KARST HYDROGEOLOGY OF MID-ROSCOMMON

Field Guide

International Association of Hydrogeologists (IAH)
Irish Group

2018

Cover page: ***A view across the Rathcroghan Uplands landscape at Kilree, near Tulsk, where the dry landscape is dissected by a deep channel, iris-covered at base. The ridges on the horizon are those at Bellanagare, underlain by sandstone bedrock, and the Plains of Boyle*.**

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Programme

Saturday 13th October

10.00 Ballinderry

The National Federation of Group Water Schemes, Mid-Roscommon Group Water Scheme, delineating Zones of Contribution (ZOCs) in karst, overview of study and excursion area, moving from ZOCs to SPZs (Source Protection Zones)
Joe Gallagher, Noel Farrell, Coran Kelly

11.00 Ogulla

The setting at Ogulla Spring, water quality issues, pressures, patterns of contamination, investigative work carried out, Source Protection Plans
Joe Gallagher, Noel Farrell, Coran Kelly

12.00 Carrowreagh

Swallow holes and dolines, the issue of surface water sinking underground, tracer testing and what it shows, general groundwater quality in karst, potential measures
Coran Kelly, Natalie Duncan, Damien Doherty

13.30 Lunch in The Rathcroghan Centre, Tulsk

14.40 Oweynagat

Caves in Roscommon, cave hydrogeology
David Drew

16.00 GSI's Roscommon Core Store

The succession in borehole GSI-16-002,Castlemine, County Roscommon
Markus Pracht

Sunday 14th October

09.10 Correal Turlough

Groundwater Flooding, the GW Flood Programme, Monitoring, Mapping and Modelling, drainage and turloughs
Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

10.00 Castlestrange Group Water Scheme

Delineating a ZOC for a weirdly karstic locality, wellhead protection
Gerry Baker

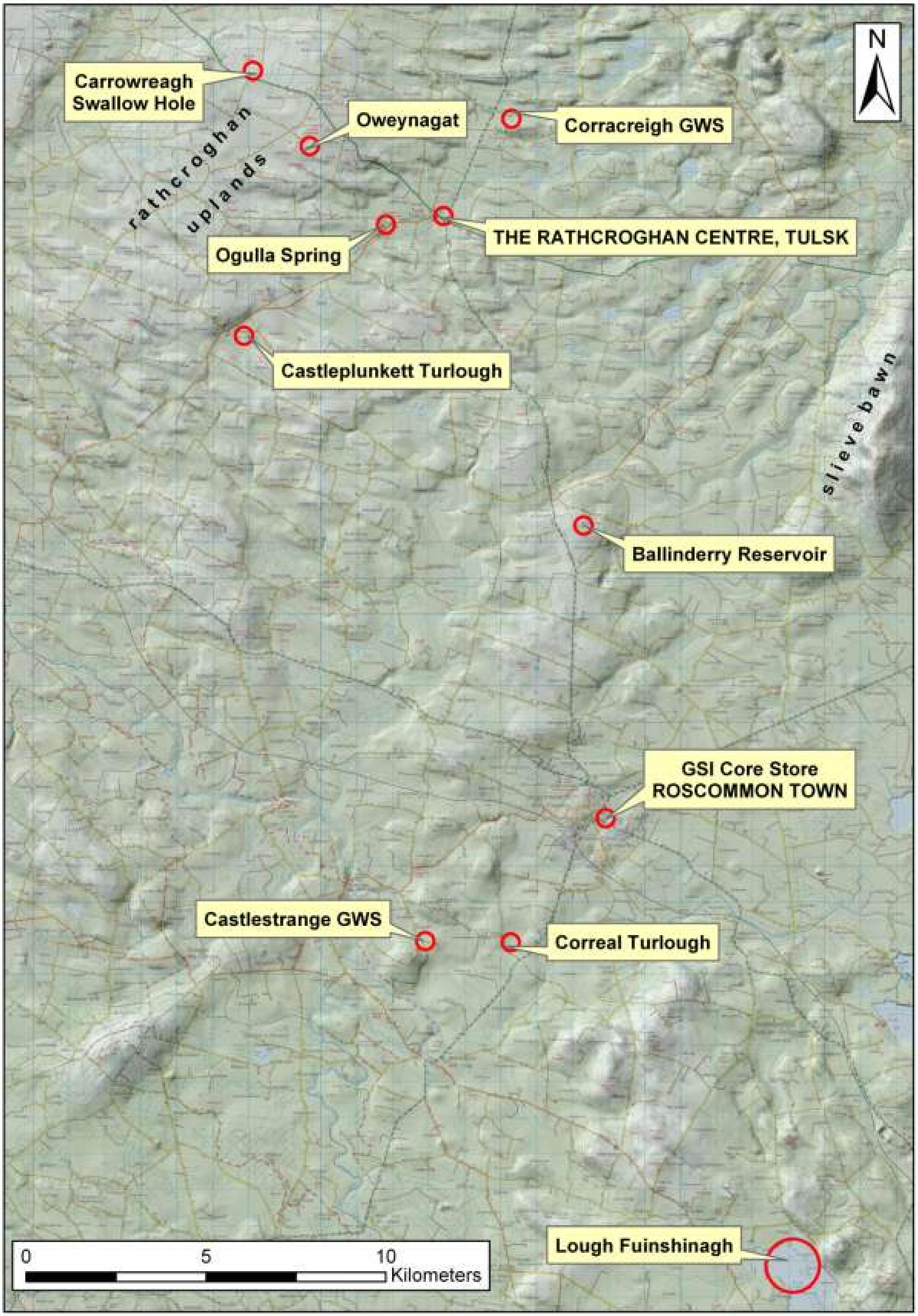
11.00 Castleplunkett Turlough

How Castleplunkett floods, future work here, LIDAR.
Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer, Shane Carey

14.00 Lough Funshinagh

Monitoring results on a weirdly karstic lake, how the lake floods, local issues.
Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

Location Map



Map showing field trip stops and other selected localities mentioned in this guide.

Preface

Just as with our field trip last year, on our annual field excursion this year we enter another sacred landscape – that of Rathcroghan and the area surrounding it, in County Roscommon. There exists an abundance of archaeological sites within this region, with many of these sites having distinct relationships with the local soils and subsoils geology, geomorphology, and hydrogelogy. In a broader sense, the wider County Roscommon has a geologically diverse landscape with many places treasured by both natives and visitors.

For early humans in Ireland, the landscape presented high escarpments, wide plains, belts of hummocky terrain, extensive bogs and deep river valleys, all of which played important and different roles in everyday life. This provided a challenging, but more often than not accommodating, territory in which to settle.

Where water was found in the landscape was of paramount importance. Much of the upland areas of Roscommon are effectively bone dry, with shallow, permeable soils and subsoils allowing ready infiltration to deep groundwater. Thus, springs, as we will see on our excursion, have long been an important focus as a water source. This continues today, with almost all of County Roscommon's drinking water supply coming from groundwater. In a ritual sense, hydrological and hydrogeological features have attracted interest, wonder, folklore and stories for centuries. So also they do today, as we hear of the most recent investigations into a particularly hidden, but particularly amazing, hydrogeological framework beneath Roscommon county.

As we examine turloughs this Sunday, we will learn that they are much changed over time. From this, consider how important these features would have been as a food source historically. Today, frogs and newts may spawn in turloughs and sticklebacks may survive in larger turlough features, retreating into underground cracks in the rock when waters are low. Shrimp and water-lice survive similarly. Where these larger fish are absent water-fleas and fairy-shrimp are found in abundance. During winter turloughs always attract flocks of geese, whooper swans, wigeon, teal, and waders such as plovers, lapwings and sandpipers.

Following the last Ice Age, and for almost two thousand years, much of the lowlying areas of the Irish landscape were inundated with water and many of the turloughs were at that time permanent lakes. Therefore it is quite plausible that they had a wider variety and more continued presence of freshwater fish and water birds at that time and for many hundreds of years after this (*i.e*. possibly up until 7,000 years ago). Turloughs such as those we will visit at Castleplunkett would therefore have been an important, concentrated source of food for prehistoric settlers in this part of Ireland.

We must always consider that what we see today in the natural landscape may have changed in many ways since we humans arrived. The investigations we will see, examine, scrutinise and discuss show us only some of the picture. Where we have difficulty interpreting, we must always be able to think outside the box. This is what makes hydrogeology such a holistic, fascinating and mind-boggling discipline.

This fact should frame much of our discussion over the next couple of days. I, and all on the IAH Committee, hope you enjoy the trip.

Robbie Meehan
IAH Field Trip Secretary,
11th October 2018

Acknowledgements

This field guide would not have been possible without significant efforts from many people, to whom the IAH are most appreciative.

All contributors produced excellent write-ups of sites, and thanks are due to all for giving us their time in preparation and delivery of the excursion.

We would like to thank all landowners for giving us permission to visit their lands, and it should be borne in mind that any future visits should only ensure when permission has been sought.

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

1. An introduction to the geology of Roscommon

Robert Meehan

Although the geology of Roscommon is absolutely dominated by 330 million years old limestones from the Carboniferous Period, there are much older rocks extending back to nearer 500 million years ago, within the county. In Slieve Bawn, the Curlew Mountains north of Boyle and northwest of Ballaghderreen there are much older rocks exposed at the surface in small windows through the limestones. These include two inliers (older rocks entirely surrounded by younger rocks) north-east of Strokestown and at Slieve Bawn. These rocks are of Ordovician age and are the remnants of a former ocean floor and the roots of a long since vanished mountain chain. They are related to rocks throughout Longford, Down, and into the Southern Uplands of Scotland, but as they occupy such a small area in Roscommon, their story is best told in detail elsewhere.

Surrounding them are some Devonian age rocks, sandstones and gravels laid down by flash floods in a poorly vegetated environment. Both Ordovician rocks and Devonian rocks are partly preserved because they have been lifted up on the east side of a fault, and are now preserved as the more resistant hills known as Slieve Bawn. In the Curlew Mountains north of Boyle and westward through Sligo to Ballaghderreen is a faulted block of the Devonian rocks, uplifted in relation to the limestones either side of the block. The Devonian rocks are mostly sandstones and pebble conglomerates, but include some volcaniclastic rocks; rock material erupted by volcanos but then carried and deposited as sedimentary rocks like the sandstones. The Boyle Road Cutting is a good place to see these rocks.

The Carboniferous limestones are dominantly well bedded, horizontal layers of a remarkably uniform nature. They were originally deposited in a shallow marine environment when Ireland was largely submerged under a warm tropical sea, and the presence of fossils such as corals reflects this. The uniform nature of these beds both across wide areas and vertically in thickness makes it difficult to map different geological formations, and they are often simply considered as ‘shelf’ limestones, from an open, shallow sea. These limestone rocks are present below the surface of the largest part of Roscommon, but are actually rarely exposed. The veneer of glacial sediments hides them, so the few rock quarries such as Keeloges, Castlemine and Largan are important examples of what the subsurface is actually like.

Only in the north of the county around Lough Allen are there younger solid rocks, recording a time when the shallow sea was filled with deltas and swamps. In these sandstone and shale rocks there are coal seams formed from ancient forests. The land surface then emerged for nearly 300 million years and many of these rocks eroded down to their present level. Only small parts of the country now remain covered by these coalfield rocks, primarily the Castlecomer plateau in Kilkenny, the Arigna district in Leitrim and the northern tip of Roscommon. Two County Geological Sites in Roscommon are representatives of this geology. The Arigna Mining Experience is a superb place to fully appreciate the underground geology of coal deposits and the mining heritage of the district. Altagowlan, which is Roscommon’s portion of a wider upland area along the Sligo county boundary, exemplifies the place of coal in the energy supply of human society, now visibly met by windfarm turbines scattered through the old coal mine features.

The most significant force to shape the form of the county as we see it today was the Ice Age which ended about 10,000 years ago. Large ice sheets covered the county for thousands of years and eroded the rocks beneath. As the ice eventually melted away, the meltwaters reorganised the sediments into iconic landforms like eskers, adjacent to large fans and deltas of sand and gravel, such as at the Cloonagh and Errit Lough Deltas in the northwest of the county. The fans and deltas now stand out as high ground with good grass amongst the boggier lake margins. Eskers were formed by sub-glacial rivers, that is, they flowed in tunnels at the base of the ice sheets. Some eskers are small and local within Roscommon, but others form extended networks and cross several counties. The Ballinasloe–Split Hills-Clonmacnoise-Clara Esker System is the most extensive of them, but the Garranlahan Esker is also large and complex. The Castlesampson Esker is smaller but equally valuable as an untouched example of the landform.

Some Ice Age features define the landscape character of large areas yet are so large they can almost only be seen when using satellite or air photo images. West of Boyle for example is a very fine discrete field of drumlins. These whaleback, elongated ridges of glacial till were left by the ice sheets which covered the county. On the ground they form low relief, breaking up any long vistas, but from above or on a map with shaded relief they clearly show the sweeping passage of ice movements. Even larger ribbed moraines, on a kilometre scale, are present across mid Roscommon, but these need a trained eye to discriminate them from remotely sensed images.

Since the Ice Age, the exposed limestone has developed into what is termed karstified bedrock. Water solution of the rock formed some caves, widespread collapse features and enclosed depressions called dolines. Where some larger, temporary lakes were formed when meltwater was prolific, unusual mushroom shaped stones were created by dissolution of the rock that was submerged. Carrowmurragh and Moyvannan Mushroom Stones near the shores of Lough Ree demonstrate it previously once had a far greater extent. Roscommon also has a wealth of seasonal lakes called turloughs, where glacially scoured basins fill with groundwater in the winter and dry out in summer as the water table lowers. Good geological examples of these include Brierfield, Correal, Loughnaneane, Mullygollan and Castleplunkett Turloughs. A special kind of turlough exists at Lough Funshinagh which is a disappearing lake. Rather than seasonal fluctuations it occasionally drains entirely as if someone had pulled the plug in the bath. A kind of pseudo karst landscape has been identified around Killeglan west of Athlone. This is a unique site with limestone boulder ridges formed as glacial deposits. Large parts are untouched and represent a pristine landscape of Roscommon before human intervention and land clearance and enclosures.

Geological processes continue to modify the landscape today, such as with seasonal flooding of the Shannon and Suck River Callows. Slow build-up of alluvial sediments and meandering of the river course can change a landscape scene in human lifespans. Collapses of limestone into cavities beneath are more sudden events and occur in some areas, but such holes are often quickly filled in by farmers and landowners. The most active but unseen geological process going on is the movement of groundwater. Since Roscommon has one of the highest percentages of water supply from groundwater, such as from Rockingham Spring, immense care is needed not to pollute the supply from badly maintained septic tanks or farm practices, as limestone areas are very vulnerable to such destruction of a valuable geological resource. Another geological resource, apart from limestone, coal and groundwater, which was formerly exploited, is the clay deposit at Lecarrow. The Knockcroghery clay pipe industry once supplied pipes for smoking tobacco to all of Ireland from this ancient clay preserved in a karstic doline.

AGE (Million Years Ago)	***ERA***	***PERIOD***	***EVENTS IN ROSCOMMON***	***IF THIS TIMESCALE WAS A DAY LONG ...***
2	Cenozoic	Quaternary	Several ice ages smothering Roscommon, followed in the last 10,000 years by the spread of vegetation, growth of bogs and arrival of humans. Deposition of ribbed moraines drumlins and eskers. Dissolution of limestone beneath Quaternary sediments.	The ice ages would begin 38 seconds before midnight
65		Tertiary	Erosion, especially of limestone. Caves, cavities and underground streams developing in mid-Roscommon. Potential deposition of clay at Lecarrow, near Lough Ree.	The Tertiary period begins at 11.40 pm
145	Mezozoic	*Cretaceous*	*Erosion.* *No record of rocks of this age in Roscommon.*	11.15 pm
205		*Jurassic*	*Uplift and erosion.* *No record of rocks of this age in Roscommon.*	The age of the dinosaurs, starting at 10.55 pm
250		*Triassic*	*Desert conditions on land.* *No record of rocks of this age in Roscommon.*	10.42 pm
290	Palaeozoic	*Permian*		10.30 pm
355		Carboniferous	Land became submerged, limestones with some shales and sandstones deposited in tropical seas across much of Roscommon. Limestones remaining today are pure and unbedded in the majority, with smaller areas of muddier limestones at the edges. Shales and sandstones with coal seams deposited in Arigna district.	Much of Roscommon's current rocks (limestone, sandstone and shale) deposited around 10.10 pm
410		Devonian	Caledonian mountain building. Sandstones deposited in the Curlews and north of Ballaghderreen.	'Old Red' Sandstone deposited at 9.52 pm
444		Silurian	Shallow seas, following closure of the Iapetus Ocean. Greywacke and shales deposited at Bohalas in the northwest of the county.	Starts at 9.42 pm
488		Ordovician	Shales, slates, siltstones and volcanic rocks form across the Slieve Bawn ridge.	Begins at 9.28 pm
542		Cambrian	Opening of the Iapetus Ocean. *No record of rocks of this age in Roscommon.*	Starts at 9.11 pm
2500	Proterozoic	*Precambrian*	*Some of Irelands oldest rocks deposited in Mayo and Sligo.*	Beginning 11.00 am
4000	Archaean		*Oldest known rocks on Earth.*	Beginning 3.00 am
4600			*Age of the Earth.*	Beginning 1 second after midnight

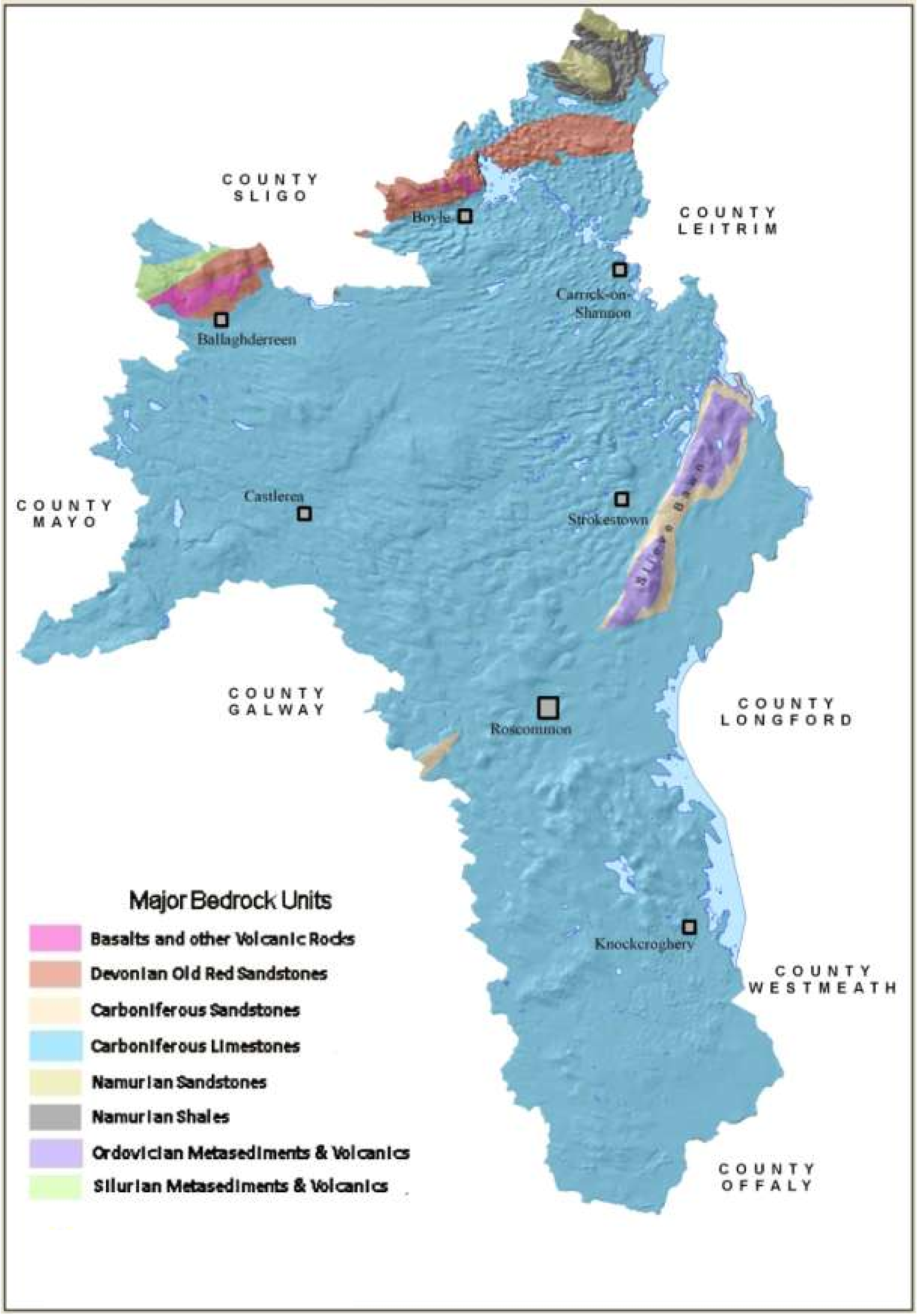


Figure 1. A simplified geology map of Roscommon outlining the main geological units.

2. Group Water Schemes.
Joe Gallagher

What is a Group Water Scheme?
A group water scheme is defined as two or more house connections sharing a common source or supply.

There are 2 types of group water scheme:

- **Private**: Local group abstracts and treats water from their own source eg well, lake and river. The group must ensure that the water is fit for human consumption. Under EU Regulations, the GWS will be legally responsible for water being supplied to its members.
- **Part Private:** Irish Water supplies treated water through the group's pipes. Members are affected by Irish Water charges.

The Group Water Scheme, in both instances is responsible for their distribution network, any maintenance including repair of leaks, scouring of lines and replacement of equipment to a standard to ensure minimum leakage or wastage. Treated water is an expensive commodity so it is important to carry out regular maintenance to ensure minimum leakage or wastage.

The National Federation of Group Water Schemes
The National Federation of Group Water Schemes (NFGWS) is the representative and negotiating organisation for community-owned rural water services in Ireland.

From the outset, the objective of the NFGWS has been to secure equality of treatment, ensuring that those it represents receive their full entitlement with regard to the financial supports already conceded to their fellow citizens in urban areas.

The primary 'external' role of the National Federation of Group Water Schemes (NFGWS) is to assist schemes in meeting the challenges of water quality legislation.

Formation of the NFGWS
Following the announcement of the abolition of service charges in respect of domestic water supplies on public water schemes operated by local authorities around the country in 1996, the private group scheme sector, serving in the region of 150,000 homes and rural businesses was excluded from the announcement and required representation. In 1997 the National Federation of Group Water Schemes was established following a series of meeting of Group Water Schemes, and was quickly recognised as the representative organisation for private and part-private group water schemes in Ireland. The Federation was incorporated as a co-operative society in 1998.

The Work of the Federation Today
- Securing funding for a range of activities and measures such as the following:
- Achieving water quality through the installation of water treatment facilities and Source Protection.

- Maintaining water quality through the implementation of a Quality Assurance Scheme, which provides a guarantee that treated water is delivered safely to members' taps.
- Water Conservation through metering of all connections and creating district metered areas.
- Meeting the numerous challenges of compliance and regulations through recruitment and training at both operational and management level.
- GWSs viability into the future through rationalisation and amalgamations.

3. Mid-Roscommon Group Water Scheme.
Noel Farrell

Mid-Roscommon Co-Operative Society Limited is a large private Group Water Scheme that was formed on June 12th 2007. It is the amalgamation of 10 smaller private group water schemes- Ardkennagh Tulsk GWS, Carnalasson Caggle GWS, Carrowcrin GWS, Derphatten GWS, Hollywell Derrane GWS, Grange Fourmilehouse GWS, Grage Lower GWS, Ogulla GWS, Rathmore Ballinderry and Shadlough GWS. In 2010, we entered into a DBO (Design, Build, Operate) contract with Glan Agua which entails the designing, building and operating the plant. This is in operation since June 2011.

Mid-Roscommon has two spring sources at different locations- Ogulla, Tulsk and Doorty, Fourmilehouse. The GWS has two reservoirs and treatment plants located at Lismurtagh, Tulsk and Ballinderry, Fourmilehouse. The Scheme supplies water to 900 members with approximately 1,800 connections.

There are bulk meters and loggers located at different points on the GWS which enable us to monitor the water usage in each area. All service pipe connections are metered. Bulk meters are monitored on a daily basis, while water meters are read four times a year, and people with high usage are notified.

4. The Rathcroghan Area, County Roscommon.
Damien Doherty, Natalie Duncan, Coran Kelly, Robert Meehan, Sara Raymond, Melissa Spillane

The majority of the bedrock of County Roscommon comprises undifferentiated pure bedded Carboniferous limestones. These rocks are categorised as karstified limestones, occupying approximately 1800 km^2 of Roscommon's 2500 km^2 (Figure 2).

Due to the combination of a temperate climate and a relatively low-lying glacio-karst terrain, there are numerous and ever-evolving groundwater-surface water interactions, which are expressed on the surface as numerous swallow holes, enclosed depressions, turloughs, large karst springs.

