KARST HYDROGEOLOGY OF THE BURREN UPLANDS / GORT LOWLANDS

Field Guide

International Association of Hydrogeologists (IAH) Irish Group

2019

Cover page: ***View north across Corkscrew Hill, between Lisdoonvarna and Ballyvaughan, one of the iconic Burren vistas.***

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Programme

Saturday 19th October

10.00 Doolin

Walk north of Doolin, taking in the coast, as well as

- **the Aillwee, Balliny and Fahee North Members,**
- **wayboards,**
- **chert beds,**
- **heterogeneity in limestones,**
- **joints and veins,**
- **inception horizons, and**
- **epikarst**

David Drew and Colin Bunce, with input from John Paul Moore

13.00 Lunch in McDermotts Bar, Doolin

14.20 Murrooghtoohy

Veins and calcite, relationship to caves, groundwater flow and topography
John Paul Moore

15.45 Gleninsheen and Poll Insheen

Holy Wells, epikarst and hydrochemistry at Poll Insheen
Bruce Misstear

17.00 Lisdoonvarna Spa Wells

Lisdoonvarna history, the spa wells themselves, well geology, hydrogeology and hydrochemistry, some mysterious heat ...
Bruce Misstear

Sunday 20th October

08.45 Hydro Hotel, Lisdoonvarna

Talk at hotel on pipe netowkrs and hydrogeological modelling of Bell Harbour
Lea Duran and Philip Schuler

10.00 Carron and Bell Harbour

Site visit to Bell Harbour catchment, walking down-catchment from Carron
Philip Schulerr

11.15 Kinvara

Springs and estavelle discharges from lowland karst, on-site wastewater effluent and karst springs
Patrick Morrissey and Luka Vucinic

