Northern Ireland. The drilling undertaken as part of the CatchmentCARE project shows that productivity is highly variable. The Clogher Valley Limestone is thought to be a highly productive aquifer but despite it being extensive across the west and centre of this catchment, there is limited information about its hydrogeology.

The Triassic Sherwood Sandstone aquifer south of Dungannon contrasts with the rest of the aquifers, due to its primary porosity and permeability and high storage and transmissivity. This is a major aquifer with high groundwater prospectivity potential.

There are also various glacio-fluvial sand and gravel complexes along the Blackwater and tributaries in Northern Ireland that are distinct aquifers in their own right. Around Shanmoy, the sand and gravels have been used for public water supply and are known to be in connection with the River Blackwater.

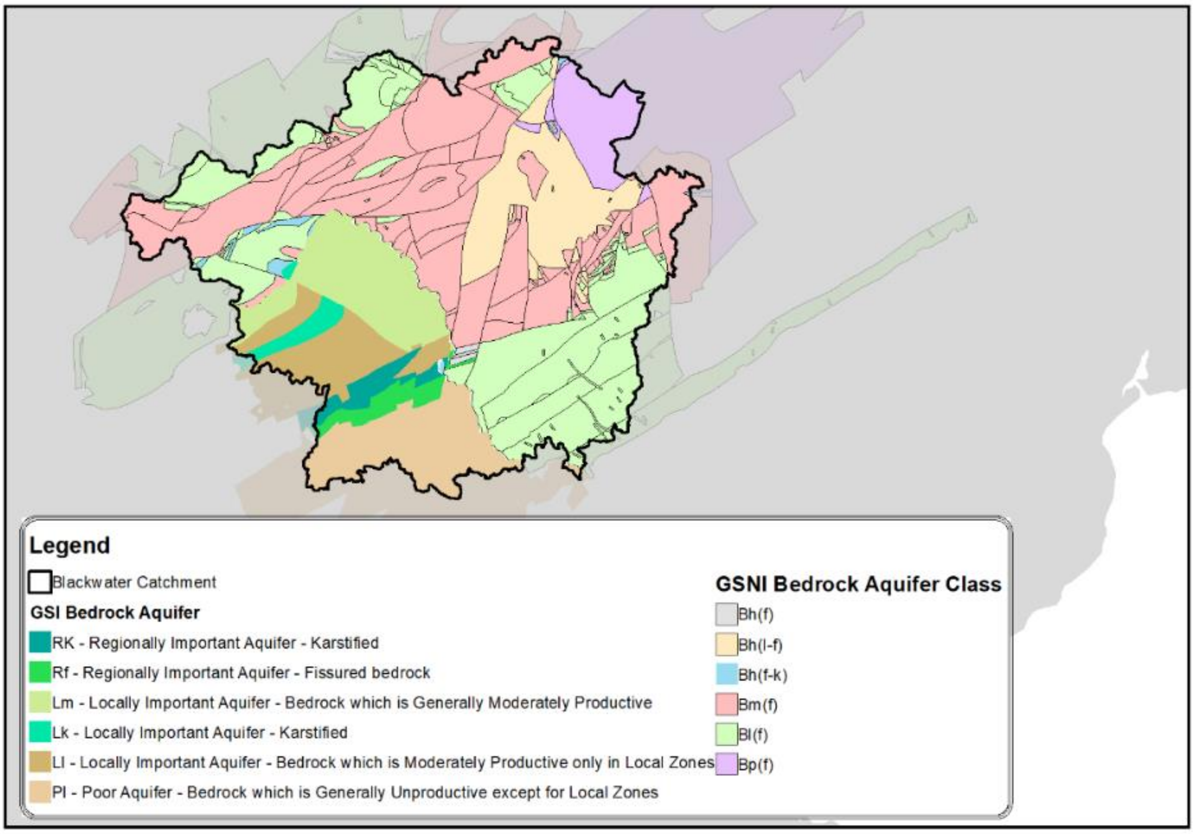


Figure 43 Aquifers in the Blackwater catchment. The legend keys for Irish and Northern Irish maps are arranged in order of greatest to least groundwater resource value.

Groundwater vulnerability (Figure 44) in the part of the Blackwater catchment south of Slieve Beagh is predominantly Low. There are areas of Extreme vulnerability beneath the blanket bog, in some inter-drumlin areas, and in the southwest of the catchment. Smaller areas of Moderate and High vulnerability occupy the lowland areas around Monaghan Town and Killyneil.

In Northern Ireland, the majority of the catchment is classified as class 2 groundwater vulnerability (i.e. at the well-protected end of the scale). In the sand and gravel aquifers along the main rivers and tributaries, which act as the 'lungs' of the rivers, groundwater vulnerability is class 4 due to the high water table. In the area underlain by the porous Triassic sandstones, vulnerability is class 3 due to a deeper water table. It is class 1 in the area underlain by the clays and peats just southwest of Lough Neagh, due to the very low permeability nature of these deposits and absence of groundwater resources.

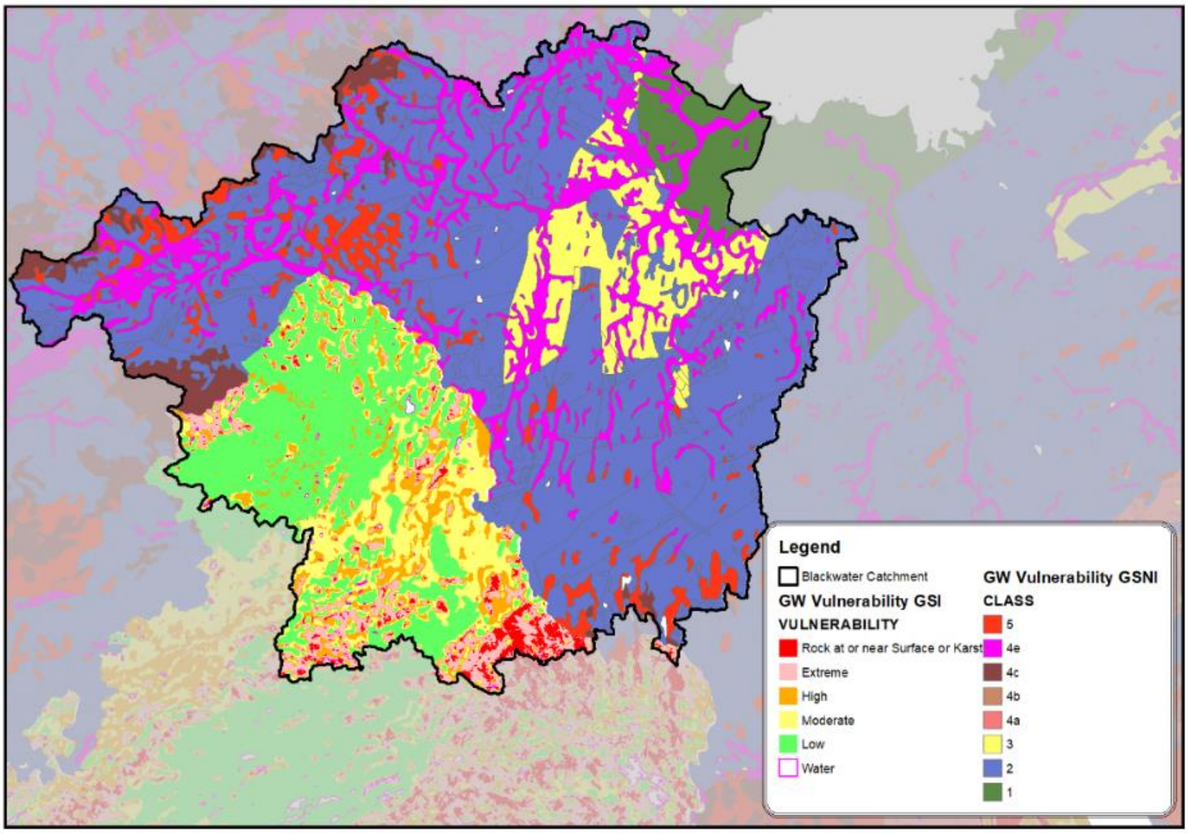


Figure 44 Groundwater vulnerability in the Arney catchment. The legend keys for Irish and Northern Irish maps are arranged in order of greatest to least groundwater vulnerability.