County Roscommon has been the subject of hydrogeological investigations and studies over the last few decades. It was one of the first counties to have a

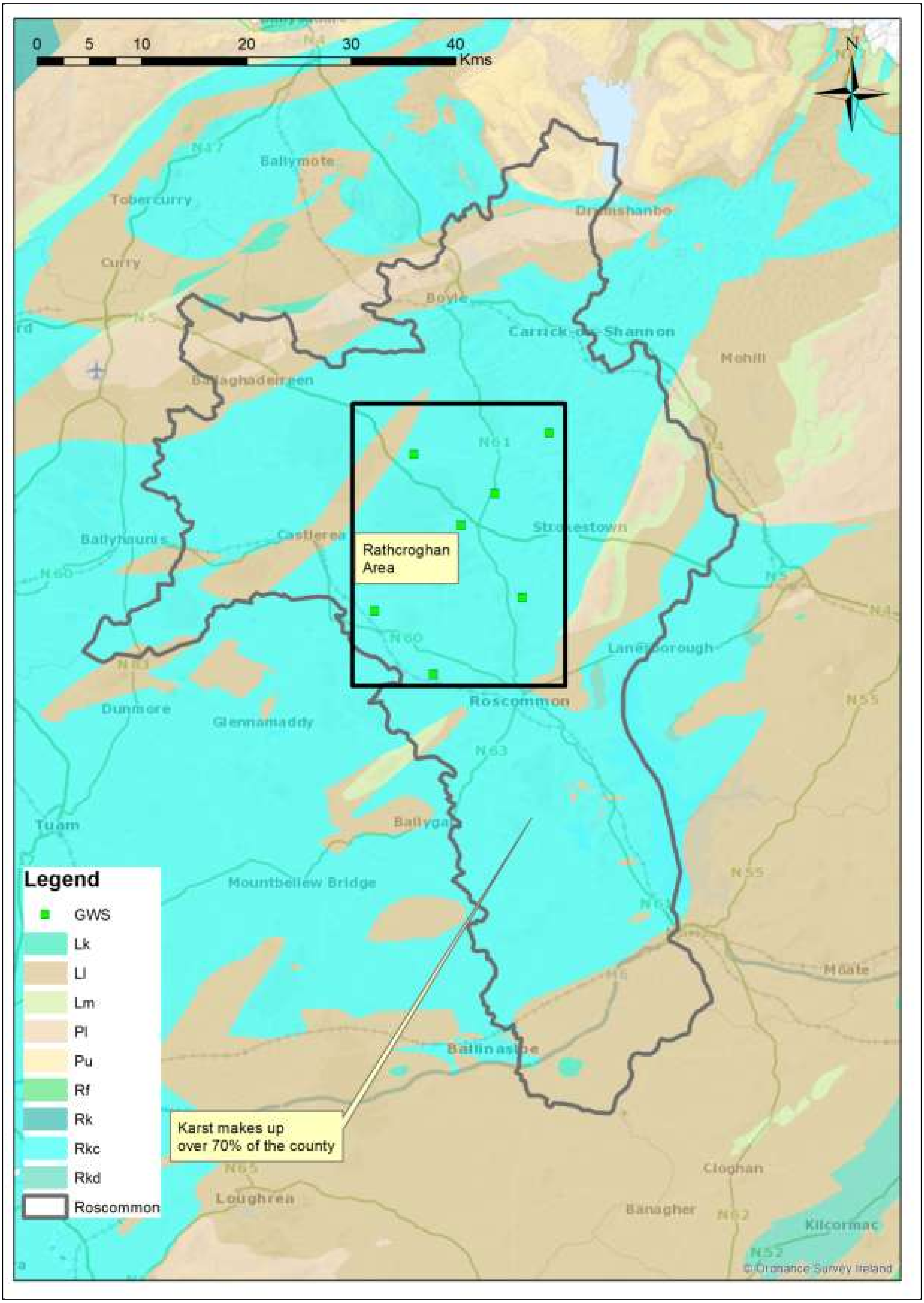


Figure 2 County Roscommon, Rathcroghan Study area, Group Water Schemes associated with the study and the bedrock aquifer map

Groundwater Protection Scheme (Lee and Daly, 2002). One of the main reasons for this is the reliance on groundwater for drinking water. In more recent times, Geological Survey Ireland and the National Federation of Group Water Schemes set about furthering the understanding groundwater characteristics for several supplies sourced by springs in the Rathcroghan area. Whilst relatively small abstractions, their respective catchments are disproportionately large which presents challenges for source protection. Additionally, this landscape presents challenges for determining optimal flood relief options, land use management, catchment management, water provision and treatment, conducting risk assessments, enforcing regulation, and building roads.

Ogulla Spring 2018
Can St. Patrick banish the nutrients?

Physical setting and hydrogeological characteristics

The Rathcroghan area is located in central Roscommon between Strokestown, Castlerea, and Roscommon (Figure 2). It is a karst limestone plateau of approximately 200 km^2 and 40-150 m above sea level. The plateau generally receives 800 mm of rainfall per year and is characterised by ephemeral sinking streams, enclosed depressions (dolines), swallow holes, caves[1], turloughs[2], a general absence of permanent surface water courses, and relatively large springs dotted around its perimeter. Several of these springs supply drinking water to Public and Group Water Schemes. Contamination of these springs is relatively common, and severe pollution incidents have occurred.

The bedrock geology (Morris, *et al.*, 1999) consists predominantly of undifferentiated Visean, pure, bedded, karstified limestone with a relatively large number of mapped karst features that are critical to the hydrological and hydrogeological regime (Figure 3). The main structural trend is southwest to northeast.

[1] Please see David Drew's text in this guide on Oweynagat cave.

[2] Please see Ted McCormack's text in this guide on Castleplunket Turlough, which is located in the Rathcroghan area.

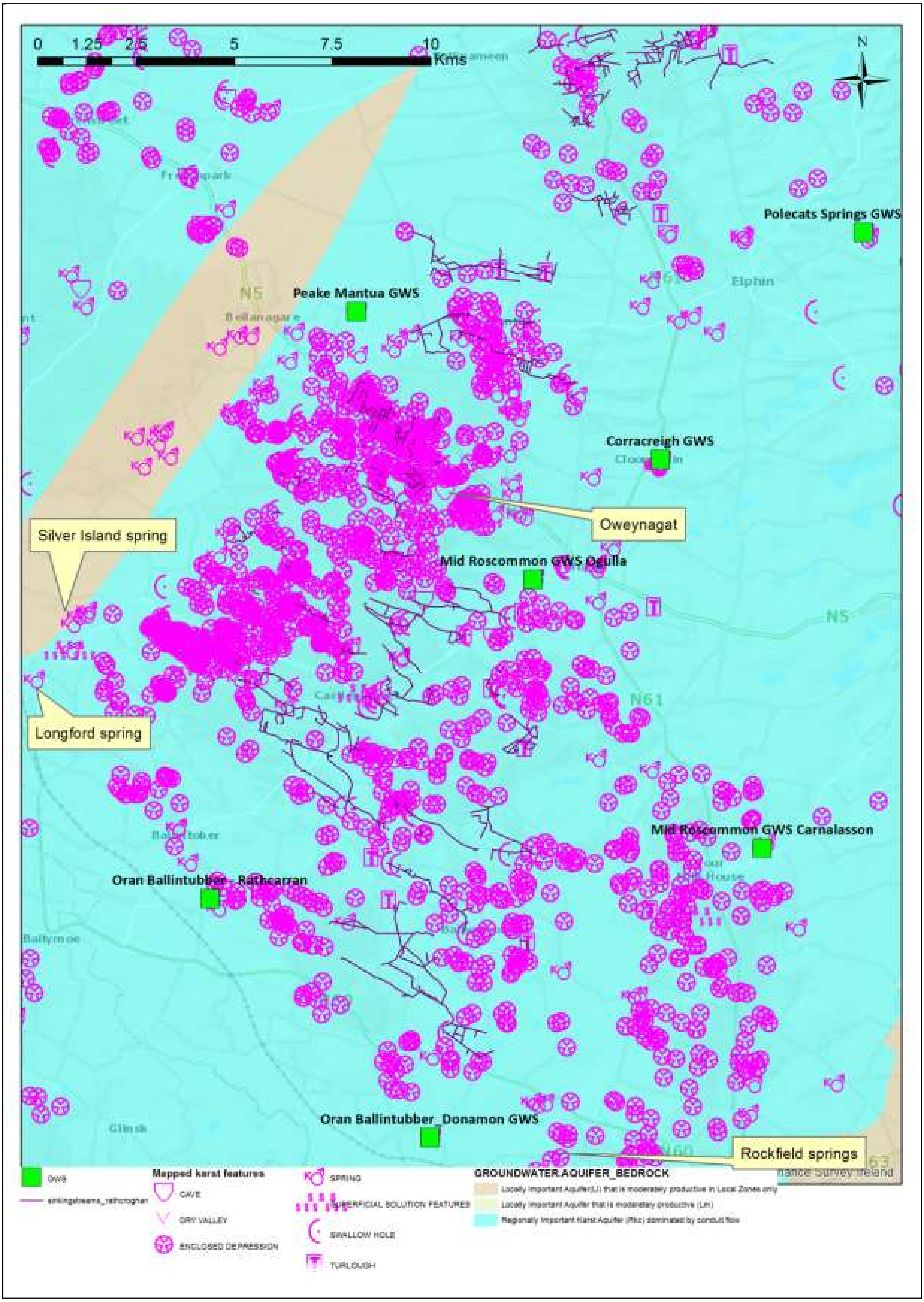


Figure 3 Bedrock aquifer, karst features and sinking streams.

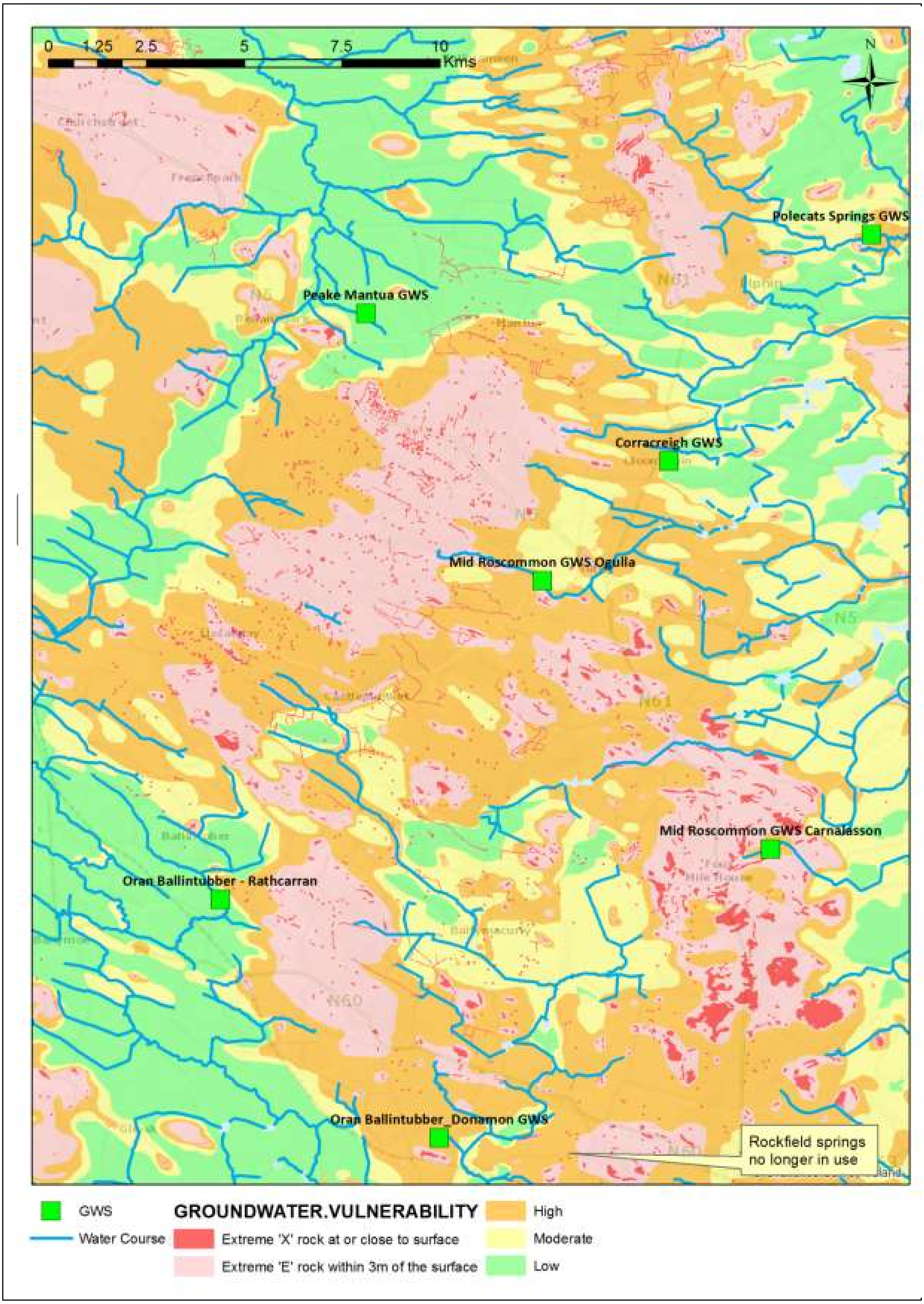


Figure 4 Current groundwater vulnerability (GSI) (1:40,000) in the Rathcroghan area.

Deep, mineral, poorly drained, ('wet') soils are the dominant soils type across the area. Many areas of cutover peat, pockets of lacustrine clay and alluvium are also mapped. Glacial till ('boulder clay') deposits are the predominant subsoil type. Bedrock is generally close to the surface across the plateau.

Groundwater vulnerability is generally mapped as 'Extreme' across the majority of the area of the Rathcroghan Uplands, where bedrock is often close to surface and karst features (swallow holes, enclosed depressions and sinking streams) are present in abundance (Figures 3 and 4). In the northeast and the central portion of the area, where drumlins occur and where 'moderate' permeability till is present; the groundwater vulnerability is mapped as 'High'. Generally off the plateau and on the lower ground, 'Low' groundwater vulnerability is mapped due to the presence of thicker, 'low' permeability subsoil.

Delineation of ZOCs and Conceptual model

In order to protect the quality of the supplies it is important to establish the surface and subsurface catchment areas, or 'Zones of Contribution' (ZOC), within in which rainfall and potential contaminants may enter groundwater and move towards the source. These ZOCs provide an area in which to focus further investigation and implement protective measures to manage the groundwater quality and sustainable abstraction rates. Given the unpredictable nature of karst groundwater, particularly the direction of groundwater flow, establishing ZOCs requires specific techniques, significant resources, suitable antecedent weather conditions, and time.

Lee and Kelly (2003), Drew (2005), and Hickey (2008) provide important insights into the groundwater behaviour in the uplands. These investigations, predominantly tracer studies, established ZOCs to the water supply springs at Castlerea and Rockfield (no longer in use) located on the western and southern perimeter of the uplands (Figure 5). One of the working assumptions made in understanding groundwater behaviour in the region is that the Rathcroghan Uplands are both a topographic/surface water divide and a groundwater divide with groundwater flow directions expected to broadly follow the topography (Hickey, 2008). Whilst this is broadly true, the tracing by Drew (2005) in the Rockfield spring area, show groundwater flow directions contrary to surface water flow, indicating complicated interactions between surface water and groundwater. All these investigations suggest that dye tracing is one of the most important tools available to determine flow directions in such terrain.

Geological Survey Ireland in collaboration with the National Federation of Group Water Schemes (NFGWS) prepared desk-based ZOCs for each of the Group Water Schemes (GWSs) as part of a national programme (Kelly, *et al.,* 2015; Meehan, *et al.,* 2015). Knowing the uncertainties on groundwater flow direction, multi-dye tracing investigations were carried out in 2015 and 2016 on and around the Rathcroghan Uplands in an attempt to establish geo-scientific ZOCs for all the water supplies in the area (Duncan *et al.,* 2015, 2016).

The tracing in 2015 and 2016 comprised dye inputs at 16 swallow holes and sampling of some 90 sample points, including springs and surface water courses. This work also included tracing done in conjunction with Geological Survey Ireland, as part of an environmental study for a road realignment proposal for the N5. The

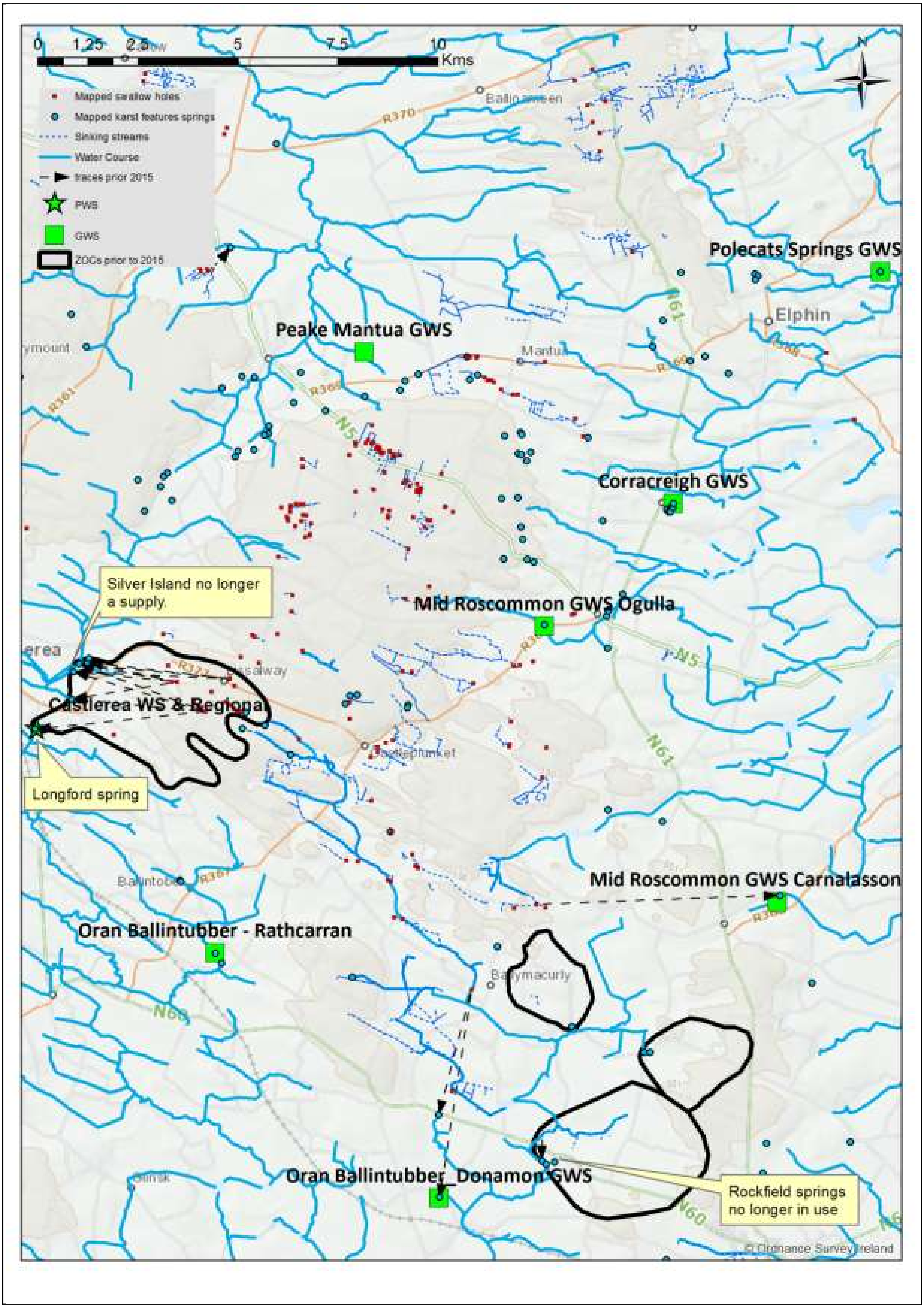


Figure 5 Rathcroghan Uplands, water courses, springs (including PWS – Public Water Supply and GWS - Group Water Scheme Springs) and ZOCs delineated prior to 2014.

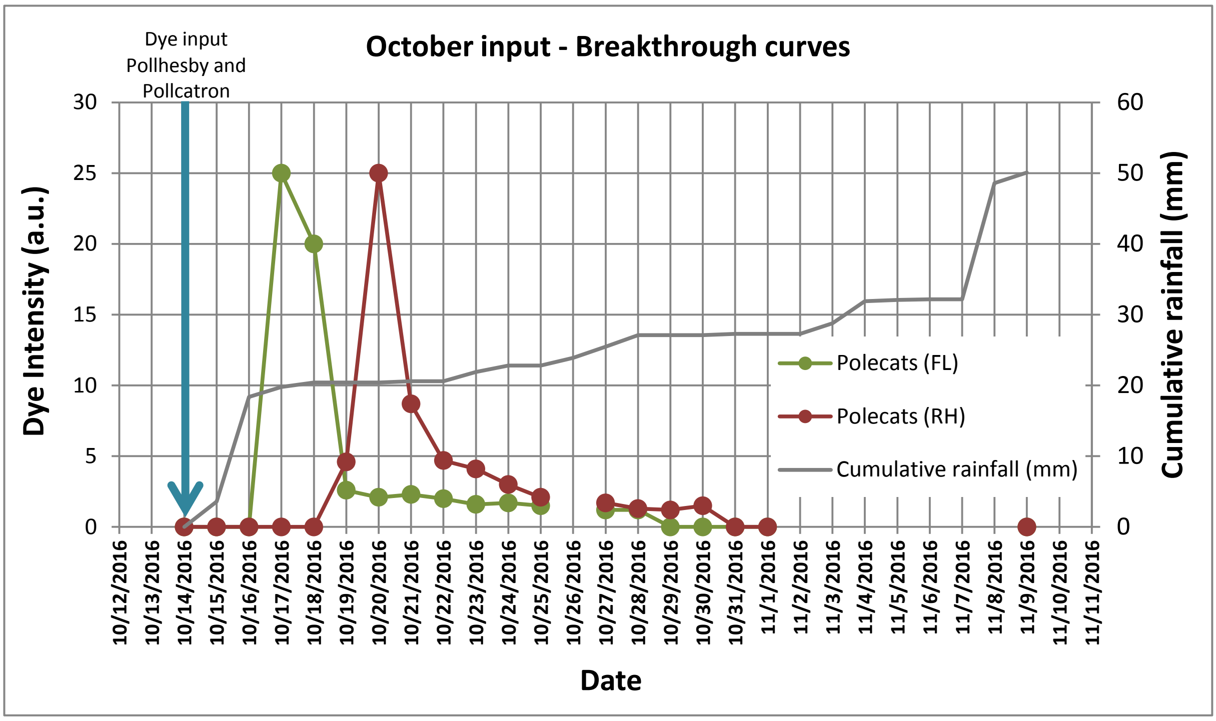


Figure 6 Breakthrough curve for Pollhesby and Pollcatron to Polecats.

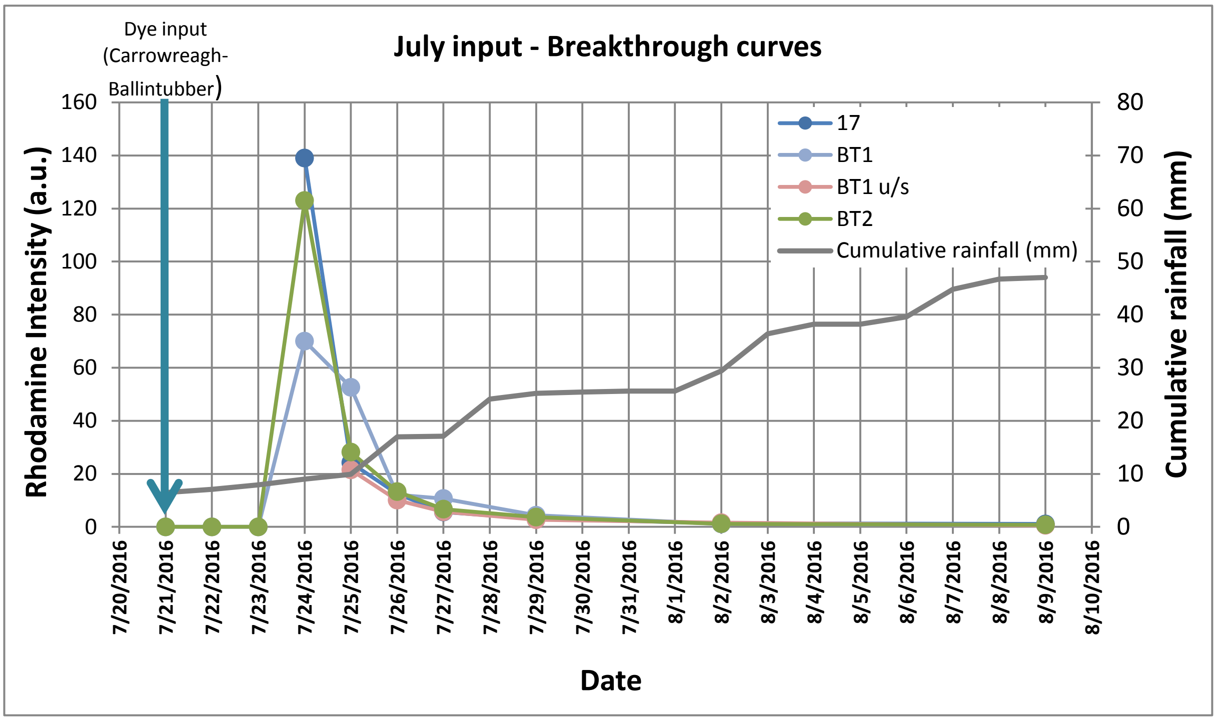


Figure 7 Breakthrough curve for Carrowreach to Ballintubber.