12.00 Caherawoneen

Channel draining catchment, local issues.
Patrick Morrissey

12.30 Lunch in O'Grady's Bar, Gort

13.45 The Devil's Punch Bowl

River resurgence, conduit flows.
Patrick Morrissey and Laurence Gill

14.30 Thoor Ballylee Yeats Tower

Catchment flooding, engineering solutions, flood analyses.
Patrick Morrissey

Location Map

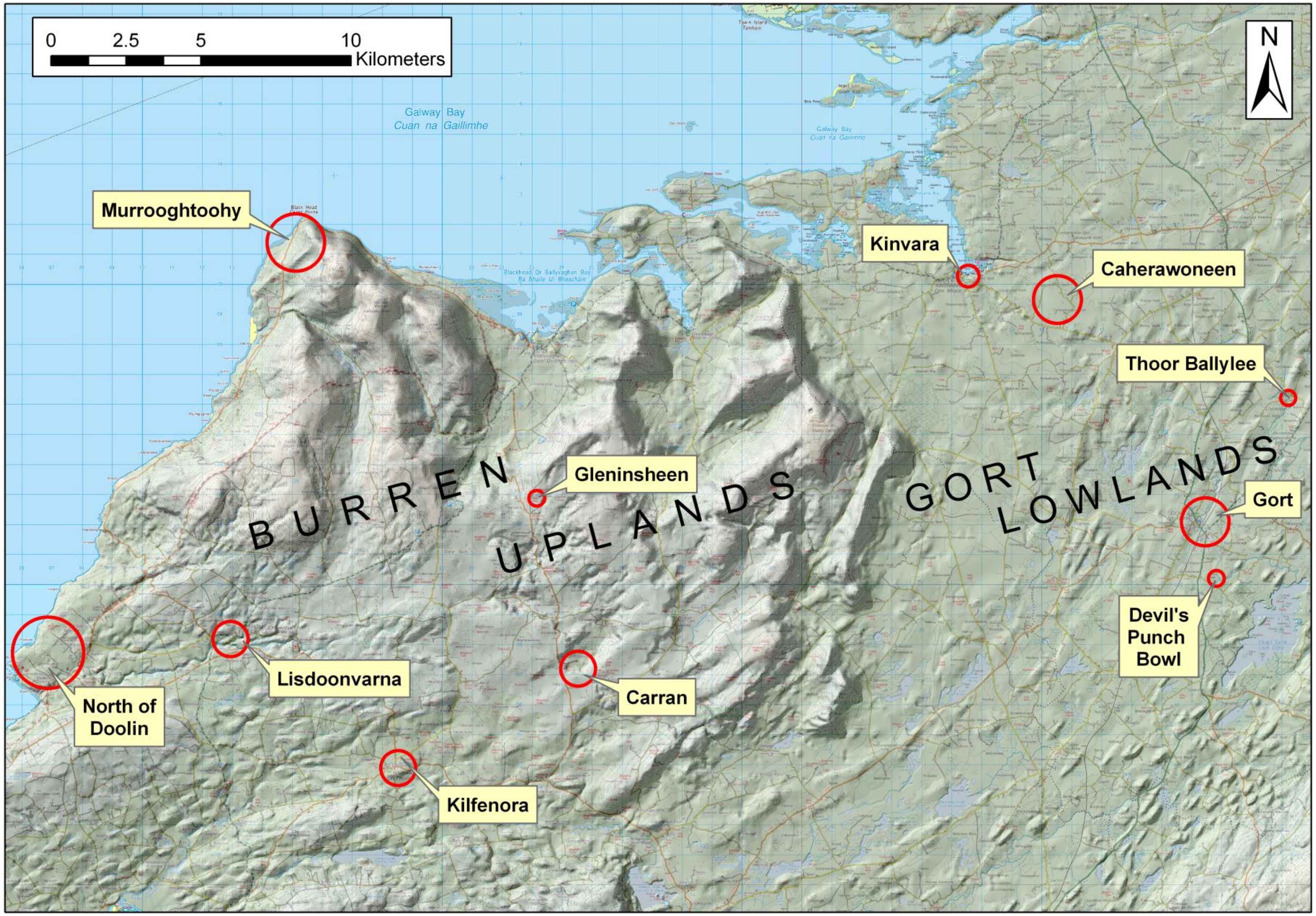

Figure 1: Map showing field trip stops and other selected localities mentioned in this guide (O.S. Licence EN 0057919).

Preface

Just as with last years field trip to Rathcroghan, on our annual field excursion this year we enter another fine Irish karst landscape; that of the Burren and the Gort Lowlands. We have been lucky with karst so far in 2019. David Drew, one of the main contributors to the trip, produced a magnificent book on the karst of Ireland, to the benefit of all passionate about hydrogeology, and indeed geology, in Ireland. We are lucky to have David, one of the Giants of Irish Hydrogeology, contribute to much of Saturday's section of the field trip; David is so fond of karst he even lives among and pretty much in it. It is fitting that we enter his territory on the back of the publication of the book, armed with ever more teasing questions and knowing facts.

The trip this year also sees another of the Giants of Irish Hydrogeology, Bruce Misstear, contribute significantly to the trip, on his recent PhD work on holy wells. Thus, our trip this weekend is like going to see the Rolling Stones in Wembley Stadium, and having Springsteen turn up as well.

I can remember my first IAH Field Trip, in the mid 1990s, also to the region around the Burren and Gort. Then, as a young postgraduate, I marvelled at the state and status of hydrogeological knowledge of this Clare-south Galway area, from the then-recent studies on the flooding which had befallen the Gort area in the mid-1990s. I remember thinking on the way home from that trip (David contributed hugely that weekend too) … 'they have this area sussed'. With so much knowledge, detailed investigation and research, data, analysis, good mapping, tracing results, and ideas, what more was needed ? This was not my first failing as a hydrogeologist (and it wont be my last); but it is one that, often, young researchers may be prone to - it's not just the stress of being a young academic that allows a student to fall into this trap. There is a basic reluctance in science to 'go back in', to replicate results, to do what has been done before, to repeat, to re-map, to prove and prove again (or to disprove). This is a trap that we endeavor to avoid.

This weekend trip should illustrate this maxim superbly, not just to my gullible self, but to any young, old, evangelical, non-believing or luddite hydrogeologist. This weekend we will be treated to a weekend of superb science. We will see so many newly mapped, modelled and interpreted to re-interpreted aspects of limestone hydrogeology we will never want to see a quartzite again. We will learn of wayboards and inception horizons and pipe network models and veining and jointing. We will veer into holy well science and find not *piseogery*, but solid science method and data. We will look at how, as hydrogeologists, we discover and discuss and help and educate engineers, landowners, lay people and policy makers. We will see how we understand the world beneath our feet, and help others understand it to.

Overall, we should see on this trip how science, not just in our discipline, has advanced in the last twenty years. In the mid-1990s, many of the techniques learned about and discussed this weekend were just not around. But the basic methods were, the tried and tested, and we will examine and discuss these too … temperature variations, electrical conductivity readings, groundwater levels, depths below ground. With all science, at any time, the new methods, as well as the old and tried and trusted, live side by side. And so science progresses, again, further.

The discussion should be fierce over the next couple of days. I, and all on the IAH Committee, hope you enjoy the trip.