Groundwater Monitoring Stations in the Blackwater catchment

As part of the CatchmentCARE project, nine GWMSs were drilled in the Blackwater catchment, comprising 23 boreholes (see Figure 45). One, two or three boreholes are drilled at the selected sites to create a Groundwater Monitoring Station (GWMS). Following the approach of the EPA's Poorly Productive Aquifer groundwater monitoring network, the boreholes were drilled to different depths depending on which part of the groundwater system is of interest.

Groundwater monitoring stations were sited across the catchment for a variety of reasons. The monitoring boreholes were sited in areas where it was thought that there would be more potential for groundwater-surface water interaction. There was also the aim of increasing the understanding of the aquifer characteristics and groundwater chemistry. In Co. Monaghan, there was a focus on the area around the Mountainwater Stream catchment.

Installing GWMSs at the sites chosen allowed the project to characterise groundwater at sites representing a wide variety of hydrogeological and catchment settings and land uses across Counties Monaghan and Armagh. The groundwater monitoring infrastructure has created a new opportunity for groundwater investigations in future farming practice, and land and catchment management approaches. The details of the GWMSs are outlined in Table 6.

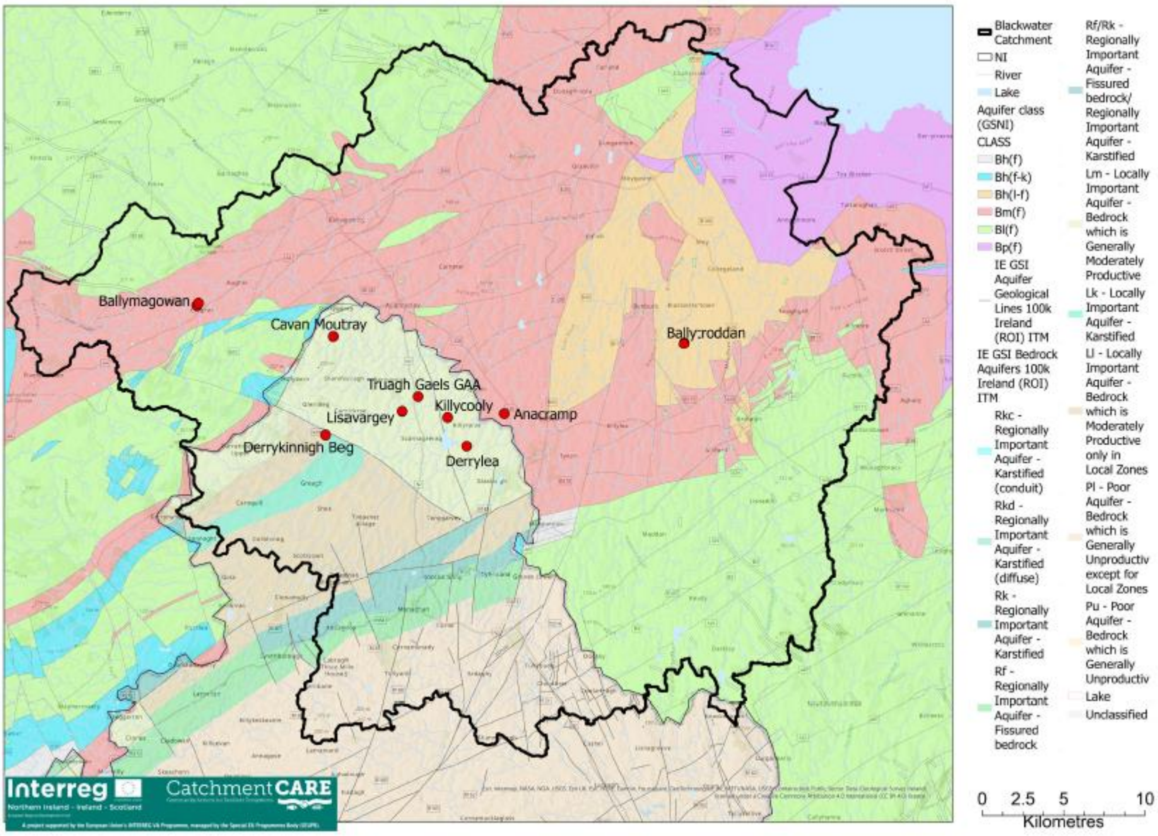


Figure 45 Groundwater Monitoring Stations (GWMSs) (red dots) constructed by the CatchmentCARE project in the Blackwater catchment. (Data sources: GSI and GSNI) (from catchmentcare.eu)

Table 6 Groundwater Monitoring Stations constructed in the Blackwater catchment (Data sources: GSI and GSNI)

BH No.	GWMS Name	Typical Resting Water Level (m btoc)	Typical Resting Water Level (m aOD)	Borehole Type	Productivity	Plain casing depth (m)	Screened or open Interval (mbtoc)
CCB01	Ballymagowan	0	63.54	Bedrock	Very High	6	6-60
CCB02		0	62.51	Bedrock	Very High	15	15-48
CCB03		2.005	61.235	Superficial/ Transition	High	3	3-6
CCB04		0	63.21	Bedrock	Very High	27	27-48
CCB05	Anacramp	3.01	32.59	Bedrock	High	12	12-102
CCB06		1.845	33.785	Superficial/ Transition	Moderate	6	6-12
CCB07		2.975	32.685	Bedrock	High	12	12-60
CCB08	Ballytroddan	0	19.53	Bedrock	High	12	12-54
CCB09		0	18.78	Bedrock	Moderate	12	12-102
CCB10		0	19.9	Bedrock	High	12	12-102
TG01	Truagh Gaels GAA	1.41	50.19	Bedrock	Poor	42	42-101
TG02		1.95	49.68	Superficial/ Transition	Poor	6.3	6.3-11.3
CVM01	Cavan Moutray	7.10	93.08	Bedrock	Moderate	47	47-100
CVM02		6.60	93.65	Bedrock	Poor	23.8	23.8-36
CVM03		4.38	95.88	Superficial/ Transition	Poor	4.6	4.6-9
DER01	Derrylea	0				24	24-30
LIS01	Lisavargey	4.065	55.77			42	42-84
LIS02		1.985	57.89			16	16-27

LIS03		1.185	58.79	Superficial/ Transition	Poor	6.9	6.9-9.7
DKB01	Derrykinnigh Beg	5.60	117.33	Bedrock	Very High	34	34-36
DKB02		3.35	119.49	Superficial/ Transition	Poor	1.5	1.5-4.5
KCY01	Killycooly	2.25	45.79	Bedrock	High	24	24-60.5
KCY02		3.10		Superficial/ Transition	Poor	9	9-17.8

- All boreholes completed at 150 mm diameter
- Boreholes completed in superficial/ transition zone are lined with slotted screen. Boreholes completed in bedrock are open hole and unscreened below the blank casing.