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resulting data, provided sufficient information on the overall groundwater flow directions to the main springs to enable ZOCs to be delineated with some confidence and the creation of site specific conceptual models.

The groundwater velocities were rapid with dye appearing in the springs within days, including those that travelled significant distances, up to 10 km in some cases. The typical average groundwater flow rate is 100 m/hour and selected breakthrough curves are provided in Figure 6 and Figure 7. The results highlight an intricate network of flow with some unexpected directions, and provided evidence for delineating a 'jigsaw puzzle' of abutting ZOCs across the entire uplands. The results demonstrate that each of the springs is fed by groundwater originating in the uplands and also that each of the main springs is fed by a specific ZOC. The total area encompassed by the zones of contribution is approximately 200 km^2. Figure 8 shows a conceptual model for the flow to Ogulla Spring. The difference between the original desk-based ZOCs and updated ZOCs is illustrated in Figure 8 and demonstrates the importance of detailed, karst specific, investigation in karst.

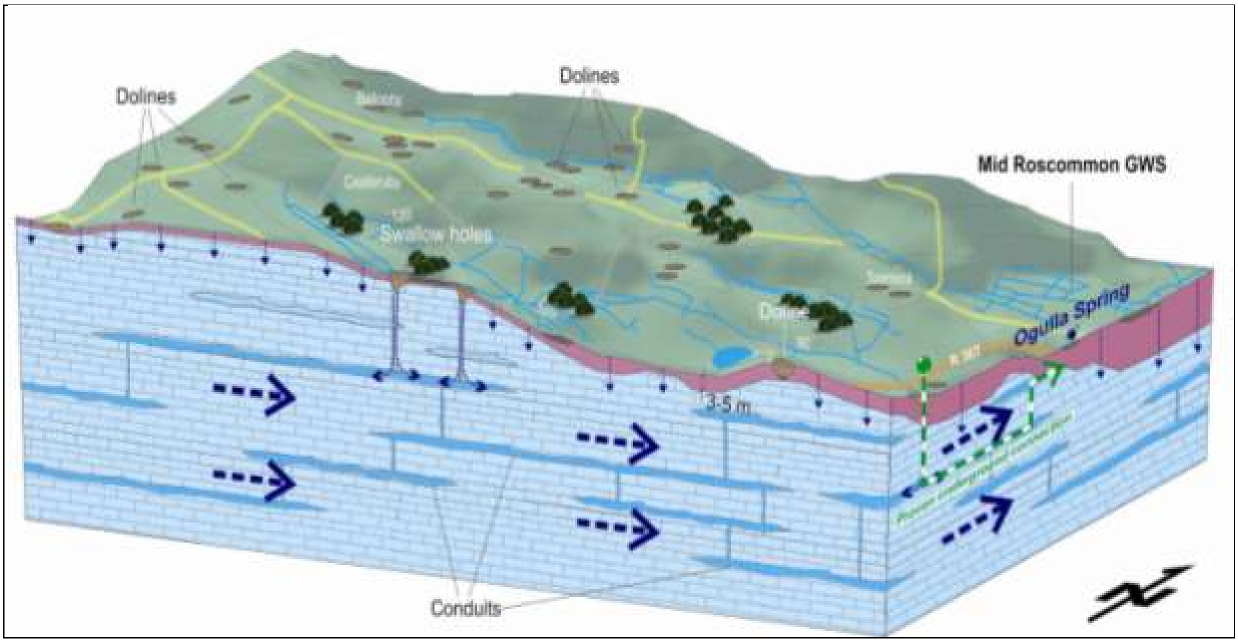

Figure 8 Conceptual model to Ogulla Spring showing one of the traces

Whilst the tracing has been successful in establishing robust ZOCs (based on the tracing and topography), uncertainties remain. Each boundary needs to be treated with caution, in particular, the boundaries to the south-western portion of the Polecats GWS ZOC which adjoins the Corracreigh ZOC; the overlapping area of the Corracreigh/Polecats ZOCs where dye injected at one swallow hole arrived at both springs; and the south-western portion of the Rathcarran ZOC. The traces also suggest that surface water and groundwater divides are not coincident in all cases, *e.g.,* traces to Corracreigh, Rathcarran and Donamon. The area of the Rathcroghan upland west of Ogulla and Corracreigh springs ZOCs and northwest of Rathcarran ZOCs is assumed to feed water westwards, where there are several springs and water courses. One trace was attempted from this area but the tracer was not recovered at any of the sampling locations.

A water balance calculation estimates the combined annual average outflow from the main supply springs, based on a range of low to high annual average recharge conditions and the area of the ZOCs, is estimated to be in the order of 1,300 to 4,400 l/s. A crude approximation of the combined mean flow from the main supply springs is approximately 4,000-5,000 l/s based on a few spot measurements. However, the measured overflow data are sparse. There are small springs within the zones of contribution which are active in wet weather that overflow to surface water courses or sink back underground and there is no information on the water course flows. It is assumed that the ZOCs are broadly correct and that the expected flow represents the total flow out from the catchment even though there are surface water courses exiting these catchments. Given the uncertainties there is a broad agreement in the water balance.

Further hydrogeological investigations are required on the flows from the springs and the sinks (to compare against the outflows), water quality information, additional tracing, field scale karst feature mapping, including investigations into the depth to bedrock in rock close areas.

On-going current work

The National Federation of Group Water Schemes and Geological Survey Ireland are currently engaged in a pilot project which includes all of the Rathcroghan GWSs. This work centres on communicating and working with the stakeholders in raising awareness, defining areas where activities and pressures can be managed through effective implementation of appropriate measures. The area encompassed by the ZOCs is large and in terms of groundwater source protection presents a challenge to the individual water supply schemes. This pilot is working to protect their schemes as a whole, rather than individually.

Conclusions

Given the uncertainties in flow directions, establishing ZOCs in karst requires specific techniques, significant resources, suitable antecedent weather conditions, and time. As Figure 8 demonstrates, the confidence in the ZOCs is directly proportional to the amount of resources invested. The dye tracing conducted in the Rathcroghan Uplands has provided a great deal of information on the groundwater characteristics, specifically groundwater flow directions and rates. The information obtained enabled individual ZOCs to be defined for each of the water supply schemes and highlights vulnerable areas within these catchments. There are areas within the ZOCs that are riskier than others and thus there is a hierarchy that can assist the schemes to tackle priority sites, *i.e.*, swallow holes and sinking streams.

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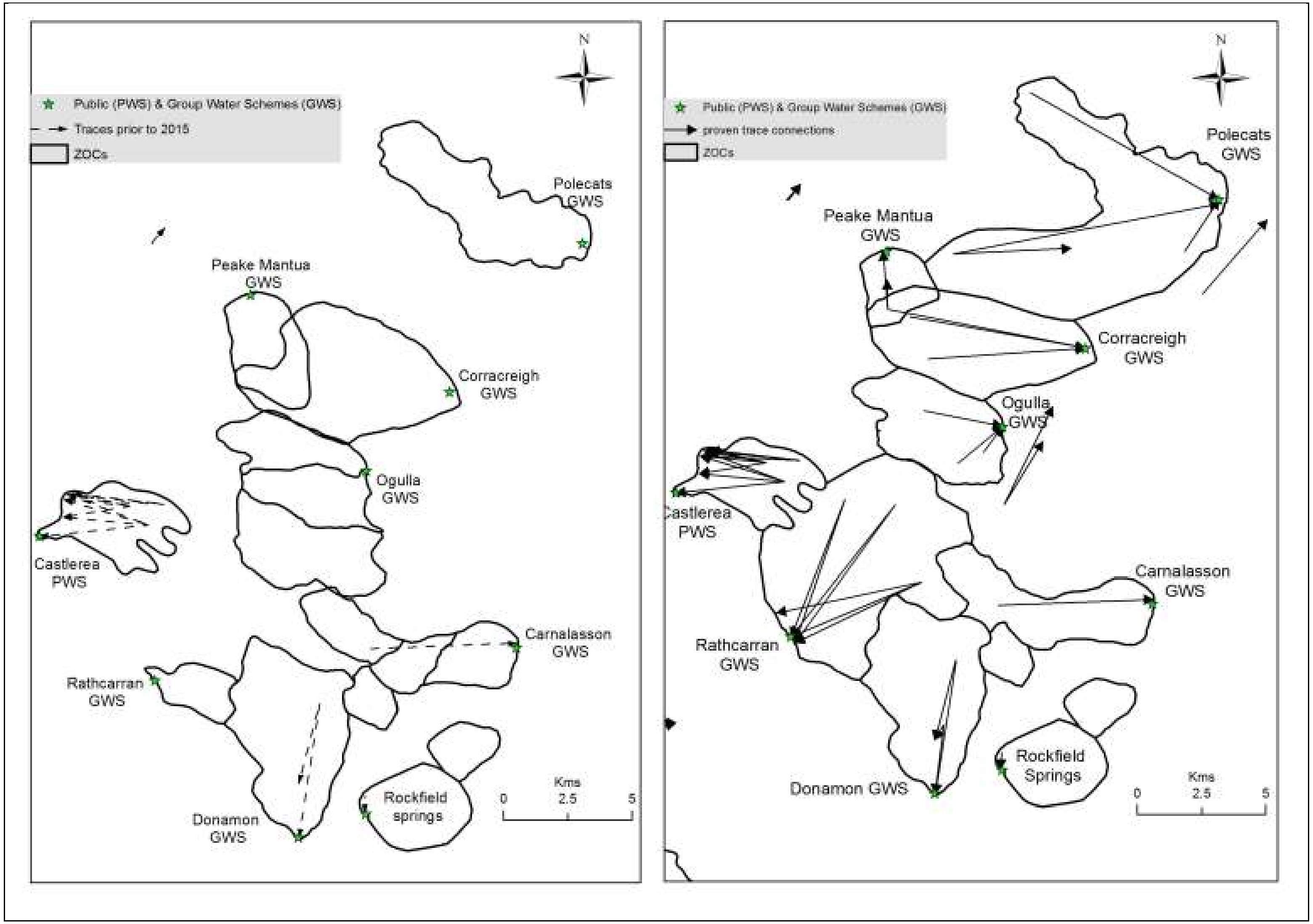

Figure 9 Proven traces and desk-based protection zones prior to 2015 on the left and protection zones established in 2017 based on subsequent tracing on the right.

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5. Caves and karst hydrogeology in County Roscommon.
David Drew

Introduction
As is apparent from this field guide book (sections 1, 4 and 7 in particular), the Carboniferous limestone in County Roscommon is highly karstified and in some aspects it could be considered to be the most 'typical' area of lowland karst in Ireland. However, diagnostic karst features, though ubiquitous (Hickey 2010 states that in excess of 1,300 such features have been documented in the County) are rarely spectacular.

Caves are commonly cited as being characteristic karstic landforms, and this is true if the somewhat misleading term 'cave' is replaced by 'conduit' or 'channel'. Caves are simply conduits that are accessible to humans and they probably represent only a small fraction of the channels available for transmitting groundwater. This may not be the case in some upland areas such as the Burren but is certainly the case in the lowland limestones that comprise the great majority of Ireland's karst terrains.

Only seven features that could reasonably be described as caves are currently known in County Roscommon, of which only one (Pollnagran), gives access to any significant extent of underground passageways. In addition, only one of the known caves (Pollnagran again) is hydrologically active; the remainder are relics of past hydrogeological conditions in the area and are disconnected from the present day groundwater circulation system.

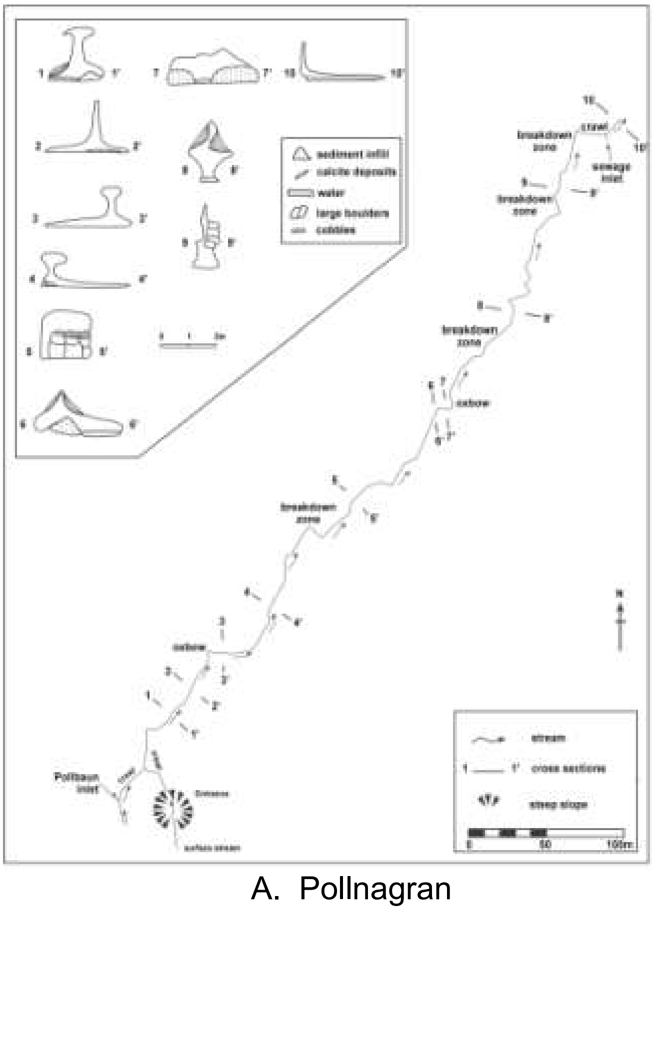
It might be expected that streams flowing from elevated areas of non-limestone strata would sink underground upon reaching the contact with the limestone –for example the Slieve Bawn ridge in the east of the County and the Curlew Hills in the west. However, this is not the case and the only stream sinks associated with this geological contact are those in the Frenchpark area on the margins of the narrow band of Boyle sandstone extending northeast from Castlereagh and rarely elevated more than 15m above the surrounding limestone. However, all of the caves apart from Pollnagran are located on low limestone plateaux of which Hickey (2010) has identified eight in County Roscommon. Plan surveys of all seven known caves in the county are given in Figure 1. Estersnow, Oweynagat and Ballynagoogh caves are fragments of ancient phreatic caves wholly unrelated to the present topography and having no flowing water. Pollnagollum at Frenchpark is a collapse doline, 5m deep, which is intersected by a small vadose cave passage containing a stream. Lissany cave is developed at the base of the epikarst in an area in which collapses are common. In wet weather the cave contains a considerable stream which deposits sand when it ceases to flow. This is the only cave of those described which is probably of post-glacial origin and which relates to present day hydrogeological conditions. Pollawaddy preserves fragments of a horizontal, phreatic network of conduits invaded in part by a sinking stream. Finally, Pollnagran, at Frenchpark, with 750m of surveyed passage, is the only example of an active, vadose streamway cave fed by a sinking stream. The water reappears from a spring only a short distance from the surveyed end of the cave having passed beneath the N5 road at shallow depth en-route. The location and character of this cave conduit suggests that it developed under present day conditions (i.e. during the Holocene). However, the cave has undergone a phase of infilling by fluvial sediment followed by the partial removal of this material by the present stream. Also there is considerable collapse of walls and roof and extensive deposits of calcite. It is difficult to believe that this developmental history could all have occurred in post-glacial times so possibly the development of the cave began during the last interglacial.

Oweynagat Cave (ITM 579538 783132) is located near the eastern margin of the low limestone plateau that extends west as far as Castlereagh. The cave is developed in undifferentiated Visean limestone, but immediately to the north is a small outcrop of oolitic limestone. The dip of the strata is to the SSE at 2-5^{o}. There are no natural surface karstic features associated with the cave other than the fissure to the northwest of the cave described below. The present day entrance is *via* a souterrain at right angles to the main cave and the first 10m or so of the main cave shows evidence of anthropogenic modification, with a roof comprised of lintel stones. Due to its location in the Rathcroghan archaeological complex the cave has been thoroughly explored and well documented, though much more from an archaeological/folklore perspective ('a gateway to the underworld' *etc*.) than from a karst-hydrogeological viewpoint.

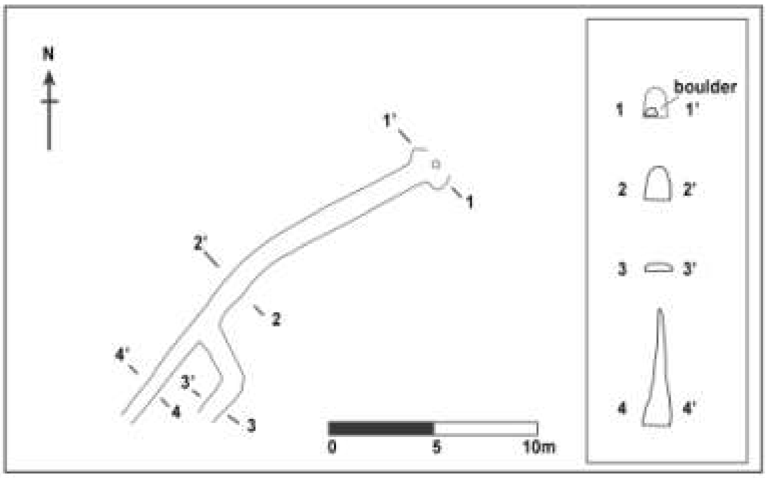
Cave geomorphology

The cave proper consists of a single rift passage 47m long, oriented NNW-SSE (Figure 10-G), the mirror image of the passage orientation of Pollnagran, the only other cave with any significant length of explored passage in County Roscommon. The rift is almost certainly more extensive, as the SSE end is blocked by collapse rocks and clay and the NNW extremity by a clay fill**.** Geophysical data (Dempsey 2012) suggests that a clay filled rift extends to the NNW along the line of Oweynagat. A hollow in the field to the north of Oweynagat is a designated archaeological site but is probably also a collapse doline as it includes a short length of rift passage oriented at 240 degrees (as is Oweynagat), which may well be the continuation of the Oweynagat conduit.

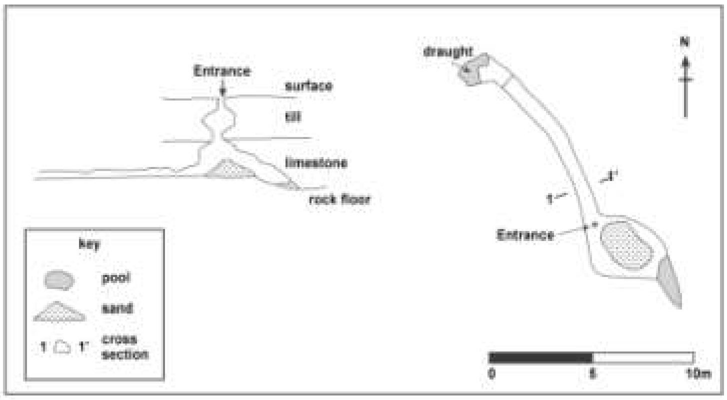
The narrow, rift-like character of the cave and its proximity to the surface (1-2m) suggests that it is simply a solutionally opened joint in the epikarst zone and therefore of Holocene age. However, the cave is almost certainly more complex and much older than this. Nowhere in the cave is a bedrock floor apparent and so the passage must be greater than 7m in height and 2m in width. The cave has a partial fill of sticky red/orange clay and boulders which in places, has been eroded away to a depth of c. 5m. The origin of the boulders is uncertain but the clay seems to be a typical cave fill deposit. Scallops (indicating past water flows) are large (10-20cm diameter) and symmetrical suggesting slow rates of flow in the saturated zone. Thus the cave was hydrologically active under very different conditions to those prevailing today. Overall, the morphology of Oweynagat closely resembles that of many of the inactive caves found in Counties Cork and Tipperary and the cave represents a fragment of an ancient hydrogeological groundwater system in the Roscommon lowland karst.



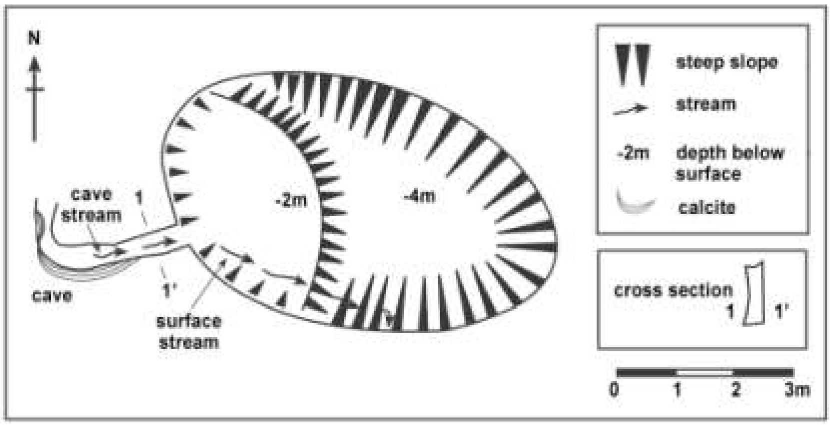
A. Pollnagran



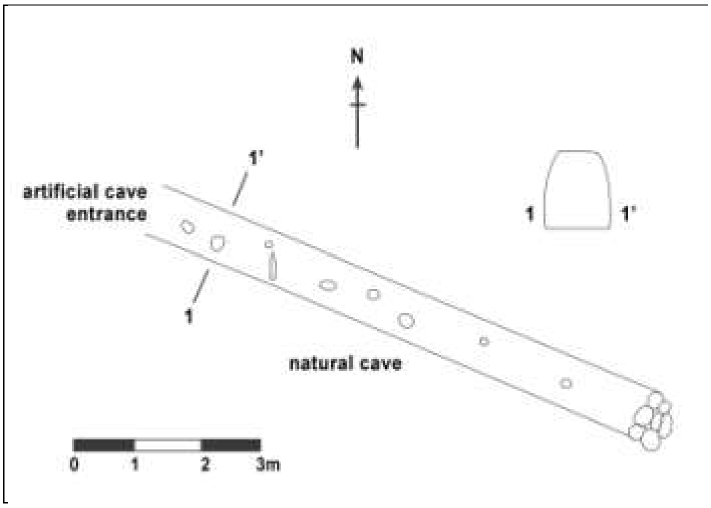
B. Ballynagoogh Cave



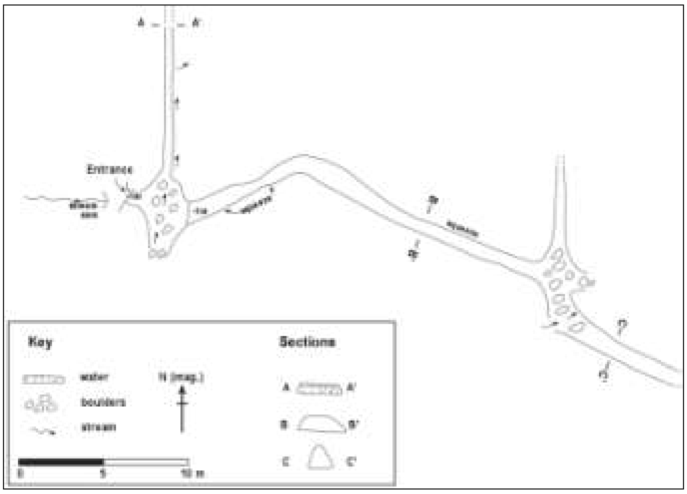
C. Lissananny Cave



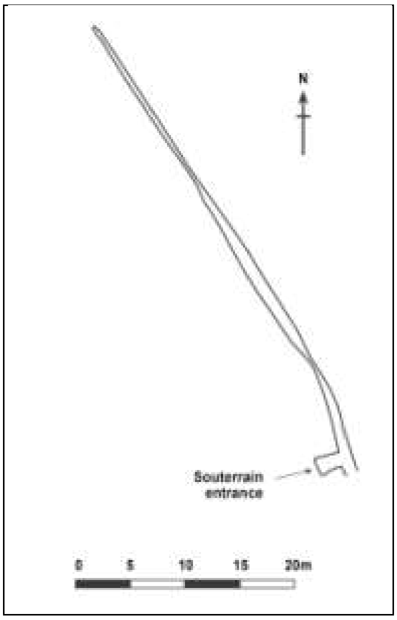
D. Pollnagollum Frenchpark



E. Estersnow Cave



F. Pollawaddy



G. Pollnagat (Oweynagat)

Figure 10 A-G Plan surveys of caves in County Roscommon (Taken from Hickey and Drew 2003).

Summary and conclusions

The limited number of caves and of explored cave passages in County Roscommon give little reliable information concerning the character of the present day hydrological system in the Roscommon karsts. The majority of the caves refer to a sub-water table origin when the environment was very different. Perhaps Lissananny Cave might be most representative sample of present day conditions in the karst aquifer.

There is also some evidence that large karst conduits do exist in the area. Hickey (2010), describes the results obtained by geophysical and drilling investigations in Mewlaghmore, east of Castlereagh, in and adjacent to lines of dolines (McGrath and Drew 2002). There appear to be conduits with dimensions of several metres located at a depth of c. 20m below ground level. The extent to which these conduits are sediment filled or otherwise hydrologically inactive is uncertain but they may represent major flow paths for karst groundwater prior to infilling by glacio-fluvial materials.