Robbie Meehan
IAH Field Trip Secretary, 17th October 2019

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 Daniel 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 Clare (and the bit of Galway we will be in)

Robert Meehan

Although the geology of Clare is 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 the Slieve Aughty and Slieve Bernagh mountains, there are much older rocks exposed at the surface in relatively extensive windows through the limestones. These include two inliers (older rocks entirely surrounded by younger rocks) on either side of the Scarriff – Lough Derg valley. These rocks include some of Ordovician age just south of Broadford and near Lough Graney, but the majority are of Silurian age, the remnants of a former ocean floor and the roots of a long since vanished mountain chain. These Silurian rocks, like elsewhere in Ireland, are related to rocks throughout Longford, Down, and into the Southern Uplands of Scotland, but as they occupy a relatively small area in Clare, their story is best told in detail elsewhere.

Surrounding them are some Devonian age rocks, making up the majority of these two mountain ranges, sandstones and gravels laid down by flash floods in a poorly vegetated environment. The rocks of Ordovician, Silurian and Devonian age are partly preserved because they have been lifted up, and are now preserved as the more resistant hills. The Devonian rocks are mostly sandstones and pebble conglomerates.

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 somewhat 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 majority of the northern part of Clare and south County Galway, and the area we will visit over the next two days. They are well exposed, often at surface, and in the Burren comprise the largest unbroken patch of bedrock outcrop in the country. Around the edges, a veneer of glacial sediments of varying depths hides them, and means an intricate, complex landscape in terms of hydrology and hydrogeology, again the focus of much of our trip.

Only in the west of the county, to the west of the Burren itself, are there younger solid rocks, recording a time when the shallow sea was filled with deltas and swamps, meaning sandstone and shale rocks dominate. The land surface then emerged for nearly 300 million years and many of these rocks eroded down to their present level.

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, iconic landforms such as drumlins emerged from beneath it, and eskers and sand and gravel into fans and deltas were deposited by meltwaters, especially along the course of the Shannon in south Clare.

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. Around Ennis 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 Clare, along the foothills of the Slieve Bernaghs and to the west of Ennis, but these need a trained eye to discriminate them from remotely sensed images.

Since the Ice Age, the exposed limestone has developed 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. Clare also has a wealth of seasonal turlough lakes, where glacially scoured basins fill with groundwater in the winter and dry out in summer as the water table lowers.

Geological processes continue to modify the landscape today, such as with diurnal and seasonal flooding of the Shannon and Fergus River Estuaries. 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 Clare has one of the highest percentages of water supply from groundwater, such as from Drumcliff Spring (Ennis), 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 this valuable hydrogeological resource.

AGE (Million Years Ago)	*ERA*	*PERIOD*	*EVENTS IN CLARE*	*IF THIS TIMESCALE WAS A DAY LONG …*
2	Cenozoic	Quaternary	Several ice ages smothering Clare, 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 sands and gravels. 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- and north Clare.	The Tertiary period begins at 11.40 pm
145	Mezozoic	*Cretaceous*	*Erosion.* *No record of rocks of this age in Clare.*	11.15 pm
205		*Jurassic*	*Uplift and erosion.* *No record of rocks of this age in Clare.*	The age of the dinosaurs, starting at 10.55 pm
250		*Triassic*	*Desert conditions on land.* *No record of rocks of this age in Clare.*	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 north and mid-Clare. Limestones remaining today are pure and unbedded in the majority, with smaller areas of muddier limestones at the edges. Shales and sandstones deposited in swampy conditions in west Clare.	Much of Roscommon's current rocks (limestone, sandstone and shale) deposited around 10.10 pm
410		Devonian	Caledonian mountain building. Sandstones deposited, forming the bulk of the Slieve Aughties and Slieve Bernaghs.	'Old Red' Sandstone deposited at 9.52 pm
444		Silurian	Shallow seas, following closure of the Iapetus Ocean. Greywacke and shales deposited in the central portions of the Slieve Aughties and Slieve Bernaghs.	Starts at 9.42 pm
488		Ordovician	Shales, slates, siltstones and volcanic rocks form near Lough Graney and southwest of Broadford.	Begins at 9.28 pm
542		Cambrian	Opening of the Iapetus Ocean. *No record of rocks of this age in Clare.*	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

The Geological Timescale and County Clare.

2. The Burren.
David Drew and Colin Bunce

Introduction

Limestone is the primary aquifer in Ireland and the extensive rock exposures of the Burren provide an excellent location for examining, in three dimensions, some of the characteristics of the hydrogeology of Carboniferous limestone.

The Burren plateau, some 370 km^2 in area and averaging 200-300m in elevation (Figure 1), is an isolated upland karst (unlike the much more extensive contiguous plateau karst of Counties Sligo, Leitrim, Cavan and Fermanagh). Annual precipitation averages approximately 1500mm of which 1000-1300mm becomes recharge: a high proportion, which reflects the extensive areas of bare rock or patchy, thin, rendzina soils.