Population, land use and significant pressures

The population of the Blackwater catchment is approximately 136,000 people. This is equivalent to about 91 persons/km^2. The biggest settlements are in Armagh and Dungannon, and in the eastern part of the catchment. Monaghan is the only large town in the Irish portion of the catchment. Approximately 41% of the total catchment population are town dwellers. The remaining 59% are largely in dispersed one-off dwellings and rely on on-site wastewater treatment systems.

The overwhelming land use in the catchment is agricultural pasture (see Figure 46). These are mostly improved grasslands. Tree cover is relatively low. Small areas of deciduous and mixed forest are scattered throughout the lowland catchment, but the largest areas of forest are coniferous plantations on marginal upland soils. Isolated small wet woodlands are often associated with inter-drumlin lakes and wetlands.

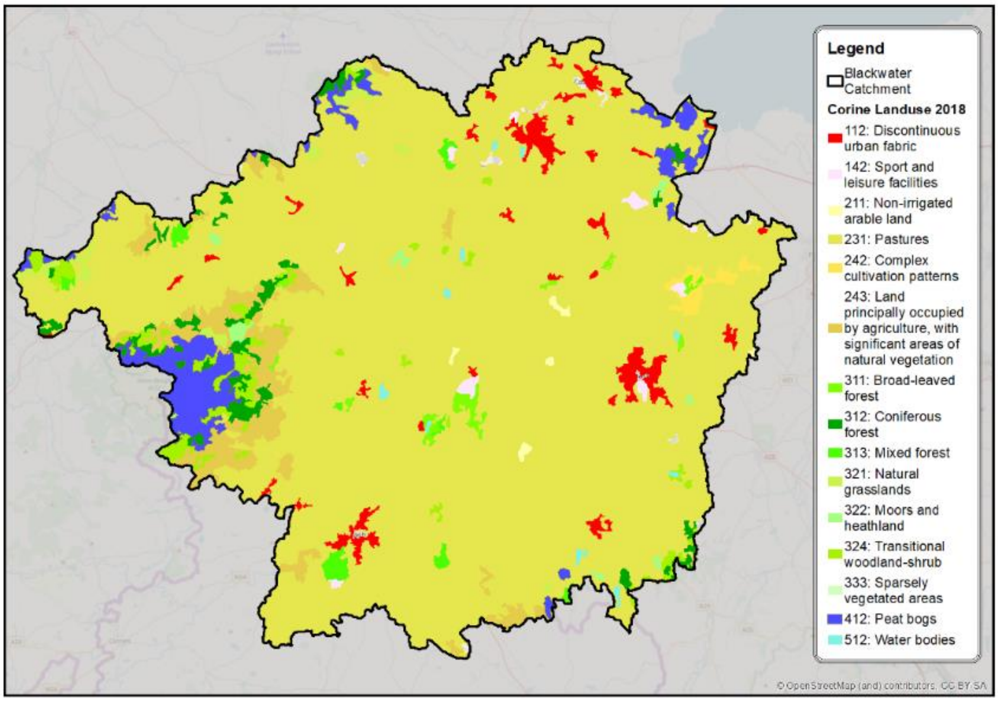


Figure 46 Land Use Map for the Arney Catchment (Data source: CORINE Land Cover 2018, EEA) (from catchmentcare.eu)

In Northern Ireland, medium- and high-risk agricultural critical risk areas are widely, and rather evenly, distributed throughout the catchment. In Ireland, agriculture is a significant pressure in the south and east of the catchment, in the more intensively farmed areas around Emyvale, Glaslough and south of Monaghan town.

Hydromorphology pressures are particularly prevalent in this catchment due to its history of major arterial drainage schemes, flood protection, high level of urbanisation, and land drainage for agriculture. The now disused Ulster Canal (built in the 1800s) also travels through County Armagh and County Tyrone. Remnants of the canal are still evident today. Hydromorphology pressures are prominent in many of the same water bodies as agricultural pressures

Significant pressures impacting on water quality in the Blackwater catchment include urban wastewater treatment effluent, domestic wastewater discharges, diffuse urban run-off, licenced discharges.

Protected Areas

Five Natura 2000 sites occur wholly or partly within the Blackwater catchment:

- UK9020091 Slieve Beagh-Mullaghfad-Lisnaskea SPA
- 004167 Slieve Beagh SPA
- UK0016622 Slieve Beagh SAC
- UK0030236 Peatlands Park SAC
- UK9020091 Lough Neagh and Lough Beg SPA

The spatial distribution of the protected areas are shown in Figure 47.

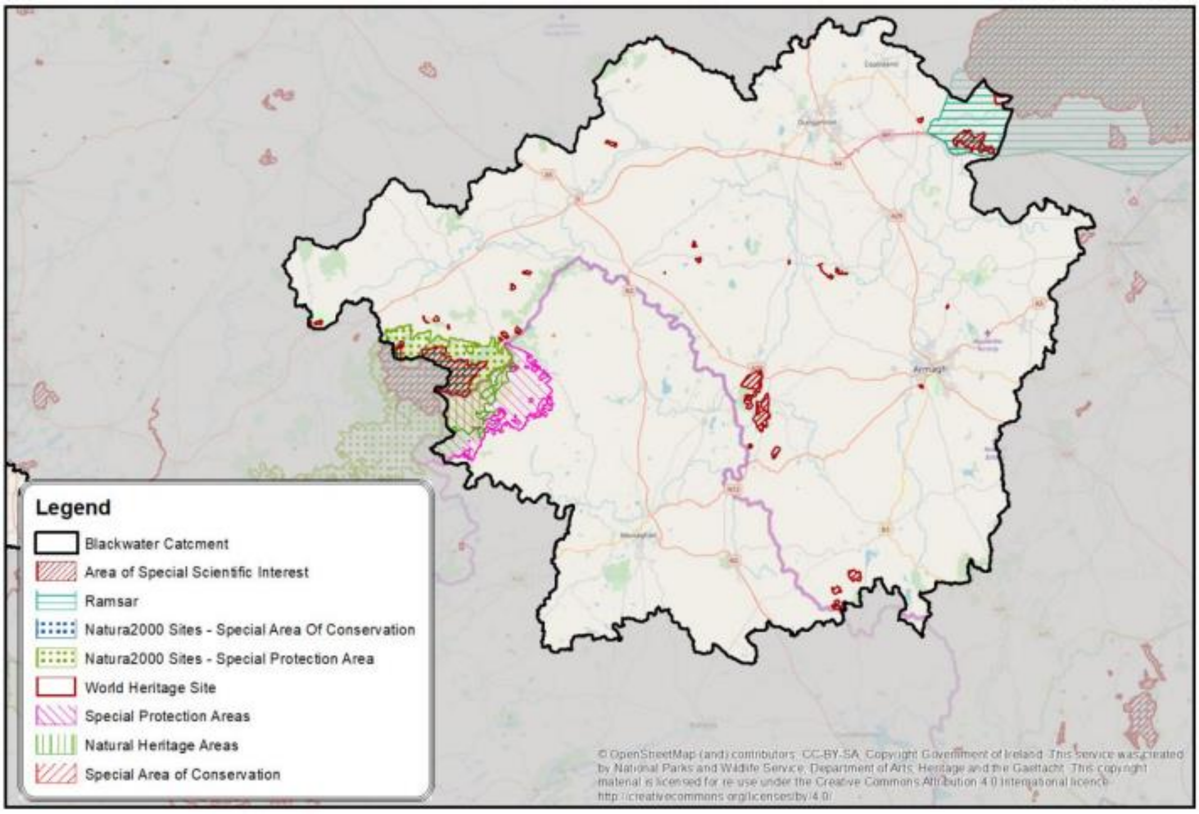


Figure 47 Biodiversity and Landscape Protected Areas in the River Arney Catchment (Data Source: NPWS and NIEA) (from catchmentcare.eu)