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6. Upper Carboniferous (Mississippian) succession in borehole GSI-16-002,Castlemine, Co.Roscommon, Ireland

***Markus Pracht** (based on reports to GSI by I..D.Somerville, UCD)*

Abstract

In borehole GSI-16-002, from Castlemine just north of Roscommon Town, a nearly complete Mississippian (late Tournaisian to late Viséan) succession has been drilled

and cored (Asbian not present). Several carbonate formations have been distinguished by microfacies analysis and their ages established by micropalaentological investigations using foraminifera and calcareous algae. Between 559 m and 893.2m (end of hole) a predominantly siliciclastic succession has been drilled, which did not yield any useful micro-fossils for age dating.. The lower part (819.6m to 893.2m) consists of tectonically deformed green, red and beige sandstone, shales and micro-conglomerates topped by an unconformity. Above the unconformity red and green shales, siltstones, sandstones and conglomerates dominate between 819.6m and 619.6m, assigned to the Fearnaght Formation. The Fearnaght Formation is overlain by 60.6m of Boyle Sandstone Formation, a cyclic sequence of white massive bedded sandstone followed by dark grey to black siltstone, topped by black mudstone/shale, The oldest marine Mississippian (late Tournaisian) strata were drilled between 245.5m and 559m (a thickness of 313.5m). They belong to the "North Midlands Province" . They comprise the Meath Formation followed by the Moathill Formation, the Ballysteen Formation, Waulsortian equivalent lithologies and the Kilbryan Limestone Formation. These rocks reflect an increase in water depth during deposition which in turn is associated with a marine transgression from the south.

The upper part of the cored succession consists of various types of Visean limestones and can be directely correlated with the standard Visean succession of Co. Galway and Leitrim . This succession is dominated by shallow-water limestone (Oakport Limestone Formation, Ballymore Limestone Formation and Croghan Limestone Formarion) that formed the Galway-Roscommon shelf.

Introduction and geological setting

The borehole was drilled as part of an ongoing mapping program to differentiate the Visean carbonate succession (*e.g.* Pracht and Somerville 2015). The borehole is situated in a tectonically defined block, bounded in the northwest by the Slieve Dart inlier and in the south-east by the Strokestown inlier. Based on the thickness of stratigraphic units (Kilbryan Limestone Formation, Oakport Limestone Formation and Ballymore Limestone Formation) in borehole GSI-16-003, Bracknagh (11.5km to the northwest of GSI-16-002), deposition in the northwest on this part of the platform/ramp was thinner than in the south-east (Castlemine borehole).

The core is stored in the GSI corestore in Co. Roscommon. The borehole is located in an active quarry (2016, see pic.1) ca.7km to the north of Roscommon Town and worked by Roadstone (ITM: 87855/71006,). The borehole collard in undifferentiated

Visean limestone and reach its target in “lower Palaeozoic” lithologies. The borehole collard in the quarry floor (no overburden, Pic.2). It was terminated at 893.2m and is as such the deepest hole drilled by GSI up to 2016. 53 samples for facies analysis and age

determinations have been collected and processed by I.D.Somerville (UCD) and M.Pracht (GSI) (MKP-16-102 to MKP-16-119, MKP-16-128 to MKP-16-148, MKP-16-153 to MKP-16-165). The age determination is based on macrofauna (corals) and microfossils (principally foraminifera and calcareous algae).The core is in excellent condition and shows only minor fracturing in places.

Lithostratigraphy, biostratigraphy and microfacies

In the lower part of the borehole the stratigraphic units of the “North Midlands Province” (Philcox 1984, Morris et al. 2003) are clearly recognisable (Fearnaght Formation, Meath Formation and Moathill Formation) The upper part of the borehole is represented by stratigraphic units of the Dunmore-Ballymoe succession of Pracht and Somerville (2015). The Boyle Sandstone Formation (60.6m thick) has been logged in borehole GSI-16-002, Castlemine, between the underlaying Fearnagh Formation and the overlaying Stackallan Member of the Meath Formation.

The description of the various Lower Carboniferous (Mississippian) formations is from oldest to youngest, beginning with with the basal siliciclastics and limestone formations of Tournaisian age. This is followed by a description of younger Visean limestone formation, which areally account for the majority of the Roscommon region and is the main focus of this study. Biostratigraphic dating of the Tournaisian and Viséan limestones has been achieved principally using foraminifers and algae, supported by rugose corals. The assemblages have been assigned to the standard Mississippian foraminiferal biozones MFZ6-MFZ14 of Poty *et al.* (2006; Table 1) (broadly equivalent to the former Cf2 –Cf6γ zones and subzones, as used in Jones and Somerville, 1996).

AGE	STAGE	SUBSTAGE	FORAM ZONATION (Poty et al. 2006)	DUNMORE-BALLYMOE SUCCESSION (CENTRAL and NE GALWAY)	BOREHOLE, GSI-16-002 CASTLEMINE (Co. Roscommon)	
MISSISSIPPIAN	VISÉAN (pars.)			FORMATION	FORMATION	
		ASBIAN	MFZ 13-14	BURREN		
		HOLK.	MFZ 12	CROGHAN LIMESTONE	CROGHAN LIMESTONE (quarry face)	"DUNMORE-BALLYMOE SUCC."
		ARUN.	MFZ 11	BALLYMORE LIMESTONE	BALLYMORE LIMESTONE	
		CHAD.	MFZ 9-10	OAKPORT LIMESTONE	OAKPORT LIMESTONE	
	TOURNN. (pars.)	COURC.	MFZ 6-8	KILBRYAN LIMESTONE	KILBRYAN LIMESTONE	"NORTH MIDLANDS SUCC."
				not present	WAULSORTIAN LST. or equiv.	
				BALLYSTEEN	BALLYSTEEN LST.	
				MOATHILL	MOATHILL	
				not present	MEATH	
				BOYLE SANDSTONE	BOYLE SANDSTONE	
				not reached	FEARNAGHT	

Table 1: Mississsppian lithostratigraphy for Central Galway, NE Galway and Co. Roscommon largely based on borehole information (see also Pracht and Somerville 2105).

Lower Palaeozoic rocks (819.6-893.5m; >73.9m)
The contact between the base of the Lower Carboniferous Fearnaght Formation and the Lower Palaeozoic ('basement') rocks is marked by an angular unconformity. The Lower Palaeozoic rocks dip from 30-40^0 and are overlain by Fearnaght Formation rocks which are gently dipping to horizontal. A tectonic fabric is recognised in the basement rocks which is not developed in the overlying Carboniferous continental red-bed clastic rocks. The Lower Palaeozoic rocks comprise grey and green sandstones interbedded with shales and minor conglomerates. Reddening of the Lower Palaeozoic rocks occurs for tens of metres below the unconformity (to c. 854m). Volcanic rocks are interbedded with the siliciclastic rocks of the Lower Palaeozoic strata.

Microfacies: Ten samples of these rocks was examined in thin section (MKP-16-156 to -165). The majority comprise medium- to coarse grained, poorly-sorted immature sandstones (feldspathic quartz arenites and feldspathic lithic quartz arenites) with angular quartz, plagioclase feldspar, orthoclase feldspar, microcline, muscovite, chalcedony and minor calcite cement.

Basal Carboniferous siliciclastic units (819.6m to 559m)
Fearnaght Formation (619.6-819.6m; 200m)
Above the unconformity an intraclastic breccia marks the base to the Fearnaght Formation. The type section of the Fearnaght Formation in County Leitrim is no longer exposed, but it is estimated that the formation can be up to 300 m thick in the Strokestown area (Morris *et al.,* 2003). The formation consists of red, green and grey mudstone, siltstone and sandstone. Calcrete horizons, caliche, pisolithic beds,

dessication cracks and dewatering structures are common. Some of the sandstone show cross bedding. In thin section the basal breccia consists of medium- to coarse-grained poorly sorted breccias with lithic fragments. Mud and sandy matrix includes detrital quartz, plagioclase feldspar, muscovite, iron oxides and chaclcedony. The sandstones are medium-grained well-sorted feldspathic arenites with angular felspar and quartz grains, occ. with calcareous matrix. Higher up in the Fearnaght Formation septarian nodules appear. No age dates are available for this unit but a lower Carboniferous age is inferred. The sediments were deposited in a continental fluvial semi-arid environment ("alluvial fan") with episodic flooding events.

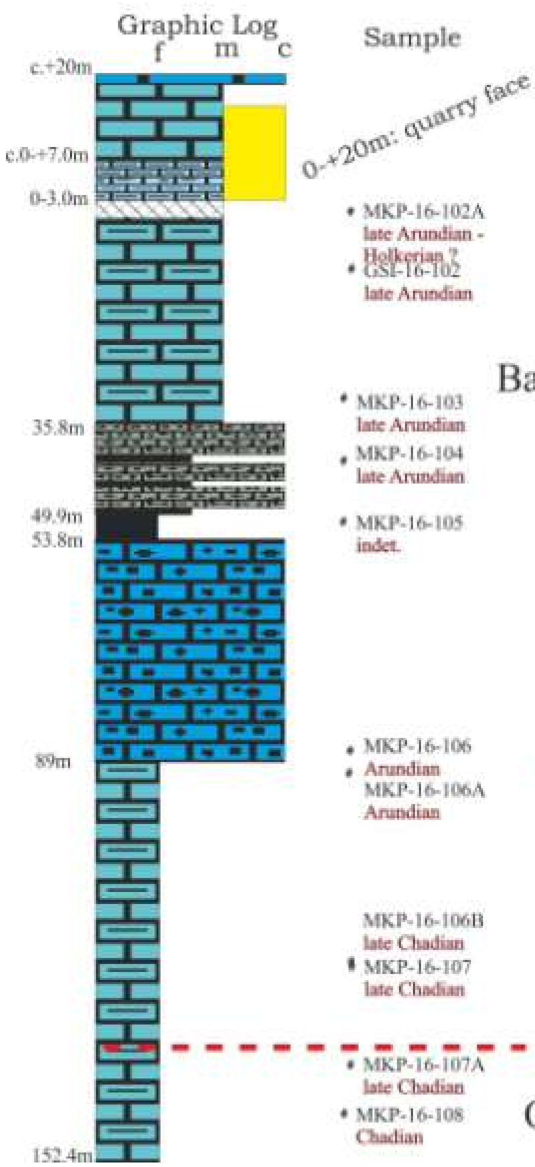
Age: The Fearnaght Formation has been confirmed as Tournaisian age, based on microfossil dating of the overlying limestones near Carrigallen (Morris *et al.,* 1981).

Boyle Sandstone Formation (559-619.6m; 60.6m)
In the north of the region, the basal Tournaisian siliciclastic unit is identified as the Boyle Sandstone Formation and has its type section near Boyle, Co. Roscommon (Caldwell, 1959; Morris *et al*., 2003) where it is c. 100 m thick. It is also present in the Slieve Dart and Castlerea inliers (Pracht & Somerville, 2015). The base is taken at the top of the first green mudstone, siltstone and sandstone beds with rip-up clasts, caliche units and dessication cracks. The upper contact of the Boyle Sandstone Formation with the overlying Meath Formation at 559 m is sharp and defined by the presence of the first marine limestone bed. In borehole GSI-16-002, Castlemine, the Boyle Sandstone Formation consists of cyclic sequences of non-calcareous white massive- to bedded (some bioturbated) sandstones (?= Drumbrick Sandstone Member, see Philcox et al. 1992, re-logged and sampled by Pracht 2016and Lyne 2018) followed by dark grey to black siltstones, topped by black mudstone/shale ?= Lough Key Mudstone Member,). The bedded sandstone/siltstones show current ripples, linsen-bedding and flaser-bedding. Some burrowing also. No age dates are available for this unit but a lower Carboniferous age is inferred.

Age: The Boyle Sandstone Formation has been confirmed as late Tournaisian based on spore data (CM Zone) from the type section in Boyle (Morris *et al*., 2003). In GSI-12-01 (Esker) borehole the Boyle Sandstone Formation (> 30 m thick) is followed by marine limestones of the Moathill Formation (Pracht & Somerville, 2015).

Meath Formation (413-559m; 146m)
This formation comprises an alternation of grey and green calcareous sandstones, red, green, dark grey and black siltstones and mudstones, with thin argillaceous bioclastic limestone intervals, and gypsum nodules and bands (see picture right).

Borehole Number/Name: **GSI-16-002, Castlemine---Reference Borehole**	
GridCoords: 0587809/0771024 (ITM)	Scale: 1:1000
Author: Dr. M. Pracht	Rockhead: 3m
Year: 2016 Elevation: quarry floor	End of Hole: 893.2m
Micro-palaeontology: Dr.I.D.Somerville	Stratigraphy: VIS



Croghan Limestone Formation

medium to coarse grained well bedded light grey lst. with crinoids, large brachiop. (Bellerophontids), oolites,

+7m to 35.8m: medium to fine grained lst. with
conspicious siphonodendron coral colonies (e.g. 2.3m, 12.5m, 13.8m)
echinod., solitary corals, brachiopods,
core variously fractured (heavily: top 3m, 11.5 to 16.8m, etc.)

Ballymore Limestone Formation

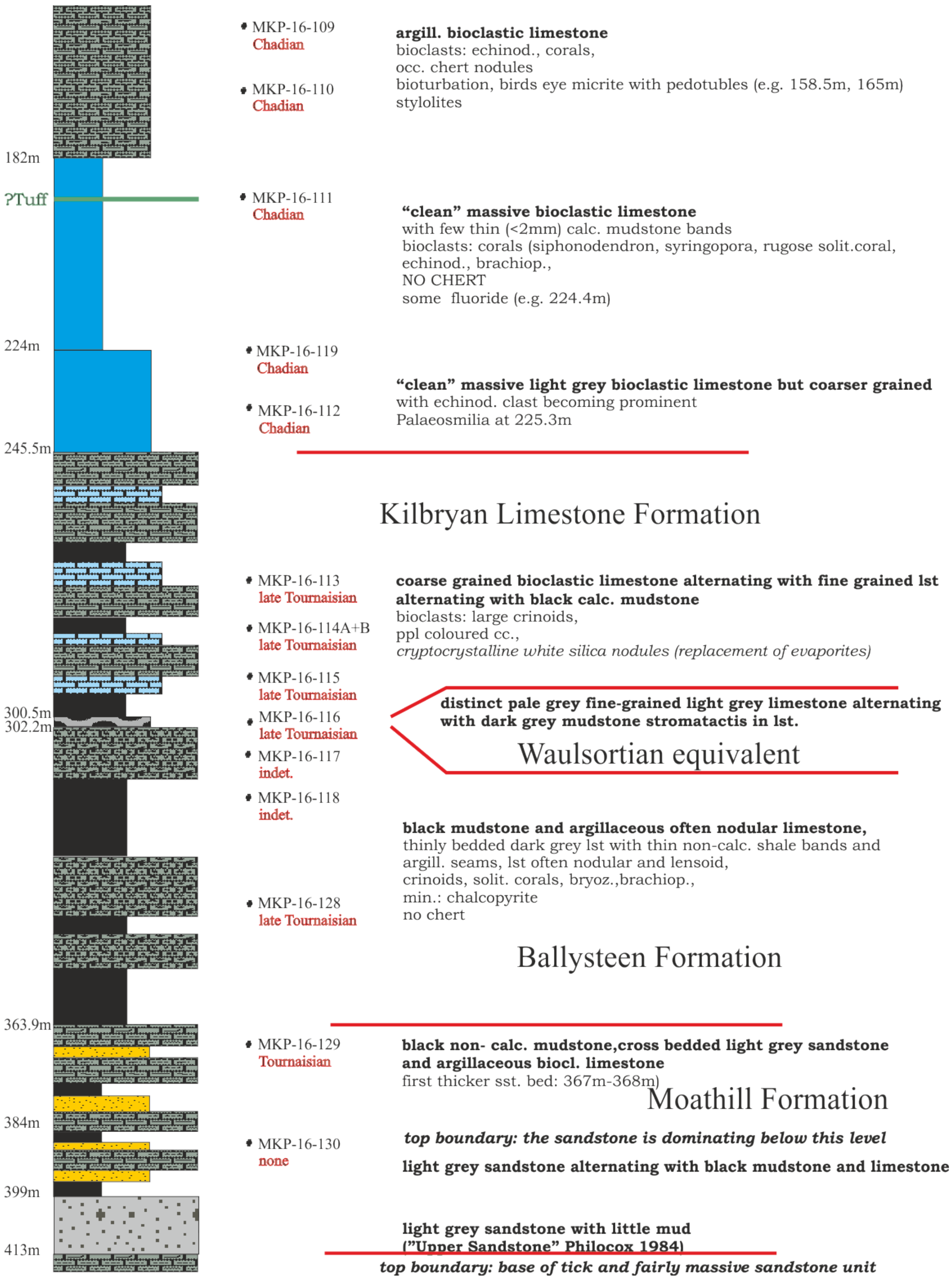
35.8m to 49.9m: coarse grained argillaceous bioclastic limestone with chert in patches with minor mudstone laminae
bioclasts: corals (fasciculate), echinoderm.,bryozoans,
dolomitisation locally
49.9m to 53.8m: black biocl. non-calc. mudstone with echiod., bryoz.,and argill. lst

53.8m to 89m: coarse grained bioclastic limestone with chert
bioclasts: coralfrag., echinoderm. ?Michelinia at 79.55m
sed./diagenetic structures: bioturbation,
some dissolution

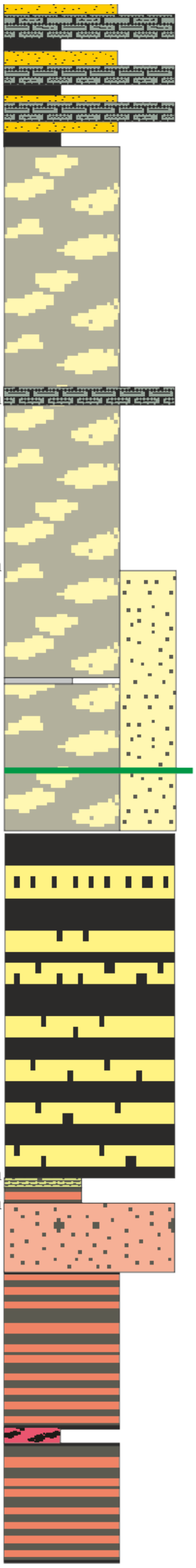
89m to 152.4m: fine grained (argill.) bioclastic limestone with chert
bioclasts:siphonodendron colonies, syringopora (e.g. 127.1m, 130.8m),
siphonodendron, coralfrag.(-caniniid), ?Michelinia at 79.55m,
Palaeosmilia at 91.45m, echinod.,shellfr., solit. coral, trilobite, braciopods,
internal erosion surfaces,
stylolites, some dolomite,some fluoride (123.3m)
fractures: 96.5m to 111m
111m downhole: darker and finer grained, homogenous,
chert: throughout, in layers (e.g. 128m, 131m, 132m)

erosional surface

Oakport Limestone Formation



MKP-16-109
Chadian
argill. bioclastic limestone
bioclasts: echinod., corals,
occ. chert nodules
bioturbation, birds eye micrite with pedotubles (e.g. 158.5m, 165m)
stylolites
MKP-16-110
Chadian
182m
?Tuff
MKP-16-111
Chadian
"clean" massive bioclastic limestone
with few thin (<2mm) calc. mudstone bands
bioclasts: corals (siphonodendron, syringopora, rugose solit.coral,
echinod., brachiop.,
NO CHERT
some fluoride (e.g. 224.4m)
224m
MKP-16-119
Chadian
"clean" massive light grey bioclastic limestone but coarser grained
with echinod. clast becoming prominent
Palaeosmilia at 225.3m
MKP-16-112
Chadian
245.5m
Kilbryan Limestone Formation
MKP-16-113
late Tournaisian
coarse grained bioclastic limestone alternating with fine grained lst
alternating with black calc. mudstone
bioclasts: large crinoids,
ppl coloured cc.,
cryptocrystalline white silica nodules (replacement of evaporites)
MKP-16-114A+B
late Tournaisian
MKP-16-115
late Tournaisian
300.5m
302.2m
distinct pale grey fine-grained light grey limestone alternating
with dark grey mudstone stromatactis in lst.
Waulsortian equivalent
MKP-16-116
late Tournaisian
MKP-16-117
indet.
MKP-16-118
indet.
black mudstone and argillaceous often nodular limestone,
thinly bedded dark grey lst with thin non-calc. shale bands and
argill. seams, lst often nodular and lensoid,
crinoids, solit. corals, bryoz.,brachiop.,
min.: chalcopyrite
no chert
MKP-16-128
late Tournaisian
Ballysteen Formation
363.9m
MKP-16-129
Tournaisian
black non- calc. mudstone,cross bedded light grey sandstone
and argillaceous biocl. limestone
first thicker sst. bed: 367m-368m)
Moathill Formation
384m
MKP-16-130
none
top boundary: the sandstone is dominating below this level
light grey sandstone alternating with black mudstone and limestone
399m
light grey sandstone with little mud
("Upper Sandstone" Philocox 1984)
413m
top boundary: base of tick and fairly massive sandstone unit



MKP-16-131 indet.

light grey sandstone alternating with black mudstone and limestone

MKP-16-132 Tournaisian
MKP-16-133
MKP-16-134
MKP-16-135
MKP-16-136 none
MKP-16-137 none
MKP-16-138 none
MKP-16-139 none
MKP-16-140 none
MKP-16-141 none
MKP-16-142 none

black mudstone with some minor thin sst. beds and minor lst., characteristic is the "gyspsum
sandstone: white -grey, greenish (446.7m), sst., laminated,thin bedded to massive, cross bedded, sometimes rip up clasts,
mudstone: non-calc., black laminated,
minor bioclastic lst., onkoids at 542.4 to 542.7m,
micrite: 526.5m to 527.5m, 537.3m,
gyspum: massive (463m to 464.7m to 465.1m, etc.) to 'blobby', white to pink
anhydrite: in sample MKP-16-139, -140, conf.

argillaceous limestone

Meath Formation

MKP-16-143 none

pale grey dolomitised bioclastic limestone (493.3m to 493.8m)
bioclasts: brachiopods, crinoids,
min.: pyrite

incoming (downhole) of greenish and reddish colours

concentrations of bioclasts (dom. brachiopods): 516.3m, 520.5m, 522.3m, 523.7m,542.4m

MKP-16-144 indet. possibly late Tournaisian?
MKP-16-145 indet. possibly late Tournaisian?

MEst?

MKP-16-146 indet. possibly late Tournaisian?