In general terms the geology is very simple: a 300m thick sequence of limestones is exposed, overlain by a thin layer of shale and then by younger sandstones outcropping in the west and southwest of the Burren. All were deposited in the Carboniferous period and have then been uplifted during the Variscan orogeny and tilted to the south with a regional dip of ca.2°.

Point recharge via sinking streams is largely confined to the contact between the limestone and the overlying impermeable shales and sandstones, with the exception of areas such as the Carran depression where thin shale bands (wayboards) within the limestones have allowed a surface drainage system to persist (Bunce & Drew 2019). Elsewhere, water sinks underground almost where it falls and hence accessible cave conduits are uncommon.

The limestones are classified as *pure bedded limestone*, and as a *regionally important aquifer* consisting of *karstified bedrock with conduit flow*, however within the aquifer there are several lithological factors that function to localise and concentrate groundwater flow. These include it's strongly bedded nature and the presence of wayboard horizons and chert within the sequence, which act as inception horizons and make this a highly heterogeneous aquifer.

Aspects of limestone geology

Bedding planes and cyclic sedimentation.

In the Burren sequence most of the limestone is described as very thickly bedded i.e. >1m (Figure 2) with most beds separated by a prominent bedding plane. Some units have few bedding planes and are described as massive, e.g. the Maumcaha Member. In hydrological terms however "*not all bedding planes are lines of weakness and few include voids before the onset of secondary processes*" (Lowe and Waters, 2014)

Some members in the limestone sequence show cyclic sedimentation - a sequence of repeated changes in grain size and/or chemical composition that reflects changing water depth during deposition. A perfect cycle begins with the sea flooding an existing land area (due to sea level rising or land subsiding); after reaching a maximum water depth early in the cycle this tends to decrease as sediment builds up. Figure 3 shows idealised changes in the sediments associated with such cycles.

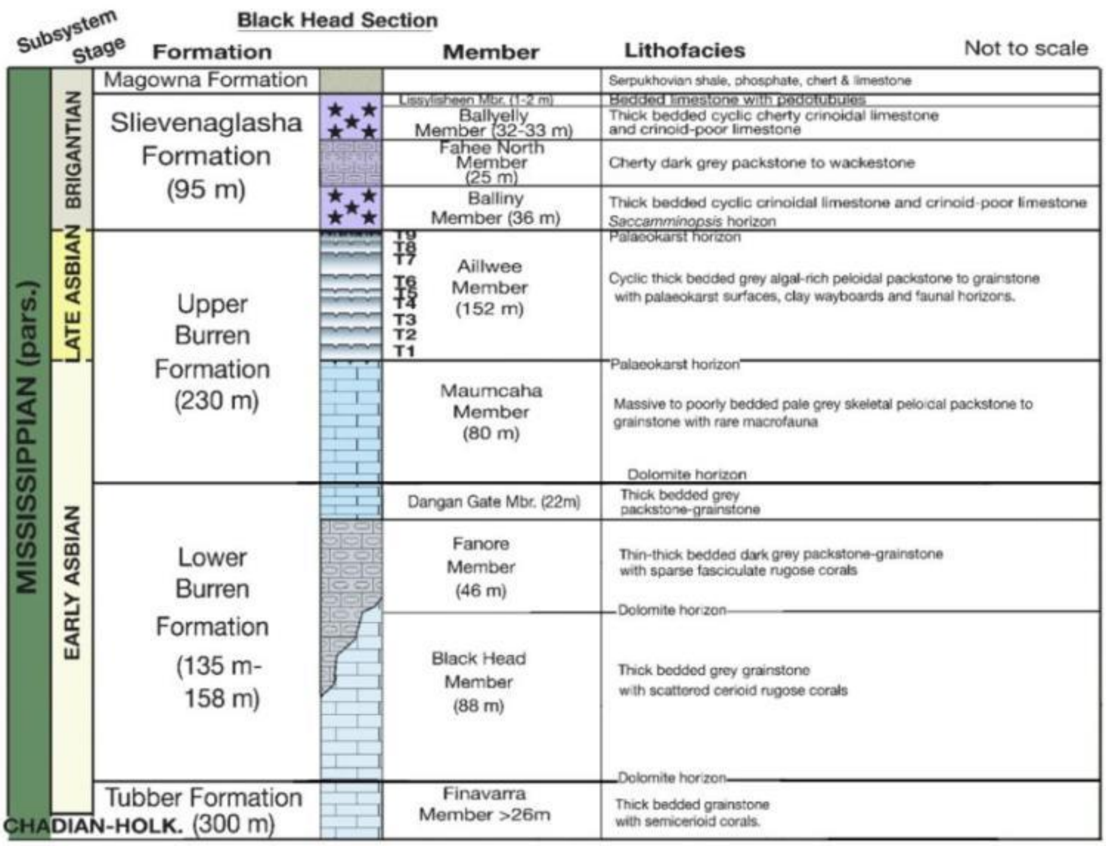

Figure 2: Lower Carboniferous Burren sequence (taken from Gallagher et al. 2006; modified by Murray and Bunce).