Water Framework Directive Status

The Blackwater catchment is divided into 57 river water bodies, and contains 9 WFD lake water bodies, all of which are in the ROI. The catchment is associated with 14 groundwater bodies.

Of the 57 RWBs in the Blackwater catchment, in Cycle 3 (2016-21), four are at High status (up from three, and with Mountainwater_020 regaining its High status). The High and Good status water bodies are generally in the upland headwater reaches in the western side of the catchment. In 2018, 13 were at Good status, 19 are at Moderate status, 9 at Poor status, and 2 at Bad status, 1 at PEP (poor ecological potential), 1 at BEP (bad ecological potential) and 4 at MEP (moderate ecological potential). The WFD status map is shown in Figure 48.

In 2021 Emy Lough was classified at Poor status (down from Moderate in 2018), and Lough More at Moderate (down from Good) status. The remaining seven lakes are at Good status, with the exception of White Annayalla Lake.

In Northern Ireland the Aughnacloy, Tandragee and Moygashel GWBs remain at Poor status in Cycle 3. This is related to the chemical status. The Knockatallon GWB in Ireland has dropped to Poor status on the basis of quantity. A small GWB has been delineated around a waste facility at Annyalla in the southwest of the catchment. This GWB is currently at Poor status. The remaining GWBs remain at Good status.

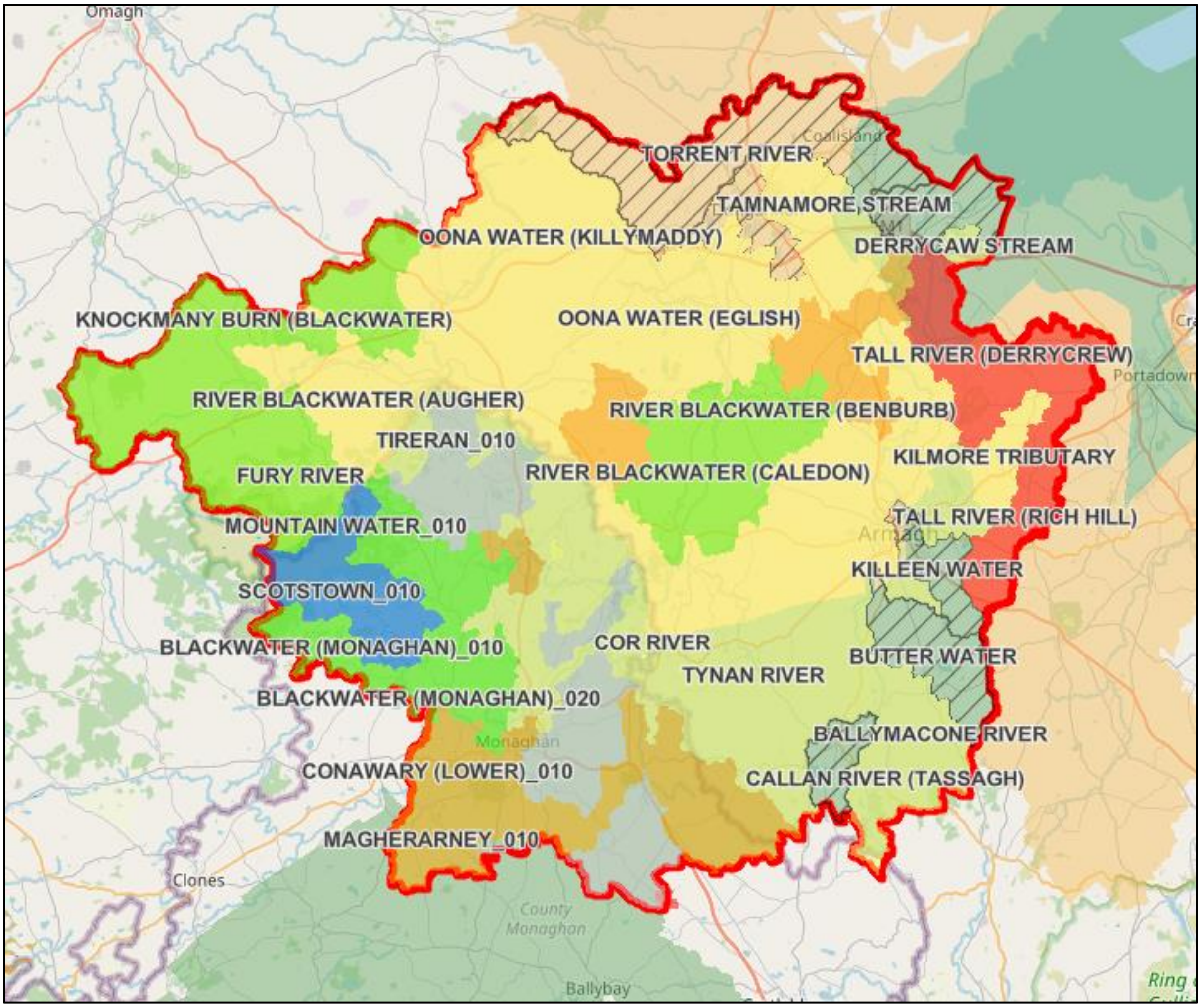


Figure 48 Surface water WFD status 2018. Image source: catchmentcare.eu storyboard. Data source: EPA and NIEA. Also shown on the map are the Groundwater Bodies that intersect with the Arney catchment.

WFD Priority Area for Action

The Priority Areas for Action selected by LAWPRO in the Blackwater Catchment in the 2nd Cycle of the River Basin Management Plan were the Mountain Water and Emy Lake (see Figure 49). A successful working group has been established and led by LAWPRO, and has brought together many stakeholders, including group scheme representatives, catchment scientists, community members, interest groups, etc.