MKP-16-147 none

basal boundary: at lowest limestone occurrence

Boyle Sandstone Formation

MKP-16-148 none

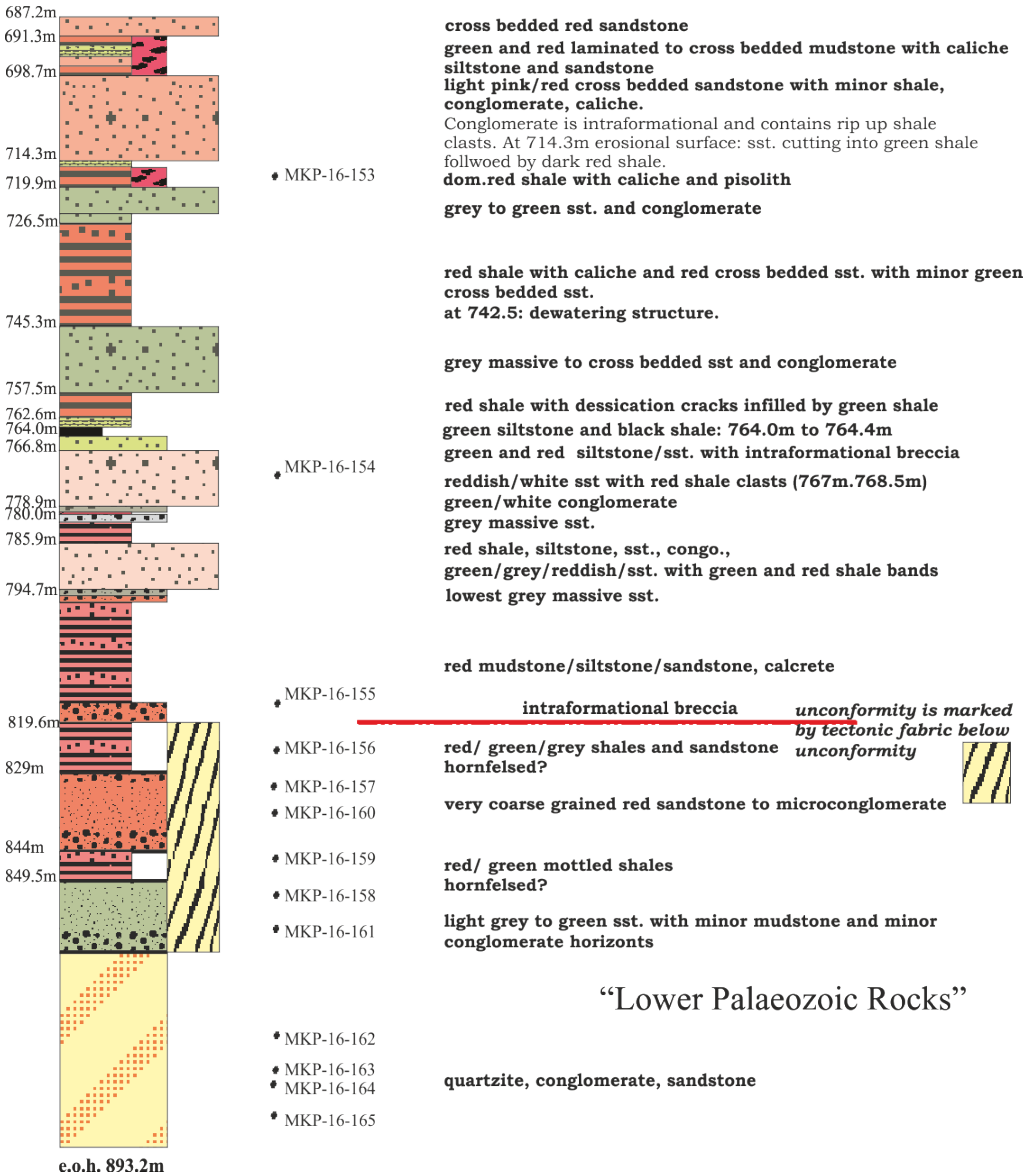
cyclic sequence of white massive to bedded sandstone followed by dark grey to black siltstone topped by black "polished" mudstone/shale
the cycles are non-calcareous. The laminated sandstone/siltstone show current ripples, linsenbedding and flaserbedding.
some burrowing in the sandsone.
towards the base of the unit: the mudstone aquires a greenish tint, the massive sandstone a purplish tint

green mudstone, siltstone, sandstone with some rip up clasts of red shale, caliche, dessication cracks

light red coloured cross-bedded sandstone with minor quartz pebble congl. and red shale
cross beds c. 45degrees inclined
open porosity in sandstone

red mudstone and siltstone with first calcrete horizon at c.685m

Fearnaght Formation (200m)



A massive pale grey fine-grained limestone unit with thin dark grey shales and oncoids in the lower part of the Meath Formation (c. 518-540 m, approximately 22 m thick) is considered to be the Stackallen Member (= "Micrite unit" of the Navan Mine area, Philcox, 1984), as recognised in boreholes to the east of the River Shannon in counties Meath and Westmeath (Morris *et al.,* 2003). The thickness of the Meath Formation (146 m) in Castlemine Borehole is very similar to that of the Strokestown borehole (BB82-4) to the northeast, where Philox (1984) recorded 155 m, with a lower micrite unit 55 m thick. Furthermore, as in the Castlemine borehole, red, pink and green siltstones and mudstones ('red bed facies') are recorded together with evaporites in the middle part of the Meath Formation in the Strokestown borehole (Philox, 1984). The base of the Meath Formation at 559 m marks an important boundary between siliciclastic-dominant units below and mixed siliciclastic and carbonate units above. The upper boundary of the Meath Formation is placed at 413 m, below a 14-m-thick pale grey sandstone of the overlying Moathill Formation.

Microfacies: Seventeen samples of limestone and sandstone were examined in thin section (MKP-16-131 to -147). The lowest sample (MKP-16-147) is a nodular silty lime-mudstone conglomerate with brachiopods. Higher samples in the Stackallan Member (MKP-16-144 to -146) comprise poorly-sorted, fine-grained silty skeletal-peloidal lime mudstones and wackestones.The main skeletal components are ostracods and rare foraminifers, with abundant detrital grains of silt-size angular quartz, feldspar and muscovite. In the middle of the formation) dolomitised silty bioclastic limestones contain crinoids, brachiopods and bryozoans. The brachiopods show partial replacement by gypsum. One sample of sandstone (MKP-16-136) in thin section is a well-sorted, fine-grained feldspathic arenite with angular grains of quartz, feldspar and muscovite in a calcarous cement. In the upper part of the formation coarse-grained poorly-sorted bioclastic limestones are present. In sample MKP-16-132 (432.2m) sandy oolitic skeletal intraclastic grainstone/rudstone is recorded with a rich and diverse biota of brachiopods, crinoids, bryozoans, ostracods and gastropods. In MKP-16-131 (418.2m) near the top of the Meath Formation is a coarse-grained shelly coquina dominated by bivalves, ostracods and oncoids with cyanophyte tubes (*Girvanella*).

Depositional setting: The formation was deposited in a nearshore, shallow-water siliciclastic-dominant shelf in which both fine- and coarse-grained clastic sediment accumulated. Periodically, shelf limestones with a rich and diverse benthic biota developed, when siliciclastic input onto the shelf was somewhat reduced. High-energy conditions prevailed during the formation of the limestones, as suggested by the transport and concentration of large shells and the presence of ooids. The lower part of the formation (Stackallan Member) represents prolonged stable lagoonal conditions associated with a major marine transgression in the area. The presence of evaporites in the succession infer arid supratidal sabkha conditions developed landward of the lagoons, as also indicated by the interbedded red-bed clastic rocks. Periods of influx of coarser-grained siliciclasics interbedded with limestones highlight the mixed character of the Meath Formation. The higher limestone beds in the Meath Formation mark more turbulent higher energy conditions with open-marine stenohaline fauna (large brachiopods, crinoids and bryozoans).

Age: Few age diagnostic microfossils were recorded in the Castlemine borehole. A sparse foraminiferal assemblage including *Endothyra, Earlandia, Tournayella, Eoforschia* and algal/cyanobacteria and microproblematica (*Girvanella, Salebra sibirica*) suggest a mid Tournaisian age (MFZ6).

Moathill Formation (363.9-413m; 49.1m)
This formation comprises an alternation of argillaceous bioclastic limestone, grey calcareous sandstone and dark grey and black mudstone. A tripartite division can be made: a lower sandstone unit (c. 14m thick ="Upper Sandstone" of Philcox, 1984, which is well developed in the Strokestown Boreholle (BB.82.4); a middle unit, 15m thick, comprising alternating sandstones, mudstones and thin limestones; and an upper siliciclastic unit, 20 m thick, with thick cross-bedded sandstones, mudstone and rare silty limestones. The formation is much thicker than in GSI-12-01 (Esker) to

the west, where it is only 17 m thick, and c. 8 m thick in GSI-11-01 (Ballymoe). The Moathill Formation represents the transitional unit into the succeeding limestone-dominant Ballysteen Formation whose base occurs at 363.9 m in Castlemine Borehole. The Moathill Formation forms part of the Navan Group which is better developed east of the River Shannon in Co. Longford (Morris *et al.,* 2003; Somerville and Waters, 2011).

Microfacies: One sample of limestone (MKP-16-129) in thin section is poorly-sorted, medium-grained silty skeletal grainstone/floatstone.The main skeletal components are large brachiopods, crinoids, fenestellid bryozoans, ostracods and rare foraminifers. One sample of sandstone (MKP-16-130) in thin section is well-sorted, fine-grained feldspathic arenite with angular grains of quartz, feldspar and mica in a calcarous cement.

Depositional setting: The formation was deposited in a nearshore, shallow-water siliciclastic-dominant shelf in which both fine- and coarse-grained clastic sediment accumulated. Periodically, shelf limestones with a rich and diverse benthic biota developed, when siliciclastic input onto the shelf was somewhat reduced. High-energy conditions prevailed during the formation of the limestones, as suggested by the transport of large size skeletal material.

Age: No diagnostic microfossils were recorded in the Castlemine borehole but in the Ballymoe and Esker boreholes the Moathill Formation is Tournaisian in age, based on a sparse foraminiferal assemblage including *Endothyra, Septatournayella, Earlandia, Eoforschia* (MFZ6), and algal/cyanobacteria and microproblematica (*Girvanella, Salebra sibirica*). Only *Earlandia* and *Salebra sibirica* are recorded in the Castlemine borehole.

Ballysteen Formation (302.2-363.9m; 61.7m)
This formation comprises light-grey and dark-grey, fine-grained argillaceous nodular bioclastic limestone alternating with black calcareous mudstone. One 2m-thick bed of black silty mudstone is developed near the base of the formation. The limestones are often bioturbated. Large crinoids along with brachiopods and bryozoans are the main macrofaunal elements, with rare large solitary rugose corals, *Caninophyllum patulum,* identified in core. The Ballysteen Formation thickens to the southwest of Castlemine, as in GSI-11-01 (Ballymoe) borehole it is nearly 100 m thick (Pracht & Somerville, 2015). The upper contact of the Ballysteen Formation with the overlying Waulsortian Limestone occurs at 302.2 m.

Microfacies: Three limestone samples were examined in thin section (MKP-16-117, -118 and -128). Typically they comprise poorly sorted fine-grained argillaceous skeletal wackestone/packstone. The main skeletal components are crinoids, brachiopods, fenestellid bryozoans, tubular foraminifers, and ostracods. Partial silicification of bioclasts is common. A minor component of detrital silt-sized quartz is present. The sample near the top of the formation (MKP-16-117) records gypsum nodules.

Depositional setting: The Ballysteen Formation was deposited mostly in an offshore open shelf /middle ramp, below fair-weather wave-base but above storm wave-base, in which fine-grained carbonate accumulated with some fine siliciclastic input. It is associated with a major deepening episode following the deposition of the shallow water siliciclastic-rich sediments of the Meath and Moathill formations. The biota is rich and diverse with abundant crinoids, brachiopods and solitary corals. The lack of sedimentary structures, poor sorting of bioclasts and abundance of bryozoans implies low-energy, relatively quiet water conditions.

Age: The Ballysteen Formation is late Tournaisian in age based on a sparse foraminiferal assemblage including rare *Pseudotaxis* (MFZ6) and the rugose coral *Caninophyllum patulum*.

Waulsortian Limestone (300.5-302.2m; 1.7m)
Within the Roscommon area Waulsortian Limestone is little known, apart from in the Slieve Dart Borehole (02-3471-01), where 45 m were recorded (Morris *et al.,* 2003). In the Galway area to the south, the Waulsortian forms large mud-mounds several tens of metres in thickness (Lees, 1964, 1994; Lees and Miller, 1985, 1995). There, the Waulsortian Limestone forms a sharp basal contact with dark grey argillaceous limestones of the underlying Ballysteen Formation. In the Roscommon region it is overlain by, and is partly equivalent to, the Kilbryan Limestone Formation (Morris *et al.,* 2003). In some boreholes to the west of Castlemine Borehole (e.g. GSI-12-01, GSI-11-01, GSI-11-315 and MGR.82.35) Waulsortian limestone is not developed, but a thinly-bedded, fine-grained nodular limestone and shale unit is present and referred to as 'Waulsortian equivalent' (Pracht & Somerville, 2015). The latter unit is differentiated from the Kilbryan Limestone Formation by its higher proportion of limestone to mudstone.

Microfacies: Only one sample was examined in thin section (MKP-16-116) from this <2 m thick unit in the Castlemine Borehole. It contains the characteristic lithology of the Waulsortian, namely lime mudstone/wackestone, with a diverse biota comprising crinoids, fenestrate bryozoan sheets, sponge spicules, trilobites, brachiopods and gastropods. Moreover, it also has large irregularly-roofed cavities with geopetal sediment. However, the cavities do not show radiaxial fibrous calcite, typically associated with stromatactis cavities (Lees, 1964, 1994; Lees and Miller, 1985, 1995; Somerville, 2003), only sparry calcite.

Depositional setting: The mud mounds characteristic of this formation with complex cavity systems developed in a deep-water distal ramp setting below storm wave-base. Low-energy conditions prevailed during the formation of the massive fine-grained limestones and their laterally equivalent bedded limestones dominated by crinoids, sponges and bryozoans (Lees, 1964, 1994; Lees and Miller, 1985, 1995; Somerville, 2003).

Age: The Waulsortian Limestone elsewhere in Ireland is regarded as late Tournaisian in age, based on very limited foraminiferal and conodont data (Sevastopulo, 1982; Somerville, 2003; Pracht *et al.,* 2004). In Castlemine Borehole the presence of the foraminifer *Pseudotaxis* suggests a probable late Tournaisian age.

Kilbryan Limestone Formation (245.5-300.5m; 55m)
The Kilbryan Limestone Formation consists of dark-grey, fine-grained argillaceous nodular bioclastic limestone alternating with mid grey medium-grained bioclastic

limestone and mudstone with some gypsum nodules and chert nodules. The macrofossils comprise mostly large crinoids. In Castlemine Borehole no thin green volcanic clay bands are recorded in this formation, which are known from other boreholes e.g. GSI-12-01 (Esker), GSI-12-02 (Fartamore) and GSI-11-315 (Corancarton) to the southwest of Castlemine (Pracht & Somerville, 2015). However, in the Ballymoe (Lisna) borehole (GSI-11-01), which is closest to Castlemine, no clay bands are present in the Kilbryan Limestone Formation, which is of a similar thickness (72 m). Furthermore, no green clay bands are recorded in the Strokestown Borehole (88.BB-4) to the northeast, in the interval above the Ballysteen Formation and below the Oakport Limestone Formation (Philcox, 1984). The upper boundary of the Kilbryan Limestone Formation and the contact with the overlying Oakport Limestone Formation at 245.5 m is sharp, with the incoming of clean light-grey coarser grained massive limestones. The Kilbryan Limestone Formation is much thicker to the west, as in GSI-12-01, where it is 108 m thick (Pracht & Somerville, 2015). In the type section around Lough Gara near Boyle and in GSI borehole 85-4 the Kilbryan Limestone Formation is 100 m thick (Caldwell, 1959; Philcox *et al.,* 1992).

Microfacies: Three samples were examined in thin section (MKP-16-113 to -115). Typically, they comprise poorly-sorted fine-grained argillaceous skeletal wackestone (some with recrystallised microsparite matrix) and poorly-sorted medium-grained skeletal intraclastic packstone. The main skeletal components are crinoids, fenestellid bryozoans, brachiopods, sponge spicules, calcareous algae (*Kamaena*), sparse foraminifers, trilobites and calcispheres. Many bioclasts are partially silicified.

Depositional setting: The formation was deposited in a moderately deep-water shelf/ramp setting below storm wave-base, in which both fine-grained carbonate mud and siliciclastic mud accumulated. Low-energy conditions prevailed during the formation of the limestones, as inferred by the presence of sponges spicules and bryozoans. The presence of the rare microproblematicum *Sphaerinvia piai* is notable, as it is usually associated with Waulsortian mud-mounds and adjacent strata. In fact, it is quite likely that the Kilbryan Limestone Formation is, in part, coeval with and lateral to Waulsortian Limestone and Waulsortian Equivalent rocks (see Morris *et al*., 2003; Pracht & Somerville, 2015).

Age: The Kilbryan Limestone Formation is late Tournaisian to early Visean? in age, based on its stratigraphic position between the older Tournaisian-aged Ballysteen Formation and Waulsortian Limestone, and the overlying lower Viséan (Chadian) Oakport Limestone Formation (Pracht & Somerville, 2015). It lacks diagnostic foraminifers, apart from *Tetrataxis*. The rugose coral *Siphonophyllia* is recorded and the large tabulate coral *Michelinia*.

Oakport Limestone Formation (89.0-245.5m; 156.5m)
The Oakport Limestone Formation consists of light-grey, massive, 'clean' coarse-grained bioclastic limestone with intervals of dark-grey fine-grained limestones. Chert nodules are developed in the upper part. The Formation has a tripartite division: a lower unit (182-245.5 m) of massive pale grey, medium- to coarse-grained bioclastic limestones rich in crinoids with *Syringopora* colonies and large solitary rugose corals; a middle interval (152.4-182 m) of darker grey, more argillaceous fine-grained limestones with bioturbation, chert nodules and occasional fenestral limestones with

pedogenic structures (e.g, rootlets); and an upper unit of massive bioclastic limestones, similar to the lower unit, but with fasciculate rugose coral colonies. Large solitary rugose corals, tabulate and rugose coral colonies, gastropods, brachiopods and crinoids are the main macrofaunal elements of the formation. Identified coral taxa include*: Siphonophyllia* aff. *garwoodi, Michelinia megastoma, Palaeosmilia murchisoni* and *Siphonodendron martini* in the upper unit.

The top of the formation is placed at the incoming of darker grey coarser grained limestones with chert nodules of the Ballymore Limestone Formation at 89 m. The 156.5 m thickness of Oakport Limestone in Castlemine borehole is slightly thicker than the 140 m thickness recorded in the Ballymoe (GSI-11-01) and Esker (GSI-12-01) boreholes, and 137 m in the Slieve Dart Borehole (02-3471-01) to the west (Morris *et al*., 2003; Pracht & Somerville, 2015).

Microfacies: Nine samples were examined in thin section (MKP-16-106A, -106B, -107 to -112 and -119). The lower unit comprises well-sorted coarse-grained skeletal grainstones and intraclastic skeletal packstones rich in oncoids. The main skeletal components are crinoids and locally abundant tubular microproblematica (*Luteotubulus),* dasycladacaean algae (*Koninckopora* sp. monolaminar), *Kamaena*, foraminifers, cyanobacteria and calcispheres. The middle unit comprises poorly-sorted medium-grained intraclastic skeletal peloidal packstones with crinoids and cyanophytes. The upper unit comprises well-sorted medium-grained skeletal peloidal grainstones and intraclastic skeletal peloidal packstones.

Depositional setting: The Oakport Limestone Formation was deposited in a shallow-water shelf setting, above fair-weather wave-base. The presence of well rounded and sorted bioclasts and peloids in coarse-grained grainstones attest to turbulent high-energy environments. However, unlike in some other boreholes in the region, no ooids were observed in this formation in Castlemine borehole. However, the presence of fenestral micrites with pedogenic structures and oncoids indicate lower energy lagoonal conditions with only intermittent higher energy events. The biota is moderately rich and diverse with crinoids, fenestellid bryozoans, colonial corals, foraminifers and dasycladacean green algae, the latter indicating growth in a shallow photic zone.

Age: The Oakport Limestone Formation is mostly lower Viséan (Chadian) in age, based on the presence of the key foraminifers: *Eoparastaffella simplex, Pseudolituotubella*, *Brunsia, Pseudoammodiscus*, *Eostaffella* (an assemblage characteristic of Zone MFZ9)*,* as well as the alga *Koninckopora* sp*.* (monolaminar wall) and abundant *Luteotubulus.* However, the presence of the rugose coral *Siphonodendron martini* in the upper unit along with *Palaeosmilia* confirms an early Arundian age. This is confirmed by the presence of archaediscid foraminifers (*Uralodiscus* and *Glomodiscus*) in the uppermost part of the Oakport Limestone (2 m below the top).

Ballymore Limestone Formation (0-89.0m; 89m)
In Castlemine Borehole the Ballymore Limestone Formation is represented by two contrasting units; a lower interval (36.5-89 m) which consists of dark-grey well bedded and nodular fine-grained argillaceous limestones showing common bioturbation, with interbedded light-grey, coarse-grained limestones and thick black

calcareous shale intervals. Chert nodules are commonly developed; the upper interval (0-36.5 m) is marked by the incoming of paler grey and finer grained 'clean' massive chert-free limestones. The quarry face at Castlemine exposes > 22 m of well bedded dark and pale grey limestones, the lower c.7m of which have been assigned to the Ballymore Limestone Formation (Morris *et al.,* 2003). Thus, over 96m of the formation are developed in the vicinity of Castlemine.

Large solitary rugose corals, fasciculate rugose and tabulate coral colonies, bellerophontid gastropods, brachiopods, bryozoans and crinoids are the main macrofaunal elements in the formation. Identified taxa include*: Michelinia megastoma, Siphonodendron martini, S. sociale.* The Ballymore Limestone Formation in Castlemine borehole (and in the overlying quarry beds) is very much thinner than the 225 m thickness recorded in Corancarton borehole GSI-11-315 (Pracht & Somerville, 2015) and in the type section (c. 170 m) at Ballymore House near Boyle (Caldwell, 1959).

Microfacies: Three samples from the lower unit (36.5-89 m) were examined in thin section (MKP-16-104 to -106). The lower part of the lower unit (MKP-16-106) comprises moderately sorted, coarse-grained skeletal grainstone with abundant crinoids, foraminifers (especially archaediscids), brachiopods, dasycladacaean algae (monolaminar and bilaminar *Koninckopora* and *Kamaena*) and rare red algae (aoujgaliids). The middle part of the lower unit (MKP-16-105) comprises poorly sorted medium-grained skeletal wackestone/ floatstone with chert lenses. The main skeletal components include: large crinoids, brachiopods and fenestellid bryozoans. The upper part of the lower unit (MKP-16-104), like the lower part, comprises moderately well sorted, coarse-grained skeletal grainstone with abundant crinoids and foraminifers, especially archaediscids, but an absence of dasycladacaean green algae although red algae (aoujgaliids) are common.

Three samples from the upper unit (0-36.5 m) were examined in thin section (MKP-16-102A, -102 to -103). The dominant lithology is poorly sorted skeletal-intraclastic packstone/grainstone. The main skeletal components are crinoids and stipes of the dasyclad alga *Koninckopora tenuiramosa;* foraminifers, notably archaediscids, are small and rare. Brachiopod and bivalves are often algal-coated.

Depositional setting: The Ballymore Limestone Formation was deposited in both a shallow-water and moderately deep-water shelf setting. The well-sorted crinoidal grainstones formed in a high-energy shallow-water shelf setting, but the argillaceous skeletal wackestones suggest a lower energy deeper water setting in which foraminifers are scarce and calcaeous algae absent. The biota in the grainstones is moderately rich and diverse with crinoids, abundant archaediscid foraminifers, colonial rugose coral thickets and dasycladacaean green algae, implying shallow water turbulent conditions within the photic zone.

Age: The Ballymore Limestone Formation is lower Viséan (Arundian) in age, based on the presence of the key foraminifers: *Uralodiscus*, *Glomodiscus, Paraarchaediscus @ involutus* stage, *Forschia* (typical of Zones MFZ10-11), as well as the dasyclad alga *Koninckopora tenuiramosa,* and fasciculate species of *Siphonodendron.* However, at 41.3 m, the presence of rare *Paraarchaediscus @ concavus* stage suggests a probable late Arundian age, close to the Holkerian. At its type locality, the age of the Ballymore Limestone Formation is Arundian to Holkerian (Morris *et al.,* 2003).

Croghan Limestone Formation (borehole collar +7m to exposed quarry top)
In the type area at Cavetown Lough near Boyle c. 107 m of Croghan Limestone Formation are recorded (Caldwell, 1959; Morris *et al*., 2003). In 2016, borehole GSI-16-102 (Sprinfield, GR: 0588939/0703394), was drilled c. 6km SE of Cavetown and 4km SE of Croghan village, penetrating the whole Croghan Limestone Formation. Although some noticeable differences to original outcrop descriptions occure, this borehole is used as reference borehole for the formation). Here, the Croghan Limestone Formation is 112.5m thick and can be devided into a lower (88.4m thick), middle (24.1m thick) and upper unit (25.4m thick). The base of the formation is taken at the base of the first dark grey thick argillaceous limestone bed, the top at the base of the light-grey bioclastic limestone of the overlying Bricklieve Limestone Formation. The lower unit consists of dark grey coarse grained argillaceous bioclastic limestone (estm. 70%) alternating with light grey medium-grained bioclastic limestone (estm. 30%) with some chert. The macrofauna consists mainly of fenestrate bryozoans, small brachiopods, solitary and colonial corals rugose corals (Siphonophyllia, Solenodendron) and crinoids. The middle unit is dominated by light-grey to brown bioclastic, medium- to coarse-grained oolithic limestone with some minor argillaceous bioclastic limestone. Bioclasts are brachiopods, crinoids and corals with bryozoans in the more argillaceous parts. Some chert and dolomite occurs locally. The upper unit consists of dark-grey argillaceous often nodular bioclastic limestone with black mudstone. In Castlemine quarry access to exposure is restricted (working quarry) and the upper 13m or so of the quarry has tentatively be assigned to this formation. Lithologically the formation consists here of medium- to coarse grained well-bedded light grey limestone with crinoids, large brachiopods and siphonodendron colonies.

Microfacies: Comprises poorly sorted skeletal wackestone and packstone (with microspar matrix), and rare skeletal grainstone. The main skeletal components are crinoids, fenestellid bryozoans, sponge spicules, trilobites, rare red algae (aoujgaliids), foraminifers, (small archaediscids can be locally abundant), calcispheres, problematica (*Draffania* and salebrids) and kamaenids.

Depositional setting: The depositional environment of the Croghan Limestone Formation varies considerably. It ranges from shallow water with medium- to high energy of the inner shelf (ooids, coated grains, photic zone) via moderately shallow water with low to moderated energy in open shelf with coral colonies and moderately shallow/deep water with low- to moderate energy of the outer shelf with reef build-up facies (geopedal peloidal sediment and in situ rugose corals) to deep watre low enery sediments of the mid- to outer shelf (with buidl-up facies- geopedal, peloidal sediments). The biota is rich and diverse with crinoids, fenestellid bryozoans, sponge spicules, solitary corals, algae and foraminifers.

Age: The Croghan Limestone Formation is mid Viséan (Holkerian) in age, based on the presence of the key foraminifers: *Paraarchaediscus* @ concavus stage, *Eostaffella, Valvulinella, Forschia* (MFZ12)*,* the dasyclad alga *Koninckopora tenuiramosa,* and *Draffania biloba*.