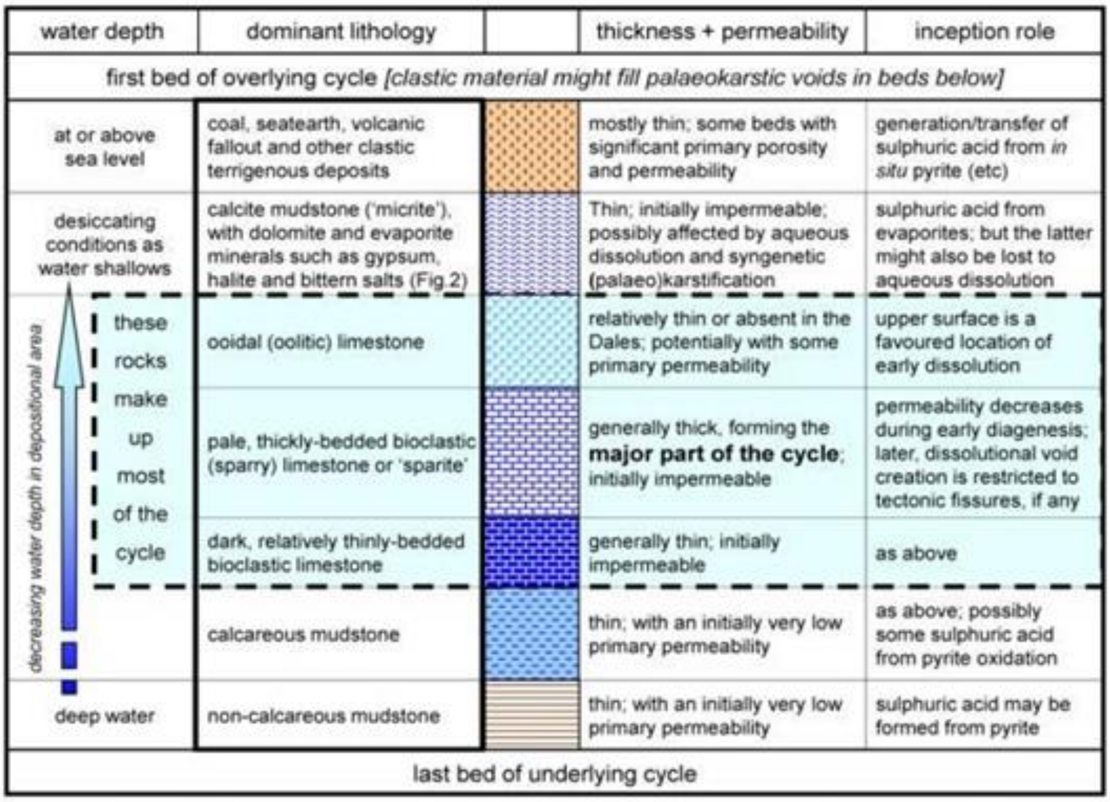

Figure 3: Idealized sedimentation sequence in a full depositional cycle. The lower two units are usually absent in the Burren cycles, the upper unit is only present in the Aillwee member (taken from Lowe and Waters 2014).