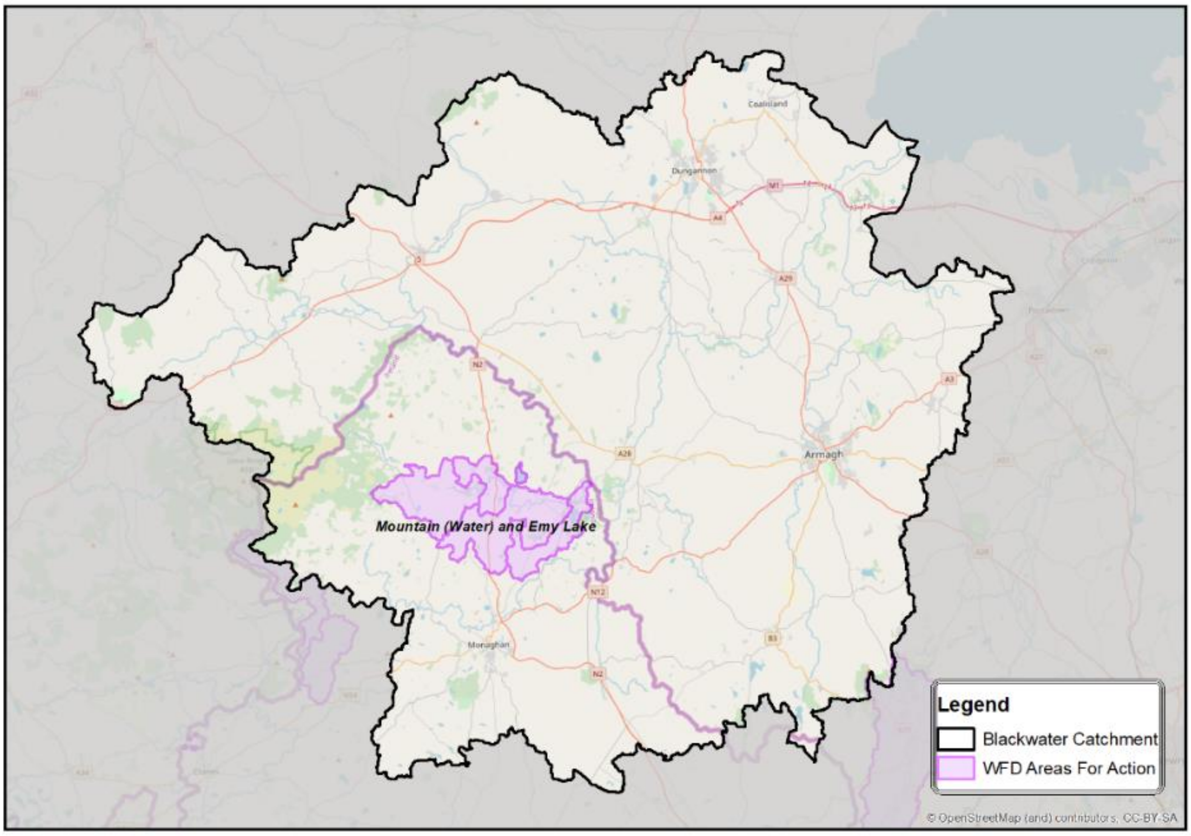


Figure 49 Priority Area for Action in the Blackwater catchment. (Data sources: EPA) (from catchmentcare.eu)

3. The Mountain Water Subcatchment

The first five sites visited on Day 2 in the Blackwater catchment will focus on river characterisation and restoration work in the Mountainwater River subcatchment. We will follow the water from the upper catchment to where some of the flow is diverted to Emy Lough in the valley.

As mentioned above, the Mountain Water and Emy Lake PAA have been selected by The Local Authority Waters Programme (previously called the Local Authority Waters & Communities Office) for local authority catchment assessment teams to drive the implementation of mitigation measures, with particular emphasis on driving collaborative and cross-sectoral actions to deliver water-quality improvements.

The river reached its lowest point around 2007 when the waters of the upper reaches were no longer classed as pristine. The main pressures on water quality at these sites is primarily agriculture. These include run off from local fields due to excessive fertilizer loading, poaching of river banks due to livestock having direct access to the watercourse, siltation of riverbed caused by bank erosion and lack of riparian habitat and tree cover or from spread of invasive species (Himalayan Balsam being the only invasive species present). There are also issues with the localised use of pesticides and herbicides on the land. This leads to a build-up of chemicals in local drinking water sources.

In response to the deteriorating water quality, The Mountain Water Phase 2 and Phase 1 Water Quality Improvements works were undertaken in order to remediate the catchment. This work involve the implementation of a wide range of remediation works, including the installation of fencing, livestock drinkers and the planting of native tree species.

Throughout the course of the day Alan McCabe, the Blackwater Officer with CatchmentCare, will introduce us to the Mountain Water river, which flows from the Sliabh Breagh Mountain towards and beyond Emyvale before joining the Blackwater River. Alan will bring us to a few stops which will show us some real-life example of Integrated Catchment Management in progress.

4. Ballytroddan- artesian wells, pump tests, geophysics, dyke

Aim of the Groundwater Monitoring Station: To assess the role that igneous dykes have in the flow of groundwater in a dual porosity aquifer.

Objectives:

1. Identify with high precision the structure and nature of the focus igneous dyke using surface geophysics.
2. Drill a borehole on either side of an igneous dyke.
3. Attempt to drill a borehole into the focus igneous dyke.
4. Perform pumping tests to determine whether dykes impede groundwater flow.
5. Provide a new location for national groundwater monitoring in an area devoid.

Geology

The site is underlain by the **Triassic Sherwood Sandstone Group**. A dual porosity bedrock aquifer which is one of the most important and utilised aquifers in Northern Ireland. In this area it is only used by farmers and light industry. There have been no targeted groundwater studies on this portion of the Sherwood Sandstone Aquifer, therefore little is known about the groundwater potential in this area.

Geophysics

Following an initial site survey to assess the availability of land and meeting the landowners, a review of the Tellus project airborne magnetics interpretation revealed the potential for the land available to be cross cut by an igneous dyke. The intention was then to construct a site whereby a study of the influence of igneous dykes on groundwater transport could be studied. A further surface magnetics survey confirmed the airborne and enabled the nature and orientation of the dyke to be better refined. From this, the location of three boreholes were staked out. The results of the geophysics surveys can be seen in Figure 50 and 51.