Summary.
A detailed study of the 893-m-thick Castlemine borehole, north of Roscommon town, has established the presence of a 849.5 m-thick Lower Carboniferous succession which rests unconformably on Lower Palaeozoic 'basement' rocks, that are exposed to the east in the Strokestown Inlier. The oldest Mississippian (Carboniferous) rocks are represented by the Fearnaght Formation, a basal red-bed continental clastic facies, dominated by red sandstones, conglomerates and mudstones with calcretes.The overlying Boyle Sandstone Formation marks a change to grey and white sandstones. The succeeding Meath Formation has a lower micritic carbonate unit (Stackallen Member) representing the first marine sediments associated with a south-to-north transgression across the region. The remaining part of the Meath Formation and the overlying Moathill Formation comprise mostly siliciclastic rocks (sandstones and mudstones) with thin bioclastic limestones with a sparse Tournaisian fauna. Evaporite (gypsum) is also recorded in this interval.

The succeeding Ballysteen Formation, Waulsortian Limestone and Kilbryan Limestone Formation highlight a change to carbonate-dominated units with only fine siliciclastic input and an open marine fauna. These formations represent a major deepening episode in the Roscommon area, with mostly fine-grained carbonate sediment accumulating on a mid to outer shelf or ramp. The deepest water setting is probably associated with the Waulsortian mud-mounds with their cavity systems, which form large banks further to the south in County Galway.

Above these deeper water carbonates is developed a standard Viséan shallow-water limestone succession (Oakport and Ballymore Limestone formations) that formed the Galway–Roscommon Shelf. This interval can be directly correlated with the type sections in Boyle–Carrick-on-Shannon area in north Co. Roscommon. It is has abundant lower Viséan (Chadian-Arundian) foraminifers, calcareous algae and rugose coral thickets and biostromes.

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7. An Introduction to Groundwater Flooding

Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

What is Groundwater Flooding?

Following a lull during much of the second half of the 20th century, the issue of flooding and flood mitigation has recently re-entered the public consciousness. This has been driven by a series of unprecedented events in the last two decades, of which the floods of November 2009 and December 2015 were the worst in living memory in many parts of the country. While national attention may be focussed on the fluvial flooding which inundated large swathes of Athlone, Longford and Limerick, it was groundwater-driven floods which caused significant damage and disruption in the limestone areas of western Ireland.

The prevalence of groundwater flooding in the western counties is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between ground and surface waters, which leaves them susceptible to groundwater flooding (Naughton et al., 2015). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Mott MacDonald, 2010; Naughton et al., 2012). There are over 400 recorded examples of turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare. Due to the record breaking rainfall in the winters of 2009 and 2015, turlough flooding impacted on dozens of homes, as well as causing widespread and extended disruption to transport networks across the region.

Unlike fluvial flooding (or fluvially-derived groundwater flooding due to seepage along riverbanks), where the flood is typically caused by high intensity rainfall, groundwater flooding is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Furthermore, the long-term hydrometric data required for traditional flood frequency analysis do not exist for groundwater flooding, impeding the calculation of flood risk (combination of likelihood of an event and the damage caused by the event) as required in flood defence scheme assessments.

Geological Survey Ireland GWFlood programme

In response to the unprecedented flood events of 2009 and 2015, the Geological Survey initiated a new programme, GWFlood, to investigate flooding specifically related to groundwater and turloughs. The phenomenon of groundwater flooding can pose a significant flood hazard for many rural communities and its increased frequency in recent years highlights the clear need for further research into the issue of groundwater flood prediction and risk assessment in karst regions. Geological Survey Ireland, in collaboration with Trinity College Dublin and Institute of Technology Carlow have developed a monitoring, mapping and modelling programme to address the knowledge gap regarding these complex karst systems. This programme is enabling the OPW and local authorities to develop flood mitigation strategies for groundwater flooding and allow for better informed decisions regarding future groundwater flood risk management. The study is providing the requisite data to address this knowledge gap by establishing a permanent monitoring network, as well as developing analytical tools to help address issues surrounding groundwater flood mapping and flood frequency estimation.

GWFlood - Monitoring

Hydrometric data is a crucial component to understanding the dynamics of surface and groundwater flow systems. Information such as stage and discharge are recorded at gauging stations across the country in rivers, lakes, boreholes and coastlines, providing data vital to local authorities and planning agencies for effective flood risk management. However, consistent long-term hydrometric data do not exist for groundwater flooding applications. A primary objective of this project is thus to establish a monitoring network to provide key baseline data for flood risk and habitat management applications. While some turlough systems posing a flood risk, such as the Gort Lowlands, are relatively well understood, there is limited hydrogeological knowledge on most Irish karst groundwater flow systems.

The project commenced in September 2016 and to date over 60 exploratory monitoring stations have been installed in counties Galway, Clare, Mayo, Roscommon, Longford and Westmeath (Figure). Data from these sites are helping to develop a preliminary understanding of the hydrodynamics and flooding potential of turlough systems across key catchments, and inform the site selection process for the permanent monitoring network. A subset of 20 sites representative of the spectrum of groundwater flooding conditions in Ireland is being established as permanent telemetered stations providing real-time information on groundwater flood conditions. The installation of pilot permanent monitoring stations commenced during summer 2017 and the remaining sites are being installed throughout the summers of 2018 and 2019.

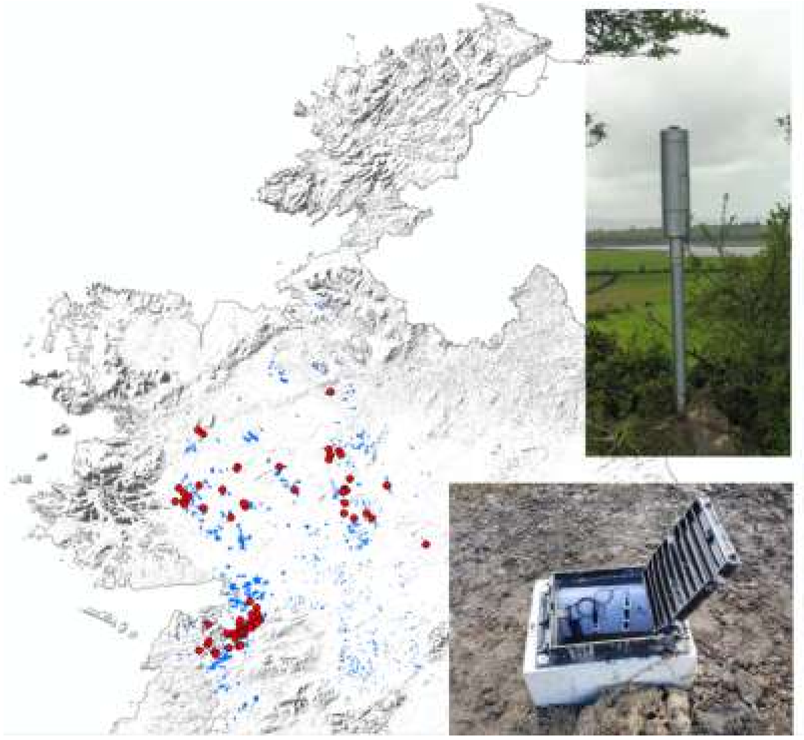
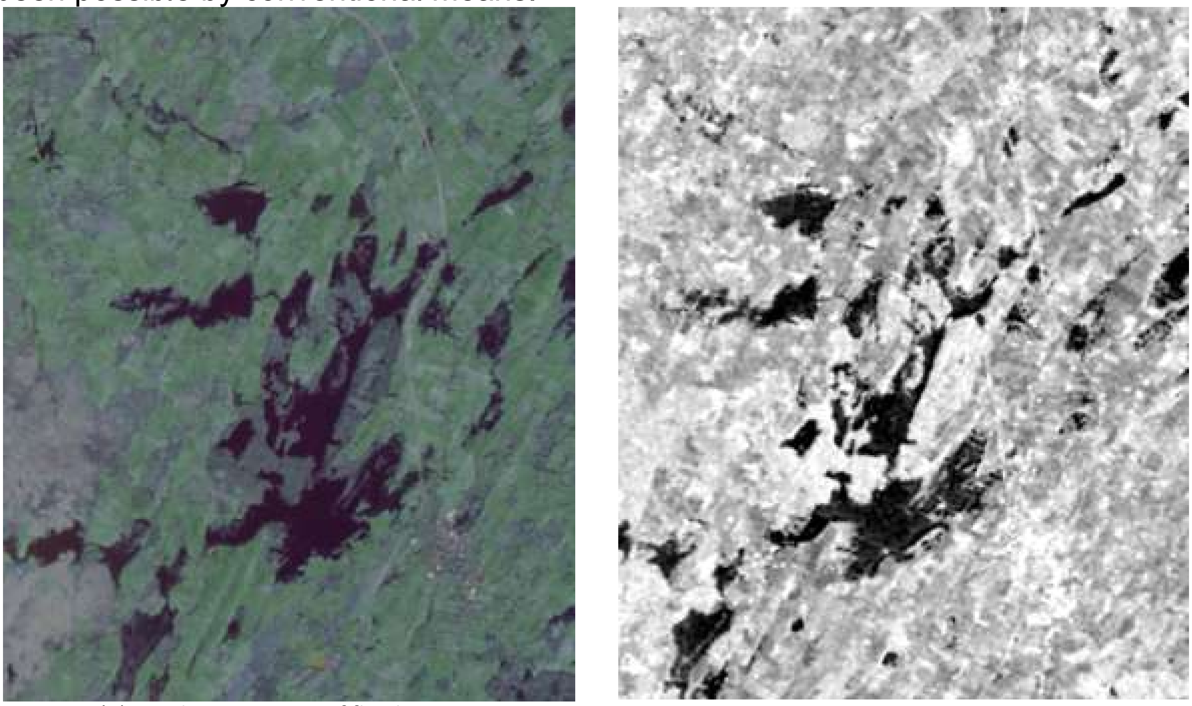


Figure11: GWFlood Turlough Monitoring Network (red) overlaid on groundwater flood hazard sites (blue) (Mott MacDonald, 2010). Insets: permanent turlough water level monitoring equipment.

GWFlood - Mapping & Modelling

The ability to describe and map how floods develop and recede accurately and at a large spatial scale is a prerequisite for effective flood risk management. In this context, the GSI is developing a revised national groundwater flood map for the OPW as part of the second implementation cycle of the EU Floods Directive. While traditional monitoring is an effective tool for flood mapping at priority sites, the distributed nature of groundwater flooding in karst lowlands hampers any systematic mapping efforts. Groundwater flooding occurs in isolated basins across the landscape. The large number and wide distribution of these basins makes them impractical to monitor using traditional field instrumentation. Earth Observation and Geographical Information System (GIS) approaches offer significant advantages in this respect.

Earth Observation satellites represent a growing data source for environmental monitoring. Passive satellite imagery, such as the USGS Landsat or ESA Sentinel-2 programmes, can be used to image and delineate floods at a catchment scale (Figure 11). In the case of Landsat, a long historical archive of images also allows the observation of past flood conditions and provides some data with which to validate hydrological models. However, an obvious limitation of satellite systems which require a clear view of the earth's surface is the issue of cloud cover. When cloud cover is extensive, as is often the case during winter floods, no useful data can be collected. Under these conditions active systems, such as synthetic aperture radar (SAR), are extremely useful as they are not impacted by cloud cover (or time of day). In this context, Geological Survey Ireland used imagery from the ESA Sentinel-1 mission to map groundwater flooding, which would otherwise not have been possible by conventional means.



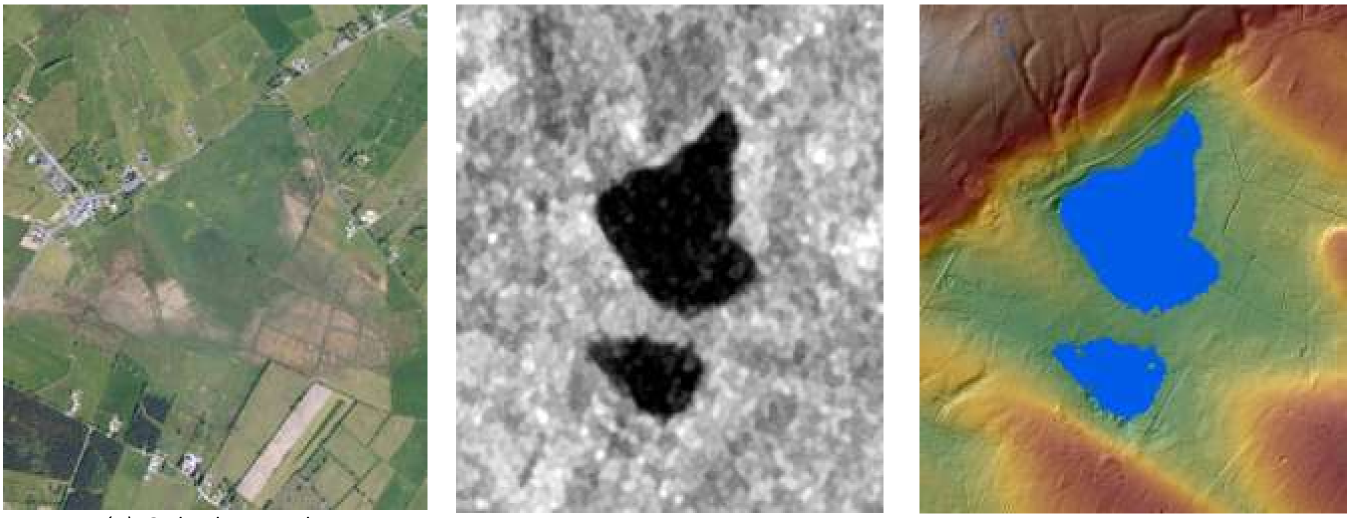
(A): Landsat-8 imagery of flooding near Gort, February 2016.

(B) Sentinel-1 SAR imagery of flooding near Gort, February 2016.

Figure 11: Landsat-8 and Sentinel-1 comparison imagery of flooding near Gort town, February 2016.

GWFlood - Hydrograph Generation using Earth Observation Data

SAR systems emit radar pulses and record the return signal at the satellite. Flat surfaces such as water operate as specular reflectors for the radar pulses resulting in minimal backscatter signal returning to the satellite thus providing a contrast between dry and flooded areas (Figure 12). While interpretation of SAR images involves a degree of ambiguity due to factors such as speckle effects and dielectric properties, overall SAR systems offer a powerful tool for water delineation.



(A): Orthophotography *(B): SAR imagery, March 2017* *(B): Flood delineation, March 2017*

Figure 12: Imagery of Castleplunket turlough Co. Roscommon showing orthophotography of it empty (A), pre-processed SAR imagery of it flooded (B) and a flood delineation overlaid on LiDAR data (C)

The information gained from SAR imagery can be further enhanced by adding contextual information from high resolution topographic mapping. The flood boundary can be cross-referenced against the topographic data to calculate the elevation of the land-water interface and thus the depth of water in the turlough. This methodology benefits from the fact that turlough flooding typically occurs in enclosed, isolated basins. As a result, and unlike river flooding scenarios, the water surface is usually flat and the flood boundary can be assumed to have a consistent elevation value.

An additional benefit of Sentinel-1 is the frequency of image capture; the satellites have been collecting imagery over Ireland at a 3-4 day revisit time since late 2014. While this revisit time may be inadequate for observing flash floods, which appear and dissipate within hours, it is suitable for monitoring groundwater flooding which occurs at a much slower rate (weeks to months). The considerable catalogue of Sentinel-1 imagery available has allowed us to track groundwater flood development through time. For sites with suitable size and topography characteristics the depth calculation process can be repeated for every satellite orbit enabling the generation of dynamic flood mapping and hydrographs (see Figure 13).

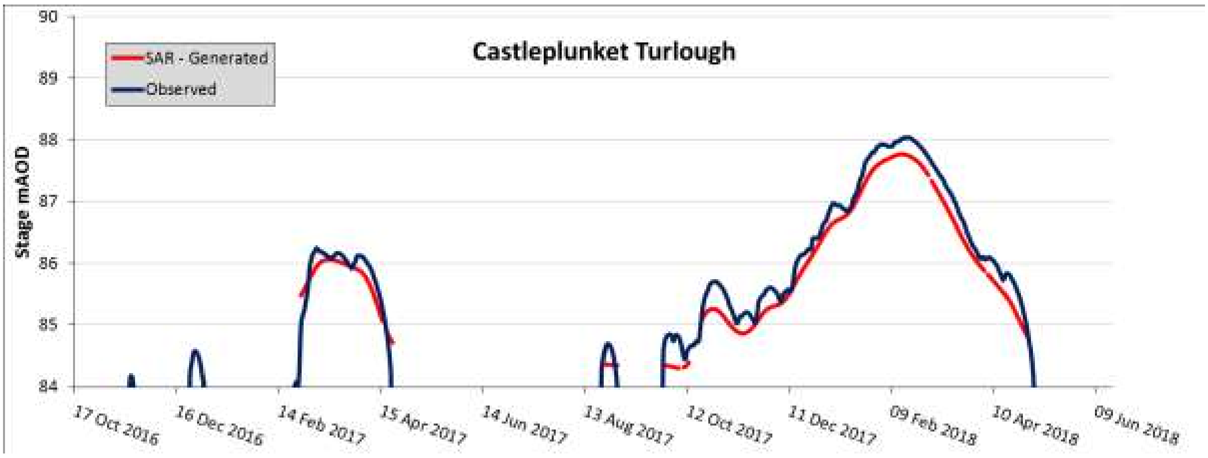


Figure 13: Sentinel-1 derived hydrograph (red) compared with physical monitoring data.

GWFlood - Modelling & Probabilistic Mapping of Groundwater Flooding

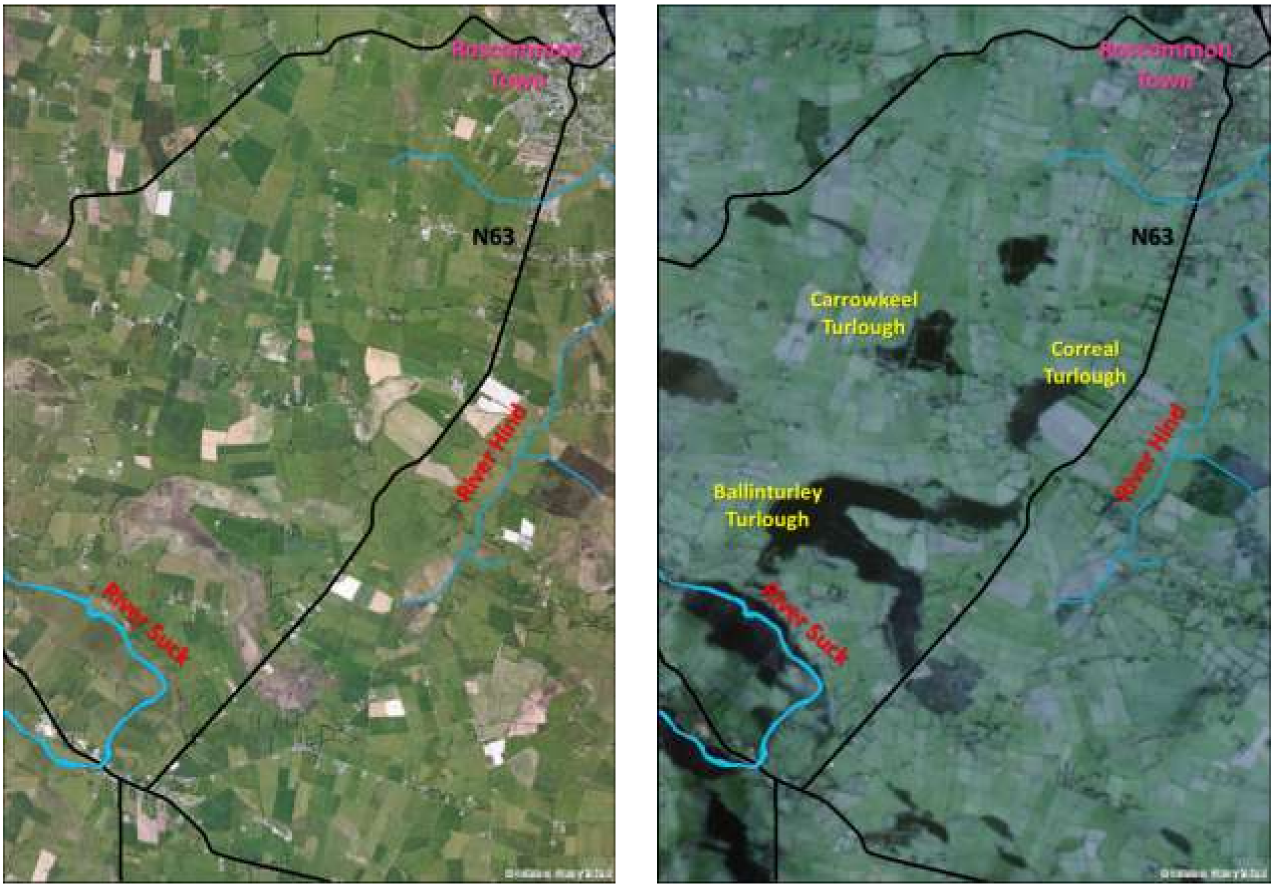
Hydrological models capable of reproducing hydrographs from antecedent rainfall and soil moisture conditions have been developed. Models for viable groundwater flooding locations are being calibrated using a combination of observed and SAR hydrograph data, which includes the peak flood extents of 2015/2016. Using long-term observational and stochastic rainfall series as input, the models are being used to construct long-term flood hydrographs suitable for extreme value analysis and the generation of predictive groundwater flood extents and maps. An example of a predictive flood map is shown for Castleplunket turlough in Figure 14, which gives indicative 10%, 1% and 0.1% Annual Exceedance Probability (AEP) extents for the turlough.

Figure 14 10%, 1% and 0.1% Annual Exceedance Probability flood extents at Castleplunket turlough.

8. Correal Turlough

Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

Correal turlough is located 5km south of Roscommon town and is part of a chain of turloughs running between the River Suck to the West and River Hind to the East. The turloughs lie on Undifferentiated Visean Limestones and have no recorded traces. Correal typically floods 2-3m deep in winter and covers an area of approximately 18 hectares during flood. While Correal is relatively small in size compared to its neighbouring turloughs, and has few recorded historic flood events, it caused some of the worst damage from a single turlough in Co. Roscommon during the 2015/2016 flood event (Roscommon Co.Co., 2016).



(a) Correal and Ballinturley Turloughs during dry conditions.

(b) Correal and Ballinturley Turloughs during flood conditions (Landsat - February 2016).

Figure 15: Comparison of dry and wet conditions at Correal Turlough and surrounding turloughs.

While Correal is one of the most potentially damaging in Co. Roscommon and has had minor drainage improvement works carried out since the 2016 floods, it remains economically unfeasible to implement a complete flood solution (similar to many groundwater flood prone areas in Ireland). The turlough has however long been considered as part of a potential drainage solution for the River Suck. Since the year 1139 there have been attempts to drain flood waters from the Suck via Ballinturley turlough and Correal turlough towards the River Hind to the east (Moran, 1994). Part of this channel was built and is still visible today; however, the channel appears to have never been completed (or has been removed since historic mapping was produced in the 19th century).

9. The Strange Case of Castlestrange ZOC
Gerry Baker

In a sleepy corner of County Roscommon lies Castlestrange, or in the local tongue *Caisleán Stráinse*. The history of how this name came to be is shrouded in mystery. Even the lakes in this land are strange, sometimes swelling and overflowing and other times shrinking and all together vanishing. Most lakes have the common decency to stay where they were intended to be but here it is as if the underworld is so thirsty for souls it must be quenched by the waters of the two lakes.

So abstruse are these lakes that they have no names and don't appear on the standard maps of the area and one must either refer to old dusty tomes to discover their true nature and extent, or look from far above. These "turloughs", as the locals call them, are named Coolmeen (in the north) and Coolneen (in the south). Coolmeen and Coolneen, a gruesome pair.

Our interest dear readers in this land is a small house. A house too small for one to live in, a house with no windows, one small door and hole to the underworld. This small portal to the depths was made as if in abhorrence or to spite that which it contains. A small prison it must seem to those who pass it and wonder what poor unfortunate is kept within. No garden, no porch, no doorstep nor bell. There it lies on a roadside, fear of death to those who might emerge without their wits about them.

The irony of course is that within that house lies the very life blood of the people that built it; water. Therein lies a well that draws water from the limestone beneath. And it was put to your unfortunate author to investigate wherefrom the water in the well might come. Standing there one might as well wonder where each drop of water within the sea came from. But in the words of my good friend Sherlock Holmes "*When you have eliminated the impossible, whatever remains, however improbable, must be the truth*". And so, standing there between two vanishing lakes and hills we ponder.

The clues are as follows: the well draws but a small volume to supply the locals, the limestone underneath is cavernous and filled with unspeakable beasts, there is a small hill directly west of the house and, most curious of all, the well lies between the two unearthly lakes. Now any self-respecting well would draw its water from that area of ground directly up gradient of it, and this was your authors original thought.