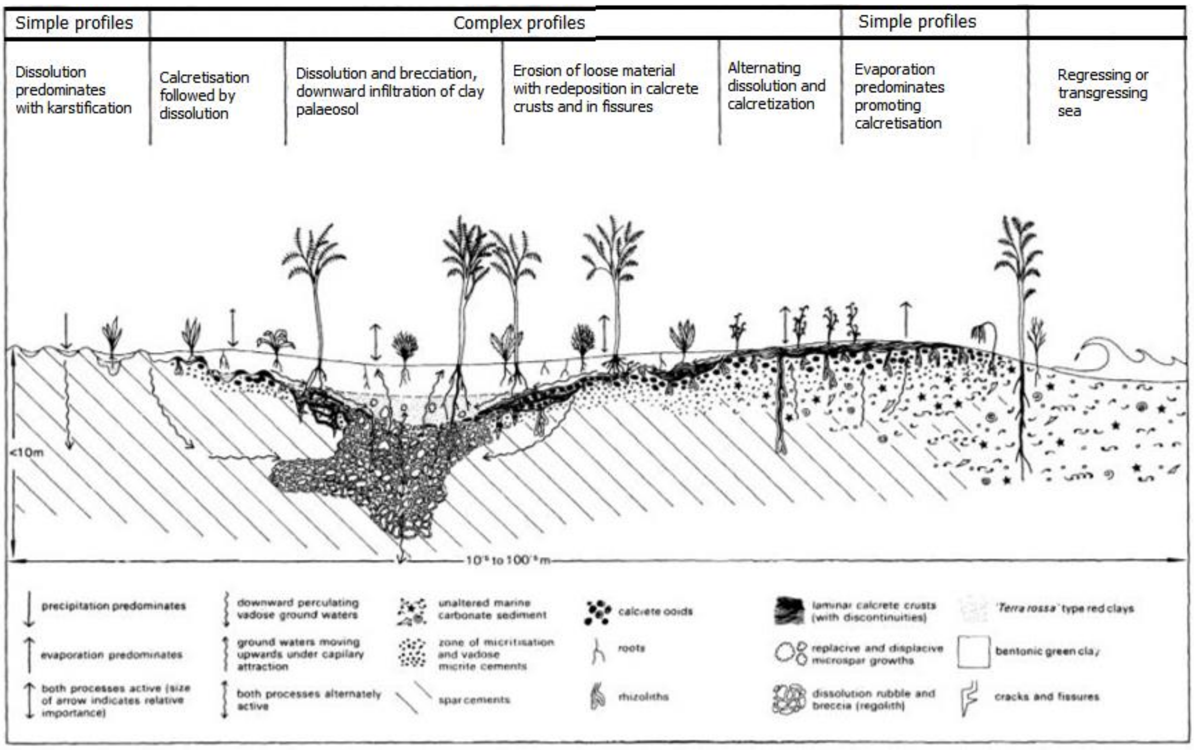

Figure 4: Variation of processes occurring on an emergent horizon (taken from Davies 1991).

Wayboards (emergent horizons).

During the Carboniferous period there was a series of global glacial build ups, during these periods Carboniferous Ireland was within the tropics and was not affected by ice directly. However there were global sea level changes which did impact on the formation of the limestone. Much of the Burren limestone was formed in a shallow (ca.20m deep) shelf sea environment; a drop in sea level would expose what had been sea bed to surface processes: dissolution, evaporation, soil formation and growth of terrestrial vegetation (Figure 4). These processes caused deposition of various sediments but usually a dark-grey, non-calcareous mudstone, sometimes containing pyrite (iron sulphide) which are termed wayboards. The limestone directly below these beds often has an irregular or undulating surface which is interpreted as *palaeo-karst* (i.e. karst erosion that happened ca.330million years ago!). In the Burren wayboards occur as shaley horizons 20-30cm thick within the Aillwee Member of the limestone sequence (Figure 5b). A Geological Survey Ireland borehole in Rannagh in the northeast Burren revealed six wayboards (see borehole log - Figure 5c), however each wayboard is laterally inconsistent and they often "pinch-out", making correlation difficult; this can be seen by comparing the borehole log with the generalised Aillwee Member sequence. However, even if there is no shale sediment present these horizons still act as important horizons for water flow.

Chert.

Chert is composed of extremely fine grained silica, it is believed to originate from types of plankton that have a silica skeleton (e.g. Radiolaria). This siliceous material is deposited at the same time as the limestone sediment, during diagenesis the silica becomes mobilised and migrates through the limestone in solution (this process is analogous with the formation of flint in chalk). Chert is re-deposited along bedding horizons and occasionally replaces the original carbonate of fossils such as corals making these fossils stand proud of the limestone; this is commonly seen at Mullach Mor in the Burren National Park.

Chert is extremely resistant to mechanical and chemical erosion and often acts as an aquiclude, however many chert beds are nodular in form and laterally discontinuous.