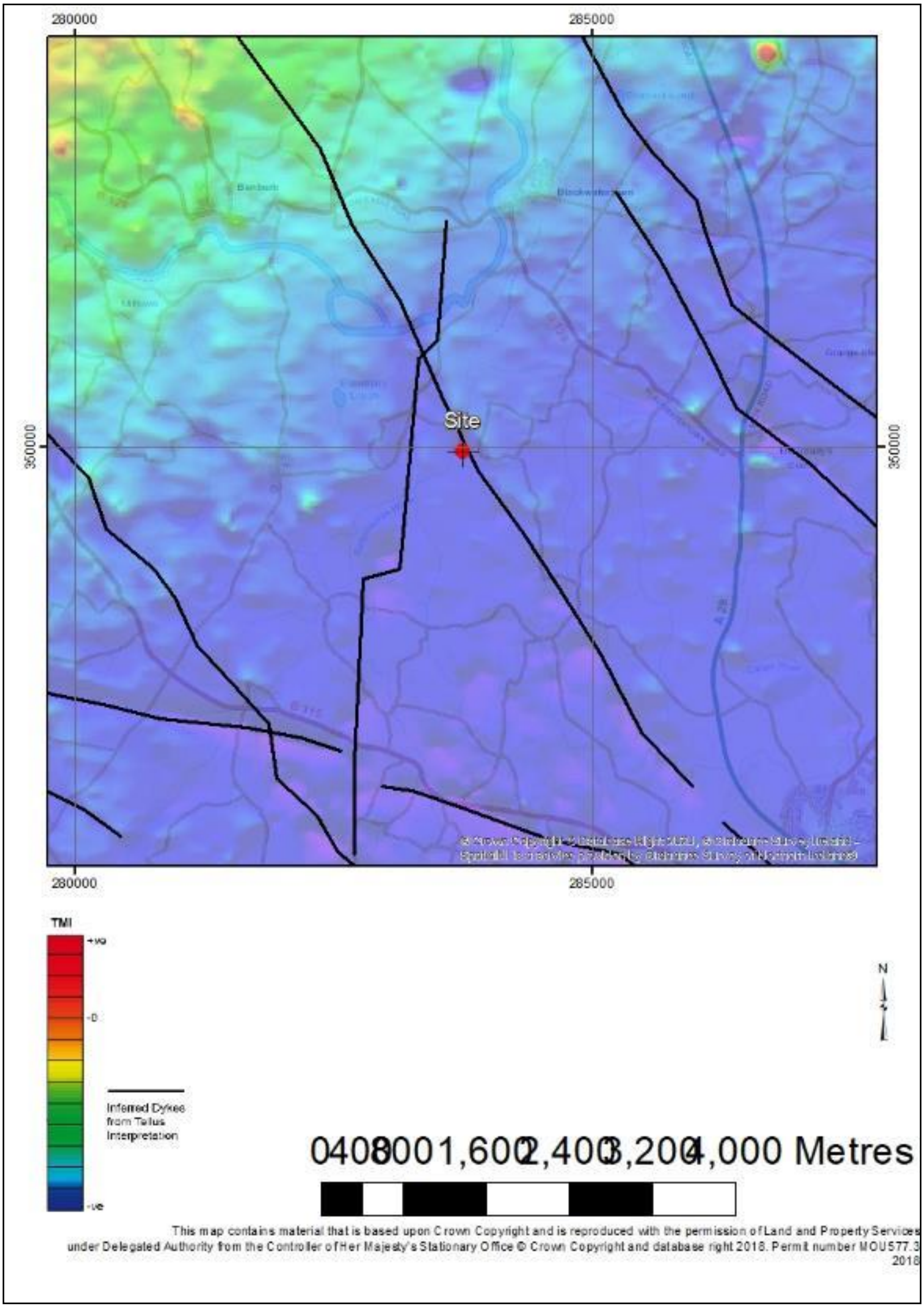


Figure 50 Airborne Geophysics. Magnetics collected during the Tellus project, with inferred igneous dyke orientations (Data source: GSNI)

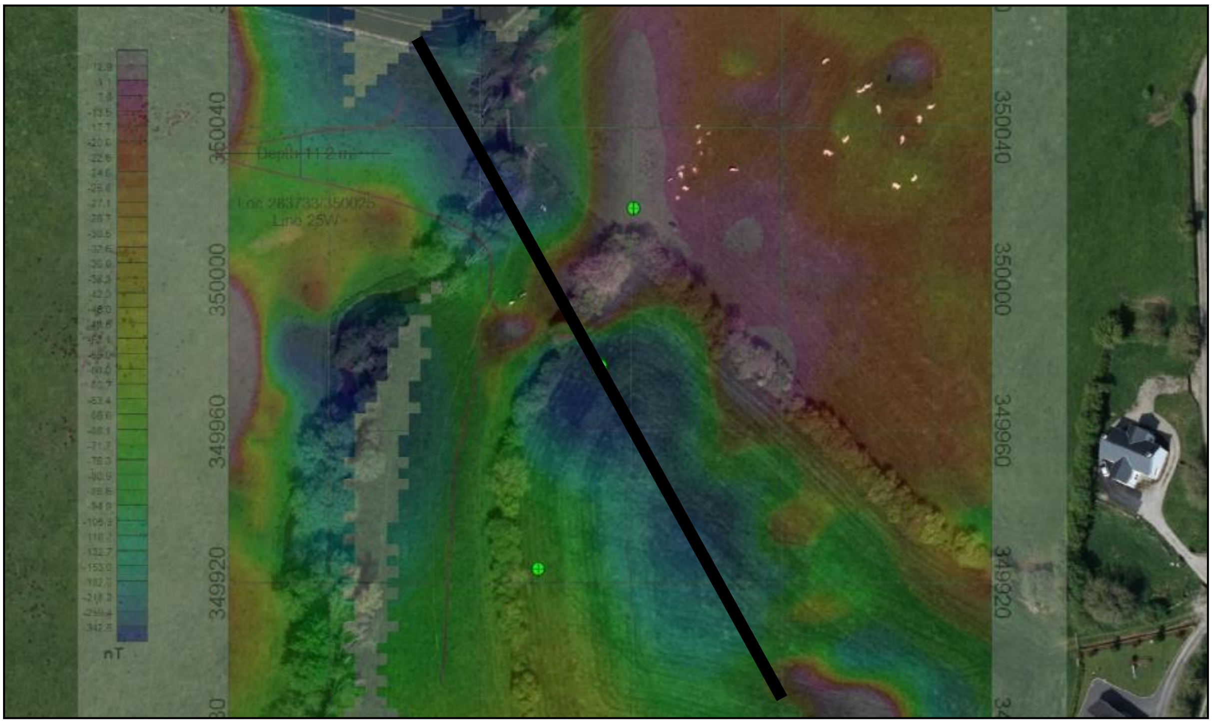


Figure 51 Surface geophysics, magnetics, at the site with the inferred strike of igneous dyke (Data source: GSNI)

Drilling

The drilling was carried out in June 2021 by Dullea Drilling using a dual rotary DTH rig with a continuous casing system and air flush. It was anticipated that a significant thickness of overburden would be encountered. Surprisingly, less than 3 m was found prior to reaching the Sherwood Sandstone bedrock.

The **first hole** produced a kaleidoscope of returns, characteristic of Sherwood Sandstone often observed close to known faults. The different colours being due to bleaching and the movement of pressurised fluids often associated with faults. This borehole encountered numerous fractures and a high flow return was observed. This turned out to be artesian, confirming the presence of confining bands of mudstone within the sandstone unit. Drill depth 54 m (terminated early to construct a water retention system).

The **second hole** aimed to drill into the igneous dyke, which considering they are normally only a few metres wide, was a long shot. Surprisingly, not only was the dyke found but the borehole stayed within it for 102 m. A testimony to the accuracy of the surface magnetics survey and the staking out. The borehole also was artesian, with a decent flow but much less than the first borehole. Drill depth 102 m.

The **third hole** was deliberately positioned across the other side of the field to keep it as far away from the other two as possible, i.e. the influence of the igneous dyke. This borehole returned sandstone and mudstone returns which were a consistent red brown colour, as expected with unaltered Sherwood Sandstone. This borehole was artesian also, which left us with the exciting task of sealing them up properly. Drill depth 102 m.

Images of the borehole production are shown in Figure 52.

Figure 52 Drilling returns from boreholes 1, 2 and 3 (left to right)

Testing

Each borehole was developed for 30 minutes after drilling ceased and then allowed to flow for a few days until they could be sealed. This ensured they were well developed.

They were then tested using a suction pump for a short period of a few hours to provide some initial estimates of aquifer properties. The estimate aquifer properties are detailed in Table 7.