However, upon closer inspection it transpired that the water levels in the two lakes are not the same but that Cloonmeen (to the north) is higher than Coolneen. While no link between the two exists over land, in cases such as this, one must consider more occult subterranean routes. There is every possibility that as the more elevated Cloonmeen sinks below ground that it drains to the lower Coolneen. There is every possibility that a drop of water, in making its wayward route from one to the other, wanders into the path of this well and is sucked out, only to be ingested by the locals or worse, fed to their animals. And who is to say that such a wayward drop would not have flown over some of the excreta from those very same animals and the cycle of

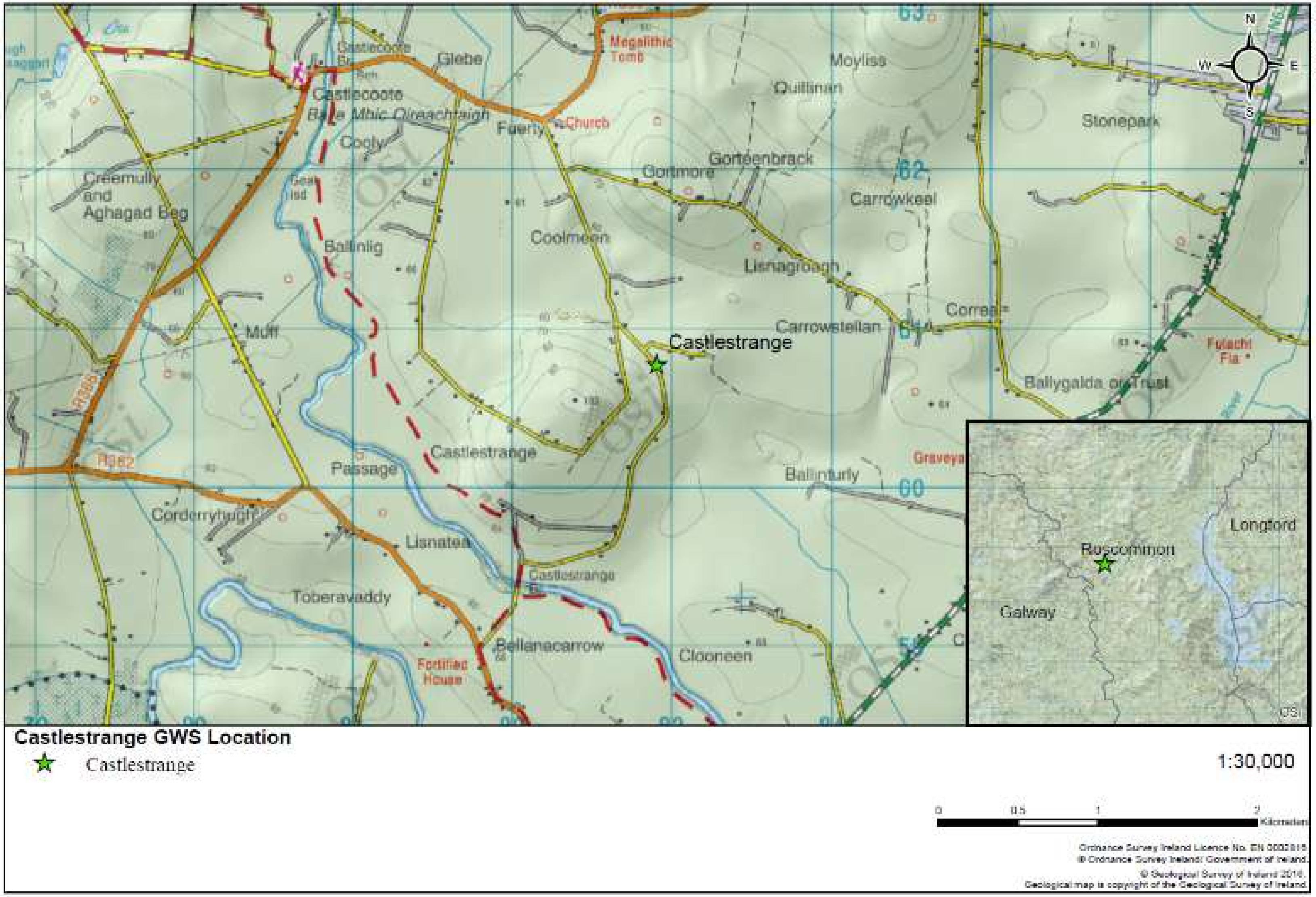


Figure 17 Location map for Castlestrange GWS.

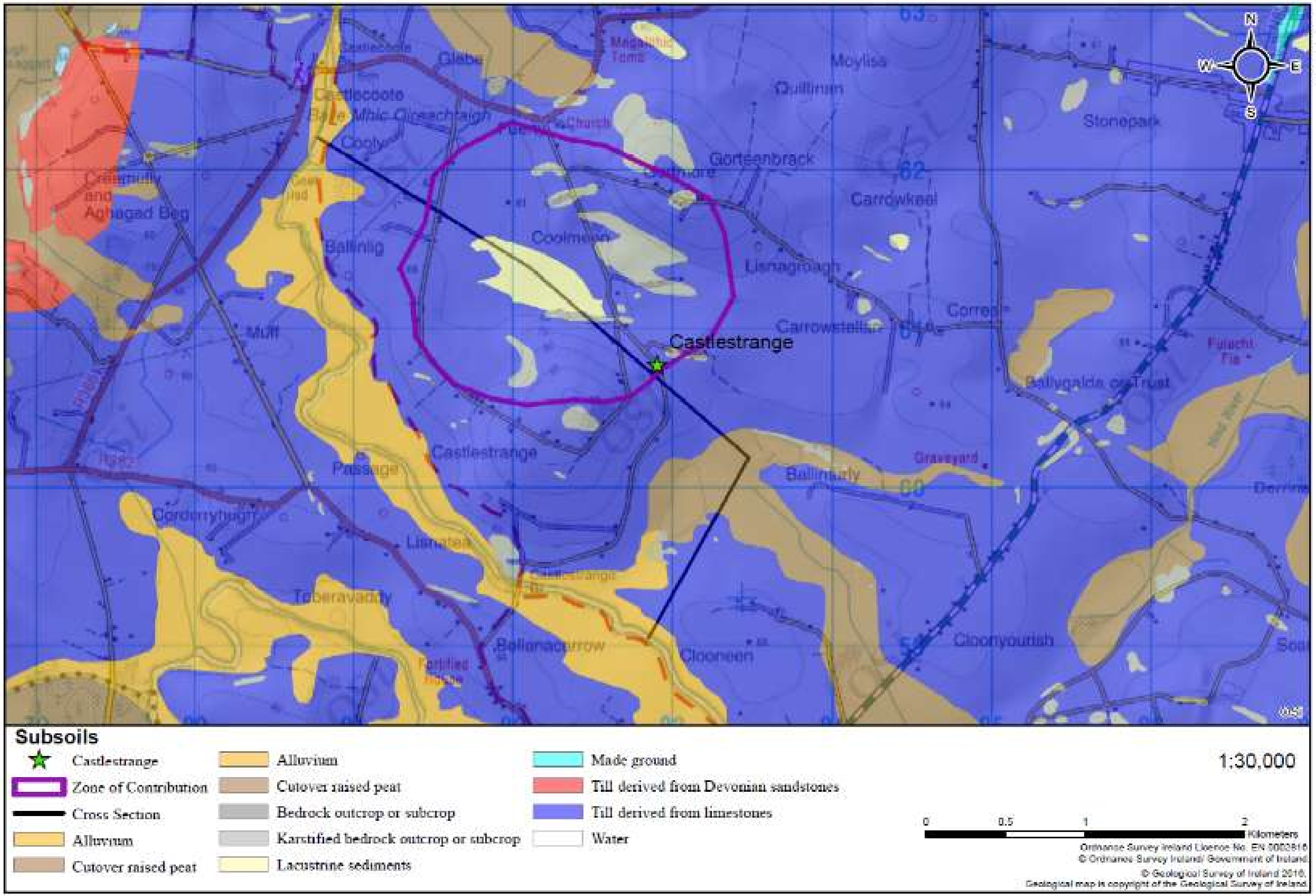


Figure 18 Subsoils map for area around Castlestrange GWS.

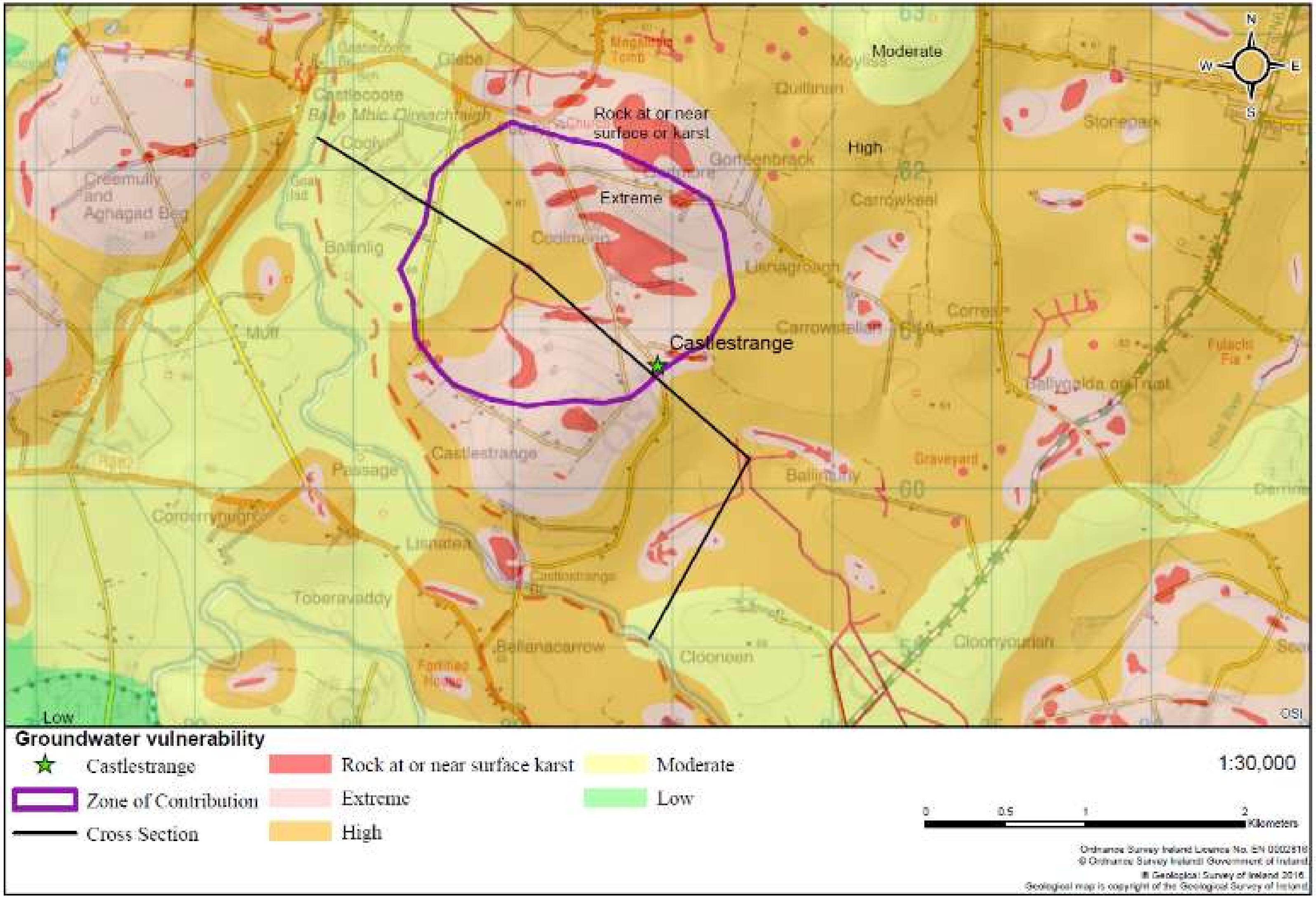


Figure 19 Groundwater Vulnerability map for area around Castlestrange GWS.

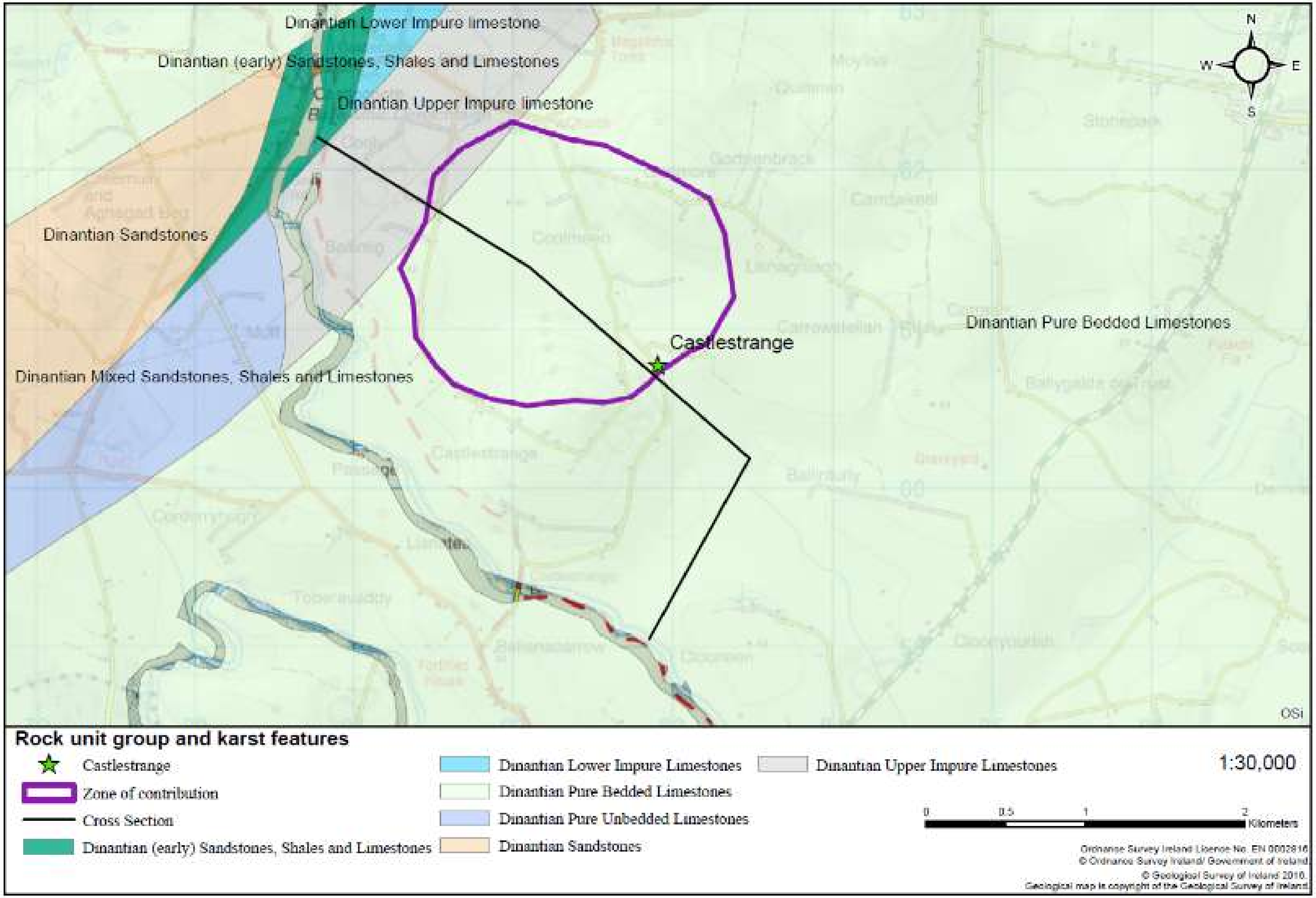


Figure 20 Bedrock map for area around Castlestrange GWS.

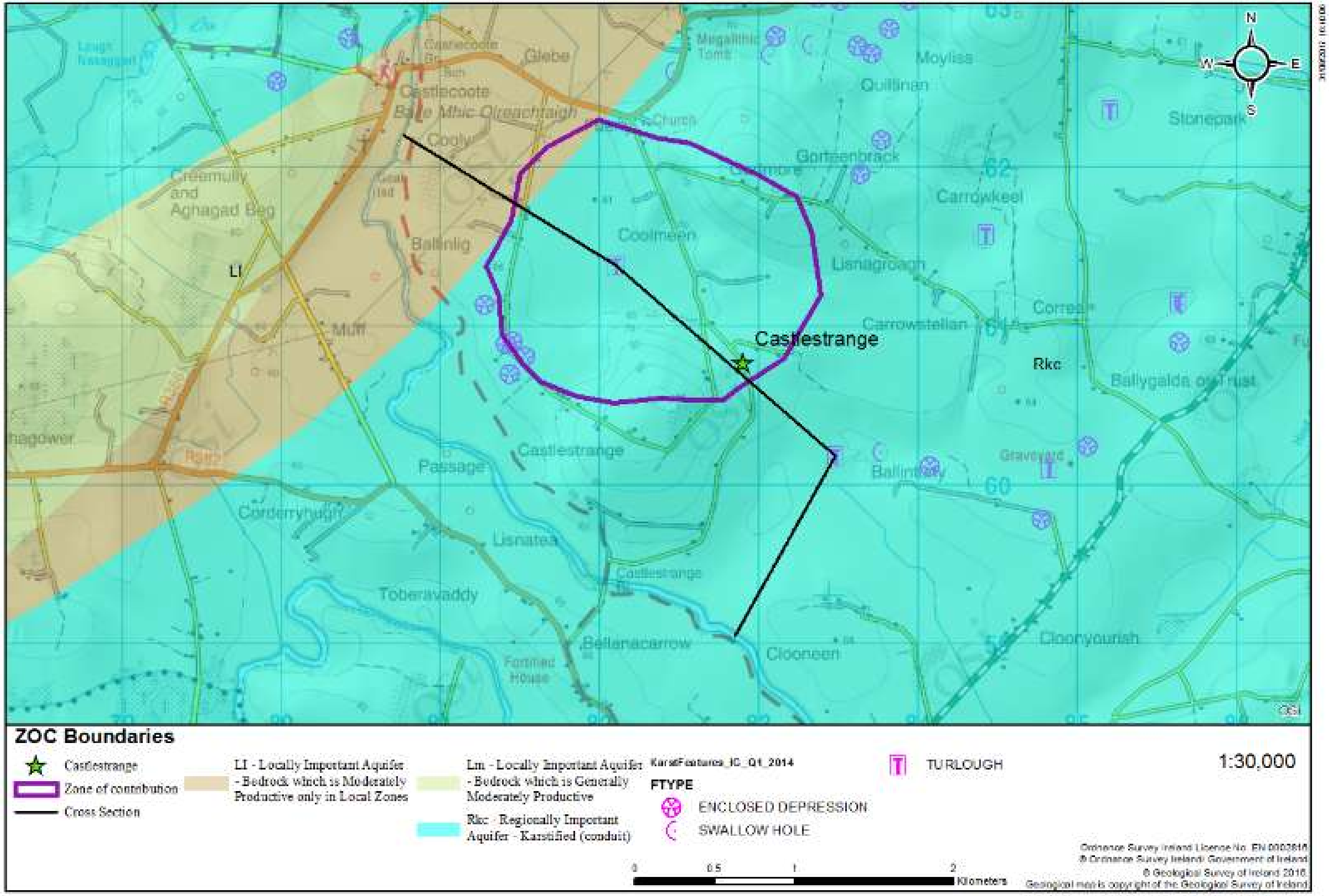


Figure 21 Aquifer map and ZC boundaries for area around Castlestrange GWS.

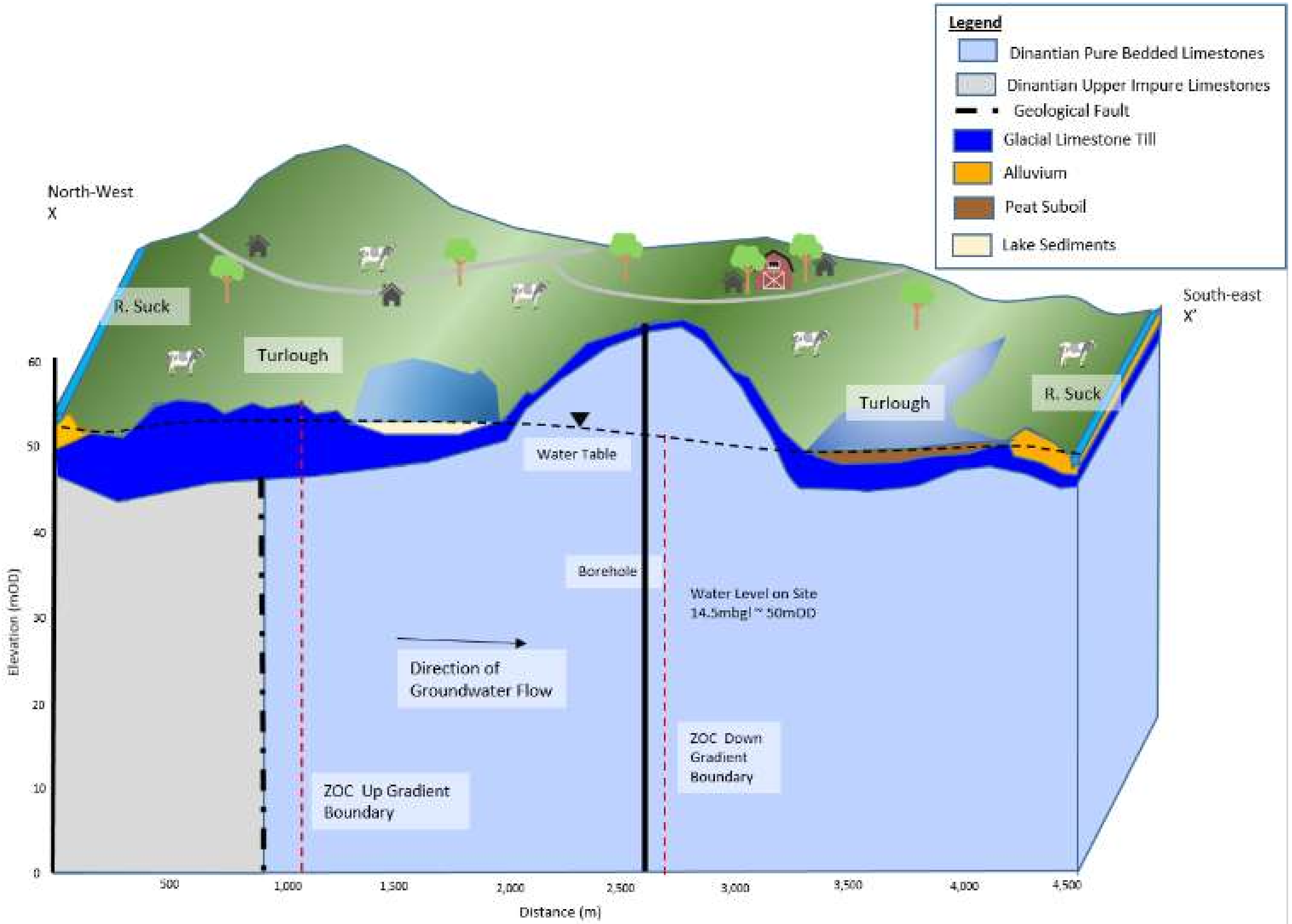


Figure 22 Castlestrange GWS conceptual site model.

pestilence is complete. And could it be that the locals so fear this doom that it is locked within a windowless hovel, shunned, never spoken off and best left forgotten.

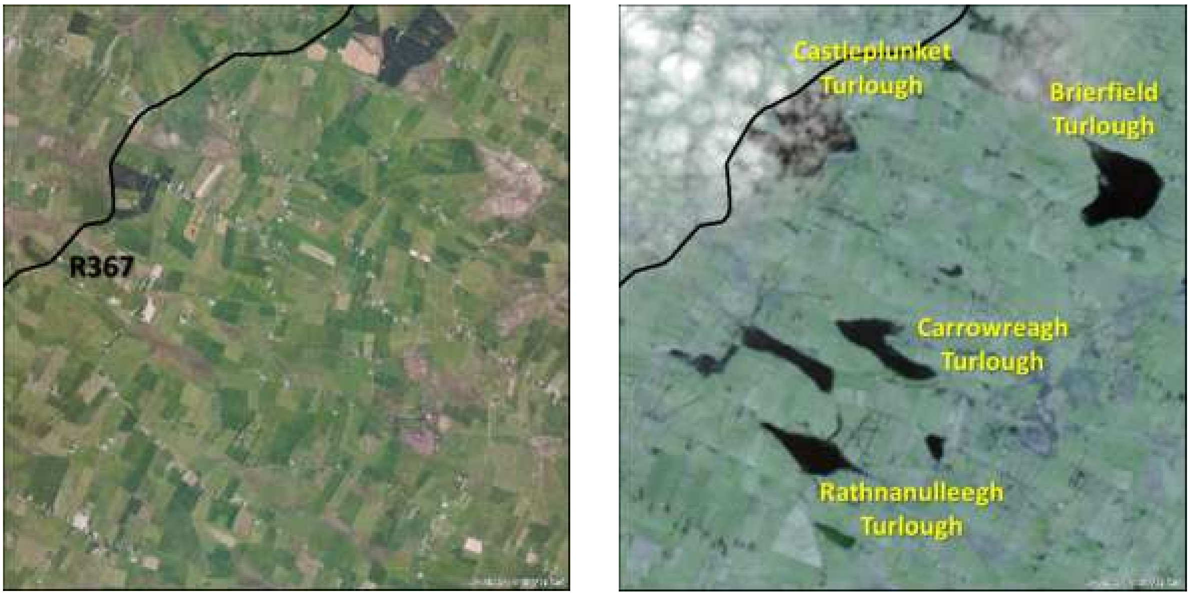
Further evidence must be gathered to enlighten our understanding and determine the true source of the water. At this point we look to the primary culprit, the shallow runoff from the hill, and then with a wider sceptical eye at the area to the north that feeds the sinking lake, Coolmeen. Further evidence is required before the snare can be tightened and the mystery completely solved.