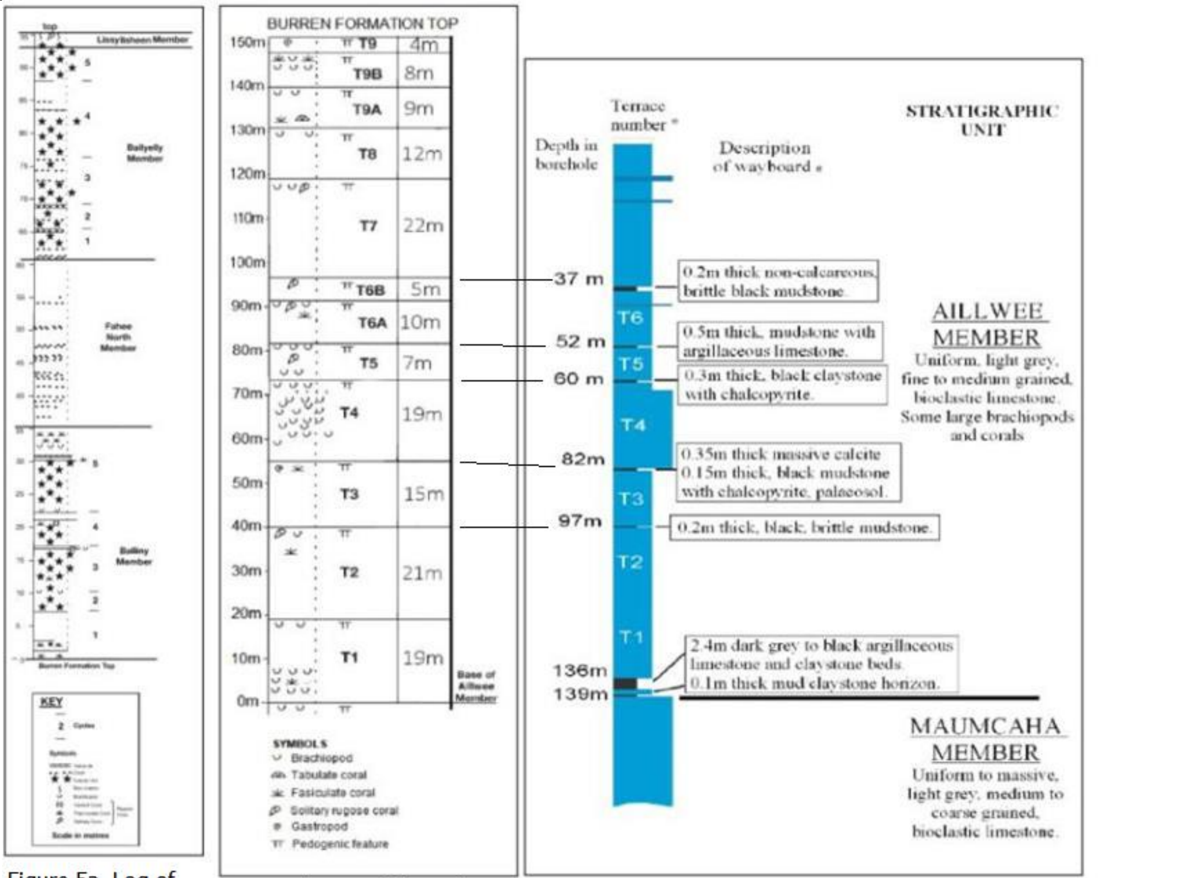

Figure 5a. Log of the Slievenaglasha formation

Figure 5b. Log of the Aillwee Member of the Burren Formation

Figure 5c. Log of borehole GSI-15-001

Figure 5: Stratigraphic log for the Slievenaglasha Formation and for the Aillwee Member of the Burren. Rannagh borehole log (on right).

Dolomite.

Dolomite (calcium magnesium carbonate) occurs sporadically in the Burren limestone sequence. It is thought to form by the alteration of calcite in limestone due to post-deposition circulation of magnesium-rich groundwater. It is less soluble than limestone and so may form aquiclude horizons.

BURREN LIMESTONES

The limestone sequence found in the Burren has been detailed in Geology of Galway Bay (Pracht *et al* 2004, and Gallagher *et al* 2006). The following notes describe the lithological variations between the three geological formations and their members outcropping in the Burren area. The Tubber Formation is the oldest and is seen only on the Galway Bay coast; above this is the Burren Formation which is divided into four members across the Burren area, but is more complex further to the east. The top formation is the Slievenaglasha Formation which is also divided into four members. Each member is described below and are shown in Figure 2.

Tubber Formation
This only outcrops on the extreme northern coast of the Burren where it is called the *Finavarra Member*. It is thickly bedded and partly dolomitized with a laterally continuous dolomite horizon at the top.

Burren Formation
The *Black Head Member*, the lowest member of the Burren Formation, consists of an 88m thickness of uniform, grey, medium to thick bedded limestone deposited in shallow water within the wave zone, macro-fossils are common, there is a dolomite horizon at the top.

The *Fanore* and *Dangan Gate Members* are usually combined and consist of an 68m thick sequence of fine to medium grained limestones, bed thickness is medium with undulating bedding planes and thin calcareous shale interbeds. Dolomite is common and there is a chert bed near the top of the sequence.