Table 7 Summary results of pump testing on BH1, BH2 and BH3

Borehole	Specific Capacity (m^3/d/m)	Transmissivity (m^2/d)
1	48	30
2	4	0.7
3	74	66

BH3 was the most productive borehole. The borehole into the igneous dyke is much less productive than the ones into the Sherwood Sandstone. However, this would still be a reasonable supply for a domestic of small farm setting. This is a highly significant result as it could mean in low productivity aquifers that are crosscut by igneous dykes, it may be worth targeting a dyke if the Tellus magnetics identifies one on the land available. This has already become a part of our package of advice to enquirers and positive results are being reported by drillers.

BH3, which was not in a fault (but twice the depth) is almost twice as productive as the one drilled into the fault.

Once the new artesian caps were installed earlier this year, two long duration tests were carried out.

1. Opening of the sample tap at BH1 for 14 days
2. Removal of the cap at BH1 for 12 days

Test 1

Average Flow Rate = 27 m^3/d

Transmissivity = Between 10 and 25 m^2/d

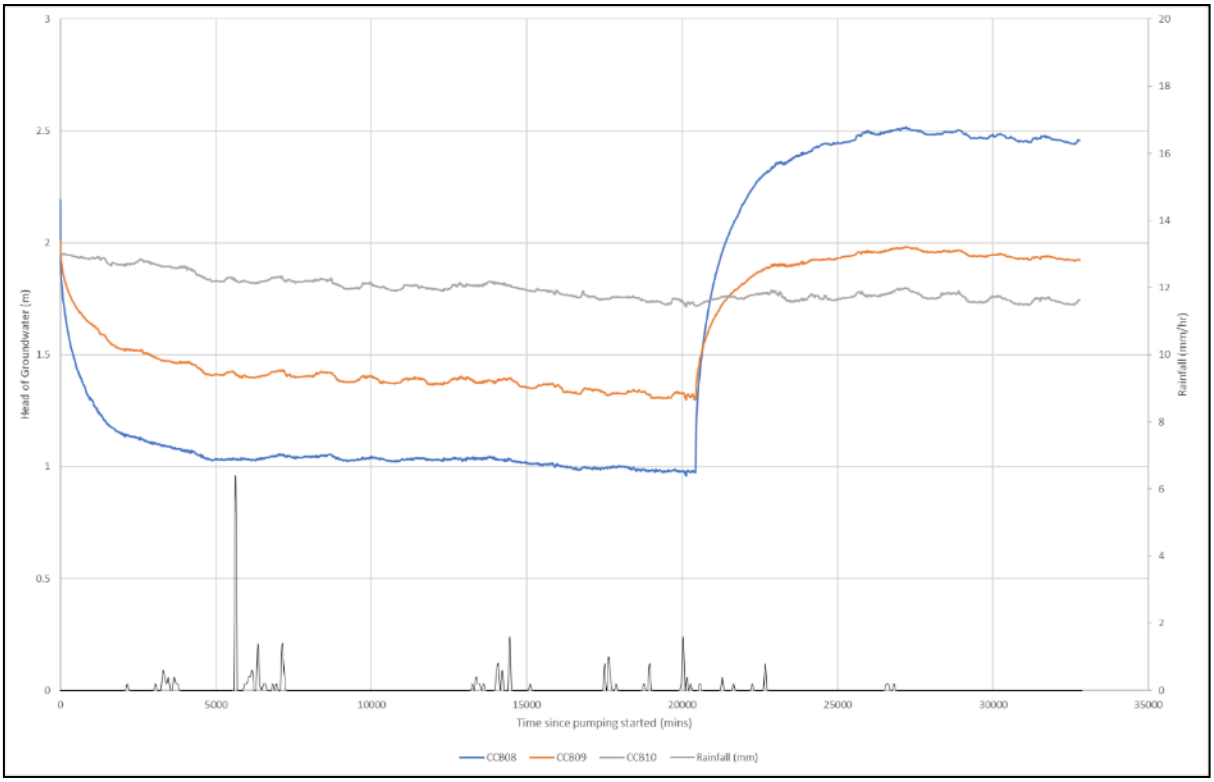


Figure 53 Pumping and recovery phases from a test conducted by opening and closing the sample tap fitted to BH1 (blue line)

From the above graph (Figure 53), you can see the response in the pumping borehole (blue line). This is matched by a similar response from the igneous dyke BH2 (orange line). BH3 (grey line), does not show an obvious response but a comparison of the average gradient of the line during the pumping and recovery phases indicates a slight drawdown during pumping followed by a slight upward recovery. However, this is not obvious and clear, therefore a higher rate pumping test was required (test 2)

Test 2

Average Flow Rate = 27 m^3/d

Transmissivity = Between 32 and 111 m^2/d

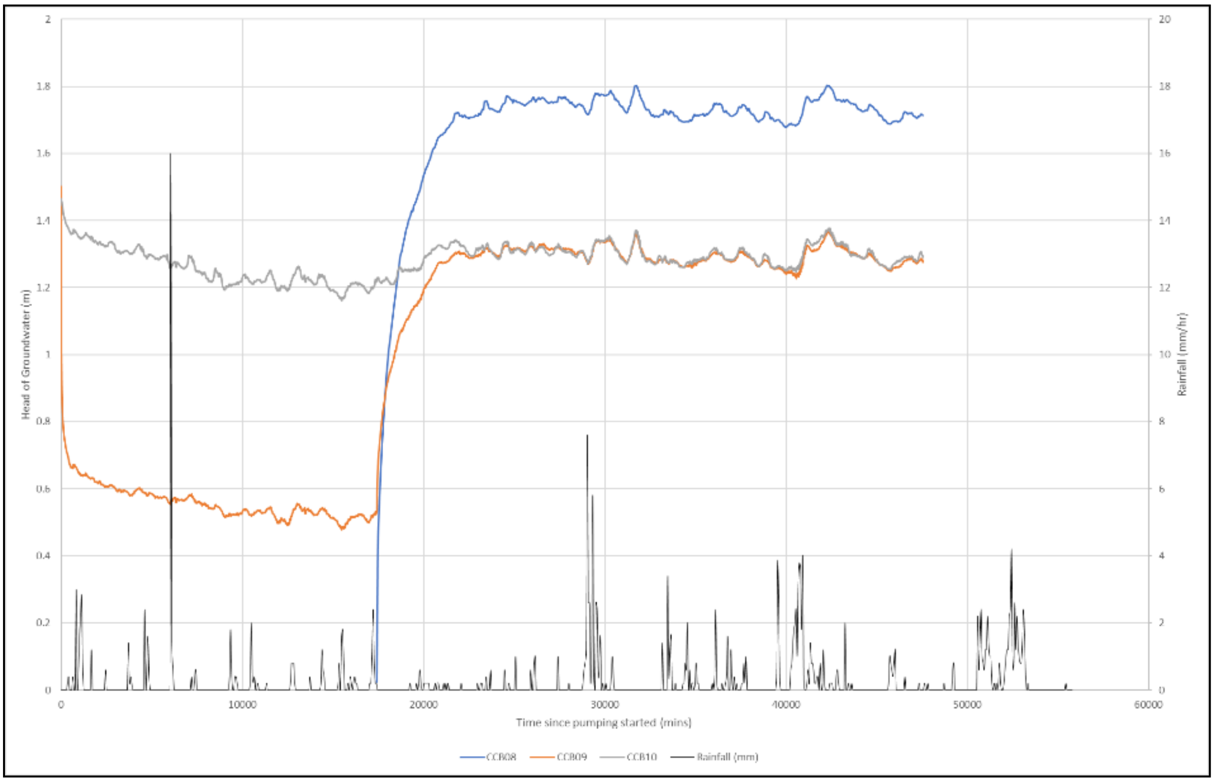


Figure 54 Pumping and recovery phases from a test conducted by removing the cap fitted to BH1 (blue line)

Like the first test, the above graph (Figure 54) shows the response in the pumping borehole (blue line). This is matched by a similar response from the igneous dyke BH2 (orange line). BH3 (grey line), shows an obvious drawdown, but this could have been natural groundwater pressure decline. However, this drawdown ceases and there is evidence of a marked recovery after the cap was reinstalled on BH1. This test therefore reinforces the conclusions drawn from the first test.