The game is afoot !

10. Castleplunket Turlough
Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

Castleplunket turlough, located approximately 21km northwest of Roscommon town is one of the largest turloughs in the Rathcroghan uplands. The turlough basin is bordered by a rock outcrop to the northeast and sloping fields underlain by till to the south. An intermittent stream enters from the northeast and flows towards ponds and a swallow hole in at the centre of the turlough. The swallow hole has recently been successfully traced to Ballintober spring in the south east. Another secondary, but larger, swallow hole exists to the east. This secondary swallow hole appears to become active only when the primary swallow hole has reached capacity and water spills overland towards it. The turlough is approximately 80 ha in size and typically floods to a depth of 7-8m.

During the 2015/2016 flood event the turlough reached 90mAOD, 2m above its normal winter level. While no houses were flooded by the turlough, it cut off access to Castleplunket turlough on both approaches of the R367. The flooding lasted many months with access to some homes only returning in the early summer.



(a) Rathcroghan uplands during dry conditions *(b) Rathcroghan uplands during during flood conditions (Landsat - February 2016)*

Figure 23: Rathcroghan Uplands dry/wet comparison

Figure 24 Flooding at Castleplunket turlough, January 2016 (RTE News, 2016)

11. An introduction to LIDAR
Shane Carey

LiDAR has proven to be beneficial to the Groundwater Section, Geological Survey Ireland in terms of picking out potential karst features, modelling water flows from turloughs and, in certain cases, improving geological maps. This article describes the basic principles of how LiDAR works, LiDAR areas surveyed by Geological Survey Ireland, principally for karst feature mapping; and survey data available from other organisations involved in the Open Topographic Data Viewer. It also touches on how geological mapping can be aided through the use of LiDAR, as well as how Geological Survey Ireland quality control and quality assess LiDAR data.

LiDAR – which stands for Light Detection and Ranging – is a remote sensing method that uses light to measure distances to the Earth (Figure 25). As technology continues to develop, capturing large datasets at higher resolutions from various platforms is becoming increasingly common. Remotely sensed data is captured from satellites, aircrafts and most recently from unmanned aerial vehicle (UAV) technology. These types of datasets can assist geological mapping. Large datasets can provide interesting new challenges too: handling "Big Data" requires more sophisticated data models and databases to store and query the data.

How LiDAR works

A laser pulse is emitted from a remote platform and detector records the time it takes for that pulse to bounce back. Bounce backs are classified into returns. Pulses that bounce off tree canopies and buildings are returned first and hence are classified as 'first returns'. Fourth and fifth returns are also captured by the instrument and these returns are classified as 'last returns'. It is these returns that are used to create a Digital Terrain model.

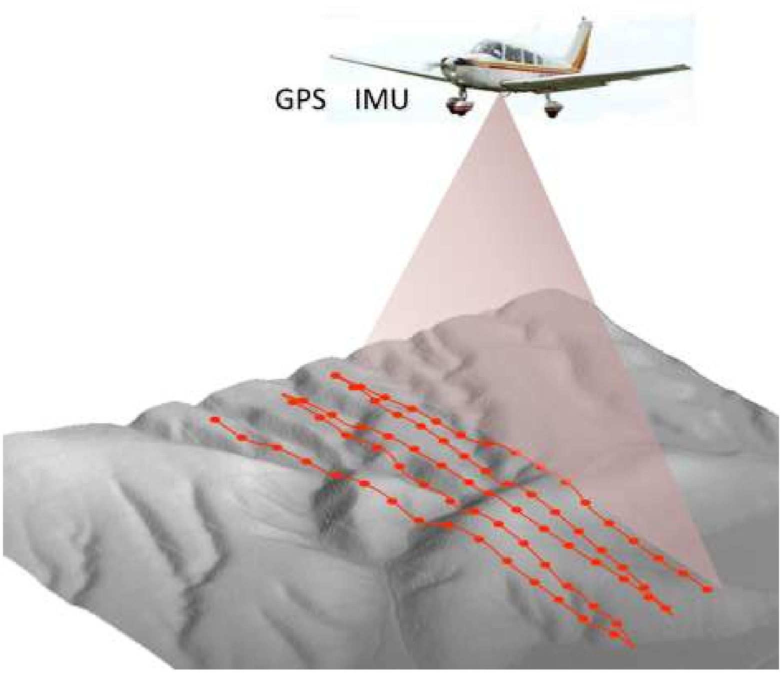


Figure 25 Image credit: Ed Nissen.
http://creativecommons.org/licenses/by-nc-sa/3.0/

Data QA/ QC: Open Source Tools

When acquiring LiDAR data, it is important to assess the data for:

- Scan angle and swath overlap;
- Point density
- Point spacing and distribution;
- Vertical accuracy

While there are propriety software packages available to undertake this type of work, many excellent open source tools are available also. To date, LiDAR data for this project has been quality assured and quality controlled using libraries such as Point Data Abstraction Library (PDAL)[1] and PKtools[2], both of which are open source projects.

Data Access: Open Topographic Data Viewer

An initiative between Geological Survey Ireland, Department of Culture, Heritage and the Gaeltacht (National Parks and Wildlife Service; National Monument Service), Discovery Programme and Meath Heritage Council to release their topographic data has led to the development of the Open Topographic Data Viewer[3]. The viewer was launched in April 2018 and in the last month; Transport Infrastructure Ireland has added their topographic data to the viewer. Approximately 4,130km^2 of LiDAR data have been released to date with more releases planned towards the end of 2018.

Figure 66 Open Topographic Data Viewer

LiDAR applications relating to Geology, Groundwater

Karst Feature Mapping and 3-D Modelling

Prior to capturing LiDAR data, karst feature mapping was undertaken by utilising aerial photographs, local knowledge and labour intensive fieldwork campaigns. LiDAR now provides a “bird’s eye view” of an area, meaning that a hydrogeologist can pick out potential karst features and patterns more readily during the desk study phase. This is likely to reduce time required in the field, as potential locations can be more accurately targeted (although will still need checking).

Figure 2727 show a hillshade grid derived from the LiDAR dataset with karst features and sinking streams mapped on top of it.

Apart from estimating the surface topography, LiDAR can also provide other information such as differences in landuse types from intensity values (such as vegetation and water). Products such as hillshade, slope, aspect, drainage networks can also be derived from the Lidar datasets. Furthermore, the data allows for 3-D analysis of karst features to be undertaken, which may not have been done in the past and may give greater insight into these karst features.

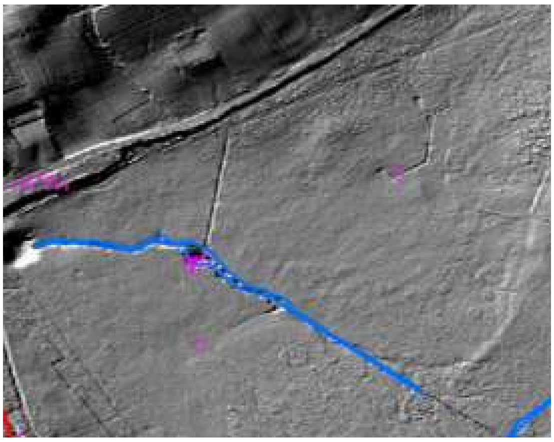


Figure 27 Hillshade dataset of Lidar data from Castleplunket, Roscommon

Geological Mapping

An example of LiDAR data supporting geological mapping can be seen from an area in North Cork. Figure 5 show the previously mapped geological boundary between sandstone (to the left - grey) and pure limestone (to the right - blue); an overlay of the recorded sinking streams (blue line) and a series of depressions identified in the processed LiDAR data (red points). Field mapping confirmed that the depressions were swallow holes and dolines. The location of these karst features is being used to refine the geological boundary i.e. shifting the limestone boundary to the west. This work will enable the 1:100,000 bedrock map to be updated.

Figure 28 Karst mapping in North Cork

LiDAR applications relating to other spheres

LiDAR has many uses, and is used within fields such as planning, engineering, archaeology, powerline mapping and volume change analysis. Figure 29 shows some examples of datasets generated from the Topographic data on the Open Topography Data Viewer.

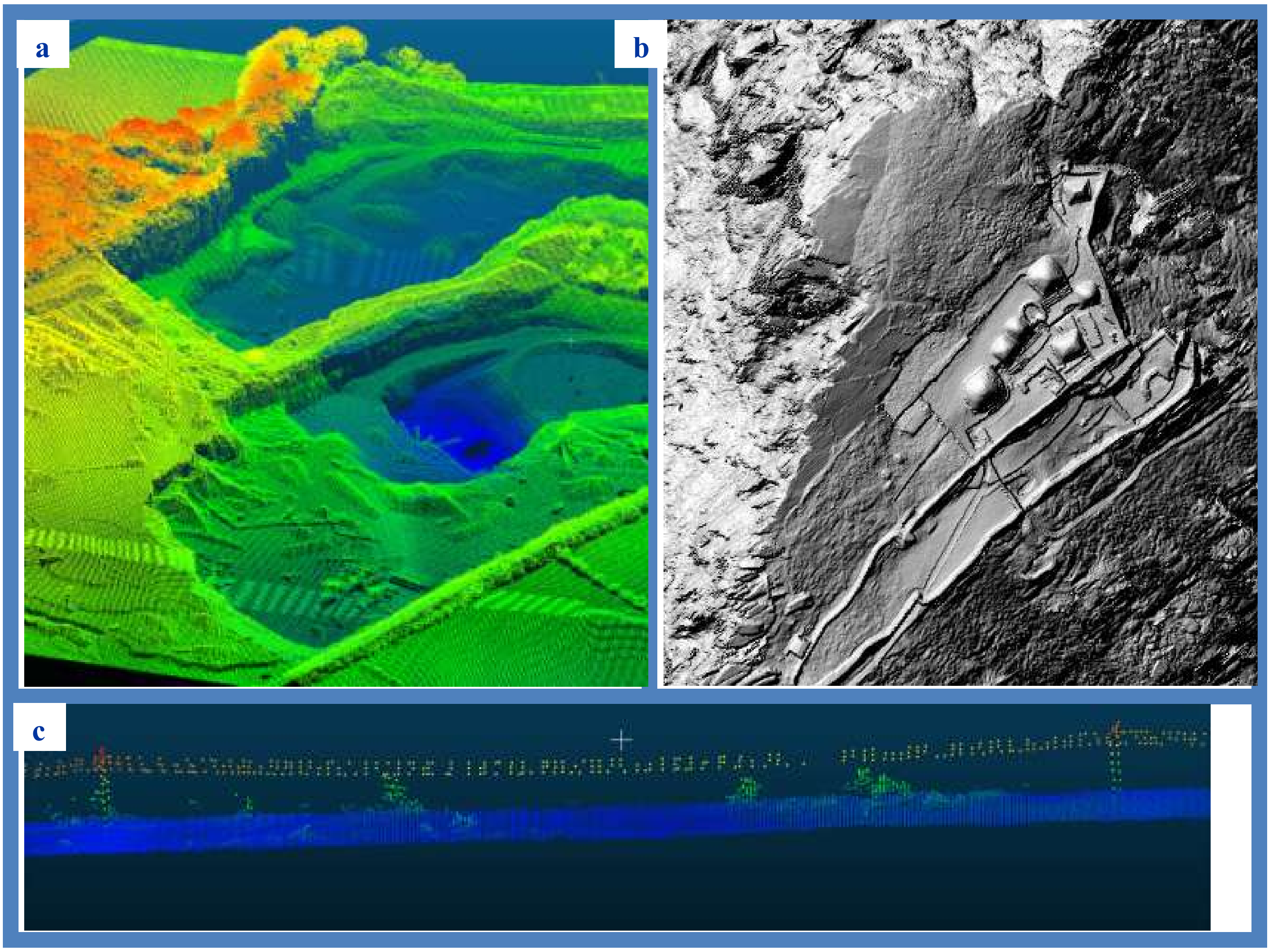


Figure 29 Example of LiDAR data from the Open Topographic Data Viewer a) Point data at a quarry site. b) Digital Surface Model of the Beehive huts on Skeillig Michael. c) Point data of Power line network

Concluding remarks

There are a number of drawbacks when considering using LiDAR: operation costs are high especially for small areas; the technology is ineffective during heavy rain and low lying clouds (commonly occurring in Ireland); it requires skilled personnel to analyse and quality control the data.

However, the benefits that we currently know of are many: vast areas can be surveyed quickly with high accuracy; there are no geometrical distortions with the data; surface densities with LiDAR are much higher when compared to other forms of data collection such as photogrammetry. This means better and more accurate results can be obtained. LiDAR also has the ability to penetrate vegetation which means surfaces below the tree canopy layer can be mapped.

References

[1] https://pdal.io/about.html#where-did-pdal-come-from
[2] http://pktools.nongnu.org/html/index.html

[3]
https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5

12. Lough Funshinagh

Ted McCormack, Owen Naughton, Rebecca Bradford, James McAteer

Lough Funshinagh is located approximately 12 km north-west of Athlone, in Co. Roscommon. The lake lies upon Carboniferous limestone and is designated as a turlough, yet it is often referred to instead as a 'disappearing lake'. This is because Funshinagh does not operate like a typical turlough. While the lake can fluctuate by a few meters every year, it seldom dries out completely (approx. 2-3 times per 10 years).

Furthermore, while the lake has apparent karst drainage features (and has been successfully traced to a spring 5km to the south), it is filled predominantly by surface water rather than groundwater. The turlough has five known streams entering it. The EPA operate a gauging station on the largest stream, with data indicating that during filling events the turlough can receive over 40% of its net change in volume from this stream alone. This suggests that the lake is predominantly surface water fed and groundwater drained. As such, the turlough essentially behaves more as a backed up swallow hole then a typical groundwater fed turlough. Similarly to other turloughs that behave this way (e.g. Blackrock and Coole turloughs in South Galway), the combination of unrestricted input and a restricted output can result in extensive prolonged flooding after periods of heavy rainfall.

Over the GWFlood monitoring period, the net rate of inflow to Funshinagh was observed at up to 1.8m^3/s during flooding periods. The rate of drainage during recession was comparatively smaller, reaching a maximum of only 0.5m^3/s. These rates of inflow and outflow are comparable with other typically sized turloughs around the country. Funshinagh, however, is one of the largest turloughs in Ireland. When compared to a similarly large (and also surface water fed) turlough such as Coole Turlough in Co. Galway which can drain at up to 3.7m^3/s (average daily rate), the rate outflow at Funshinagh is significantly lower. This low drainage capacity relative to the recharge rate is pivotal to prolonged flood patterns of Lough Funshinagh, and is the reason the turlough is rarely completely empty.

In 2016, Funshinagh rose over 2m above its typical winter level. This represented an increase in water volume from approx. 5 million m3 in a typical year to approx. 14 million m3. The high water levels flooded two houses and made two other houses inaccessible. Due to the relatedly slow drainage rate at Funshinagh, the effects of the floods were being felt long after winter 2016. Based on observed average daily outflow rates following the 2015/2016 flood, Funshinagh would require up to approximately 600 days to drain until empty (assuming there are no further flood events). In reality the turlough has seen additional flood events and it remains unusually high in summer 2018. In this manner, the water level in the lake can be seen as a reflection of multiannual flood patterns rather than seasonal flood patterns as in normal turloughs.

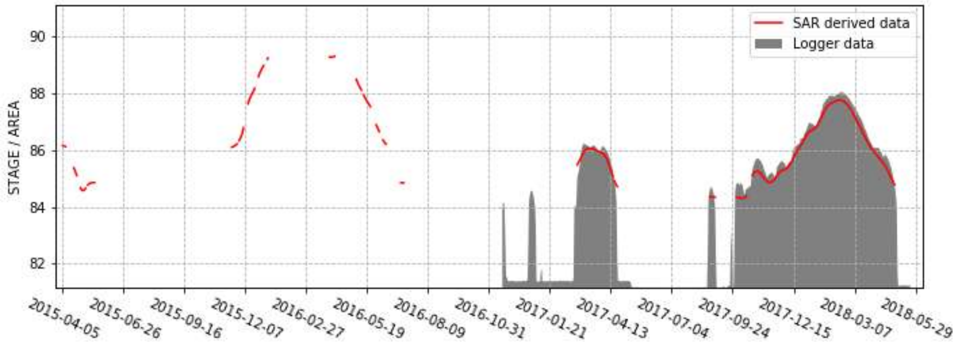
In 2016 Roscommon County Council (RCC) investigated the possibility of Funshinagh's primary swallow hole being blocked. Heavy machinery was used to dig at the likely swallow hole in an attempt to unblock it; however, these efforts proved ineffective. GSI monitoring data showed no noticeable difference in the rate of drainage before and after the works. The construction of an outlet channel from Funshinagh has been considered by RCC, but it has thus far been deemed economically unfeasible. RCC recently tendered for a flood relief scoping study to further investigate potential flood solutions.

(a) Funshinagh in dry conditions (Summer 2004) *(b) Funshinagh in typical flood conditions* *(c) Funshinagh in peak flood conditions (February 2016)*

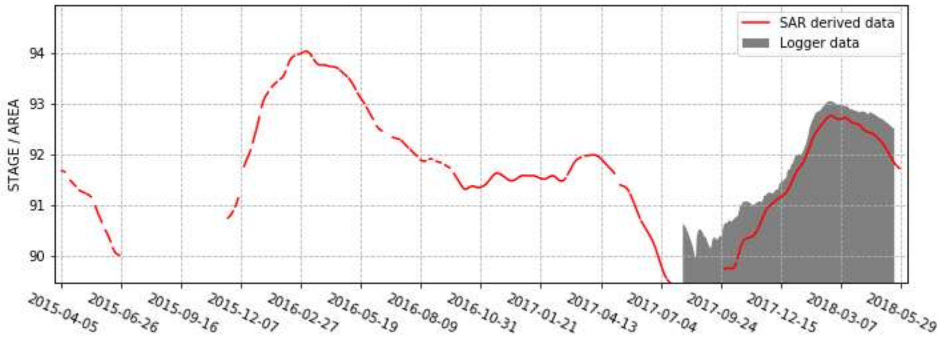
Figure 30 Lough Funshinagh during dry, wet and flood conditions.

Table 2: Datalogger and SAR derived hydrometric data for selected Roscommon Turloughs

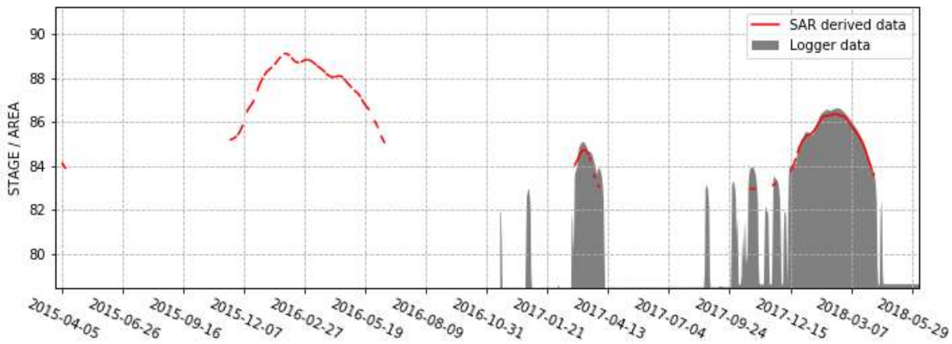
Castelplunket



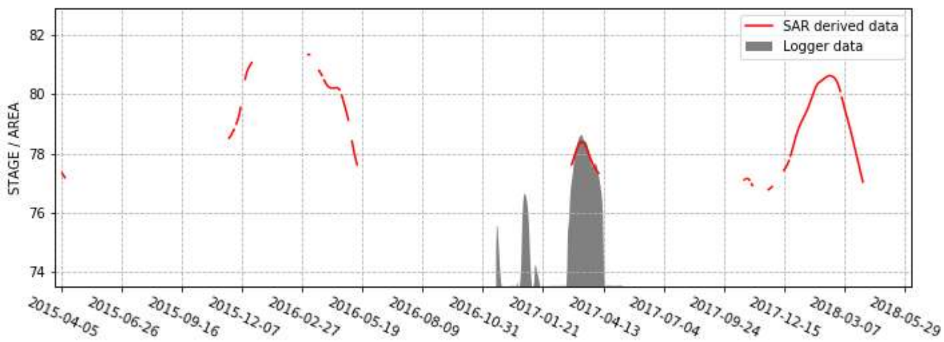
Brierfield



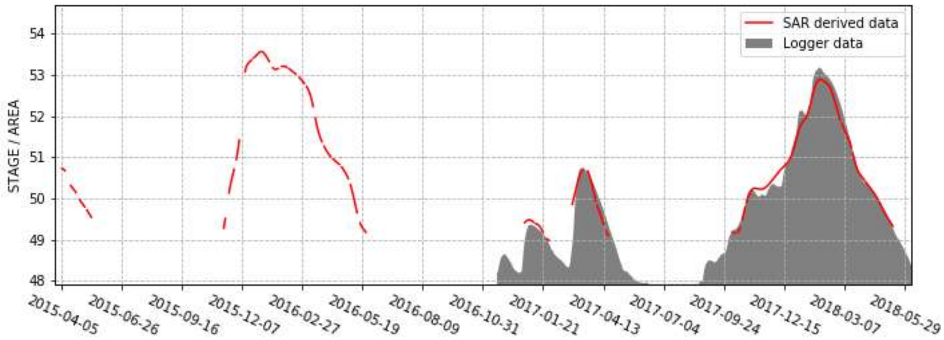
Carrowreagh



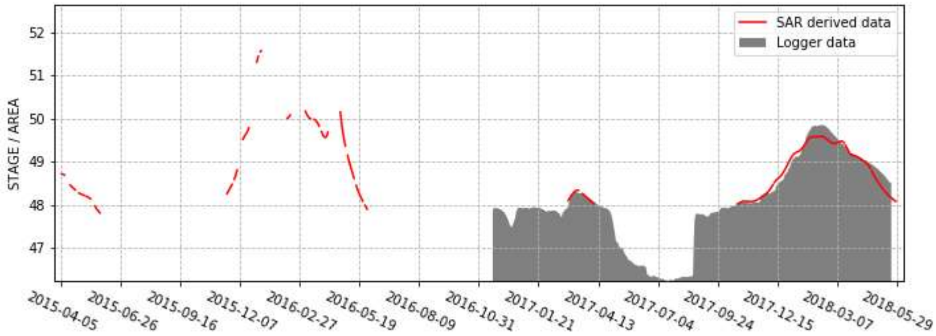
Rathnanulleegh



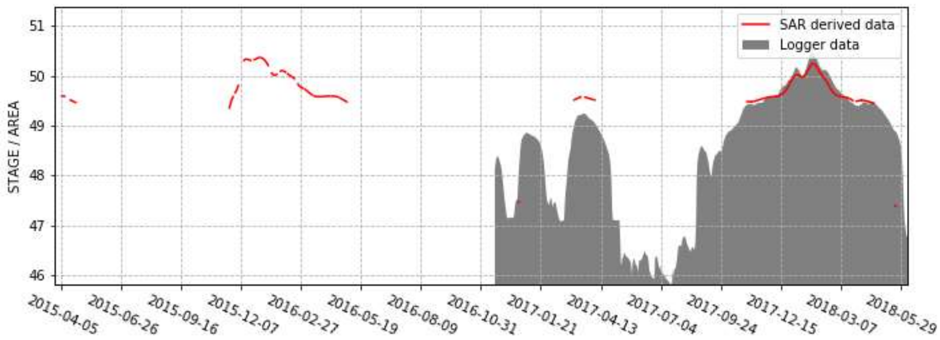
Carrowkeel



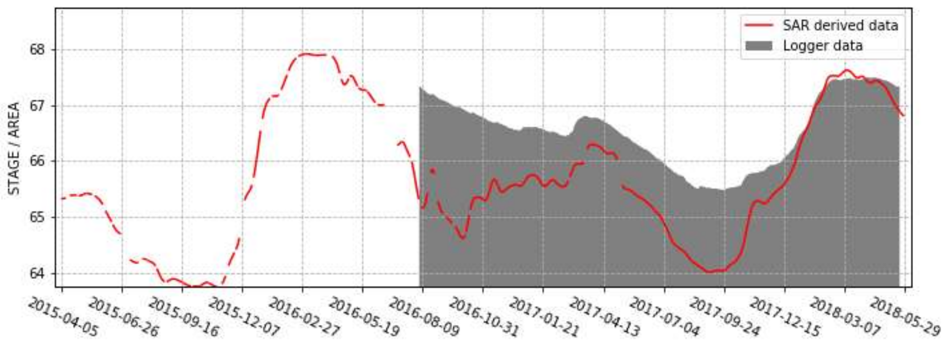
Correal



Ballinturley



Lough Funshinagh
(note: vegetation causes significant interference to SAR accuracy below 67m)



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