This demonstrates that there is hydraulic connection between the sandstone aquifer and the igneous dyke. It is not the solid barrier often intimated.

Chemistry

A round of samples were collected from each of the three boreholes. Some of the results are shown in Figure 55 and Table 8 below.

Table 8 Results of water quality samples collected from BH1, BH2 and BH3

	Average			
DetName	**CCB08**	**CCB09**	**CCB10**	**ResultUnits**
Alk_CaCO3_tot	257	218	244.3333	mg/L
Aluminium	5	15.2	5	µg/L
Calcium	63.91	41.724	37.38767	mg/L
Chloride	17.3	15.9	18.16667	mg/L
EC_field	668	421.9	505.175	µS/cm
Eh_field	253.3	406.2	213.1	mV
Iron	1880	476	276	µg/L
Magnesium	19.9	23.3	21.46667	mg/l
Manganese	211	26.7	8.503333	µg/L
Nitrate as N	0.04	0.04	0.083333	mg/L

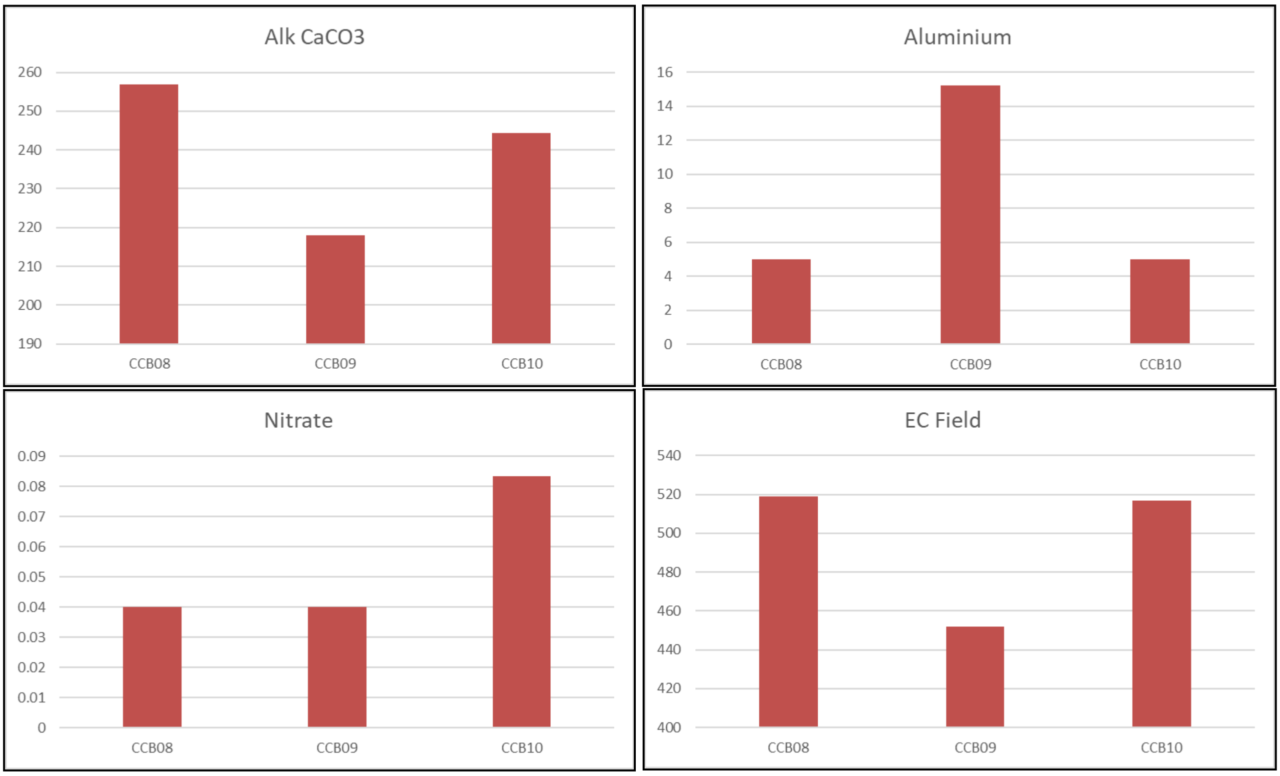


Figure 55 Comparative water quality results from BH1, BH2 and BH3

Artesian Borehole Caps

Artesian wells are fun to encounter, for all about 10 minutes until you realise that you are now responsible for ensuring that they are sealed properly.

When planning to drill any borehole (unless you have good confidence otherwise), plan to encounter an artesian borehole and design it so that you can fit an install a suitable cap. Flowing boreholes are not good.

In our case, having used uPVC pump chamber casing, it was possible to glue over the top, a top sleeve with a nylon flange plate fitted (see Figure 56). This was supplied by Boode. A temporary plug was used to seal the borehole to carry out the gluing.

Figure 56 (Left) Applying glue to a uPVC top cap. (Right) Temporary plug to glue on top cap.

We then procured spare nylon flange plates and set about designing a cap that would allow the following:

1. Sample tap – To open and allow samples to be easily collected.
2. Logging pressure – Effectively groundwater level logging.
3. Air valve – For if the artesian conditions declined, to prevent a vacumn.

The result is shown below (Figure 57). Solinst manufacture an artesian well assembly that enables their leveloggers to be read out by either connecting at surface, or by suspending a logger on a direct read cable. They need to make improvements to this but in our case (with a few failures) they have worked.

I also suggest gluing in place with superglue, the rubber o ring to the base of the top flange to prevent it bulging and getting damaged. It is what does all the work to seal the borehole.

Figure 57 (Left) Modified nylon artesian well top flange plate with sample tap, air valve and pressure logger bulkhead fitting. (Right) Open borehole showing nylon flange ring below uPVC edge. (Bottom) Underside of nylon top flange plate showing the all important O ring glued in place.

References

Papageorgiou F., Anders B. & Folye L. CDM Smith. 2023. Blackwater Catchment Hydrochemistry Report. Sampling and Analysis of Groundwater at selected location on the island of Ireland. British Geological Survey and Geological Survey Ireland

Papageorgiou F., Anders B. & Folye L. CDM Smith. 2023. Arney Catchment Hydrochemistry Report. Sampling and Analysis of Groundwater at selected location on the island of Ireland. British Geological Survey and Geological Survey Ireland

Schuster, E.T. and White, W.B. 1971: Seasonal fluctuations in the chemistry of limestone springs; a possible means of characterizing carbonate aquifers. Journal of Hydrology 14, 93-128.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., and Weiler, M. (2014), Karst water resources in a changing world: Review of hydrological modeling approaches, Rev. Geophys., 52, 218–242, doi:10.1002/2013RG000443.