The *Maumcaha Member* consists of 80m of massive (un-bedded), grey coarse grained limestones, there is a thin but laterally continuous dolomite horizon at the base, it contains few macro-fossils.

The *Aillwee Member* is the upper member of the Burren Formation and consists of 152m of thickly bedded, grey coarse grained limestones deposited in cycles often separated by clay wayboards (Figure 5b). The wayboards within the Aillwee Member give rise to the classic terraced appearance of much of the Burren's hillsides. There are nine distinct terraces (T1 to T9) that each represent a minor cycle, other cycles (T6A, T6B, T9A, T9B and T9C) do not form significant terraces and are defined by the presence of significant bedding planes at the top. Each cycle consists of thick bedded (1-8m), dark-grey limestone largely devoid of macro fauna but usually with a coral or brachiopod horizon at the top and represents a shallowing-upward sequence which culminated in a palaeo-karst surface at the top with pedogenic features.

Slievenaglasha Formation (Figure 5a)
The *Balliny Member* is the lowest member of the Slievenaglasha Formation and consists of 36m of thick bedded cyclic limestone, there are no wayboards or chert beds. This member was deposited in five cycles (ranging in thickness from 3 to 10m) each cycle culminating in a shallow subtidal environment, but not in a subaerial emergence since no palaeo-karst or pedogenic features are seen.

The *Fahee North Member* consists of 25m of well-bedded, dark-grey limestone with no indication of cyclical changes in water depth. There are many chert horizons and few macro-fossils, these were deposited in a deep open-marine, sub-tidal environment.

The *Ballyelly Member* has a total thickness of 32m and consists of thick bedded, cyclic limestone deposited in five cycles. There are many chert horizons in the lower four cycles, and macro-fossils of crinoids and corals are common in many horizons. There was no sub-aerial emergence at the end of each cycle.

The *Lissylisheen Member* is the upper member of the Slievenaglasha Formation and is only a few meters thick. It consists of medium to coarse grained limestone with few macro-fossils and no chert. They were deposited in a high energy, sub-tidal but shallow water open-marine environment with evidence of cyclical changes in water depth.

FRACTURES

During the Variscan Orogeny compressional forces were exerted across the area in a broadly North-South direction. Ubiquitous across the entire Burren are calcite veins with a N-S orientation, they are generally thin (<1cm) and formed due to lateral extension in an E-W direction (Gillespie *et al*, 2001). In some areas, e.g. Carran, silica rich veins (upto 1m in thickness) are also present which sometimes also contain sulphide minerals (Walsh *et al* 2019). The N-S veins are vertically persistent through the entire sedimentary sequence and can be seen clearly in aerial photography.

Other vertical fractures, called joints, are formed by de-stressing of the rock due to removal of the overlying sediment burden or isostatic lift. They are more locally variable in orientation and are not vertically persistent through the limestone sequence.

Horizontal fractures can also be found due to bedding plane slip, this occurs where thickly bedded rocks are folded and the layers of rock slide over each other. This is common on the wayboard horizons where the shales act as "lubrication", calcite will be deposited in any voids created and is often seen as slickenslides associated with the wayboards (see Rannagh borehole log).

HYDROGEOLOGY

The major hydrological features of the Burren are shown in Figure 6 including surface streams, the internal and external springs and the presumed location of the groundwater basin divides. The positive water tracings from which the underground drainage basins were largely delineated are shown in Figure 7. The information available for the various catchments varies greatly, being particularly limited in the case of many of the areas draining directly to the sea, but well documented in catchments such as the River Fergus, St. Brendan's and Ballyvaughan where intensive tracing experiments were practicable.

Point recharge occurs at the contact with the overlying Namurian rocks and commonly forms cave conduits, these usually follow veins (usually oriented north-south) and joints (commonly oriented east-west) particularly in their vadose component. In some instances caves have developed with significant controls from both impeding layers and veins eg. Poll Gonzo (Bunce 2010). Veins extend vertically through a considerable thickness of strata allowing the water to descend to depth in a short horizontal distance (Moore & Walsh 2013, Bunce & Drew 2019).

Much of the diffuse recharge forms sub-horizontal, shallow groundwater flow, sometimes developed entirely in the epikarst layer, so that numerous small springs and seepages occur where a bedding plane carrying groundwater flow intersects the land surface; in a valley, a cliff or the walls of a doline for example. The water commonly sinks again often within a few metres, reappearing once more from a spring further down-slope. Few of these springs have baseflow discharges exceeding 20 l s^{-1} and many cease to flow after 10 days or so without rain (Drew 1990).

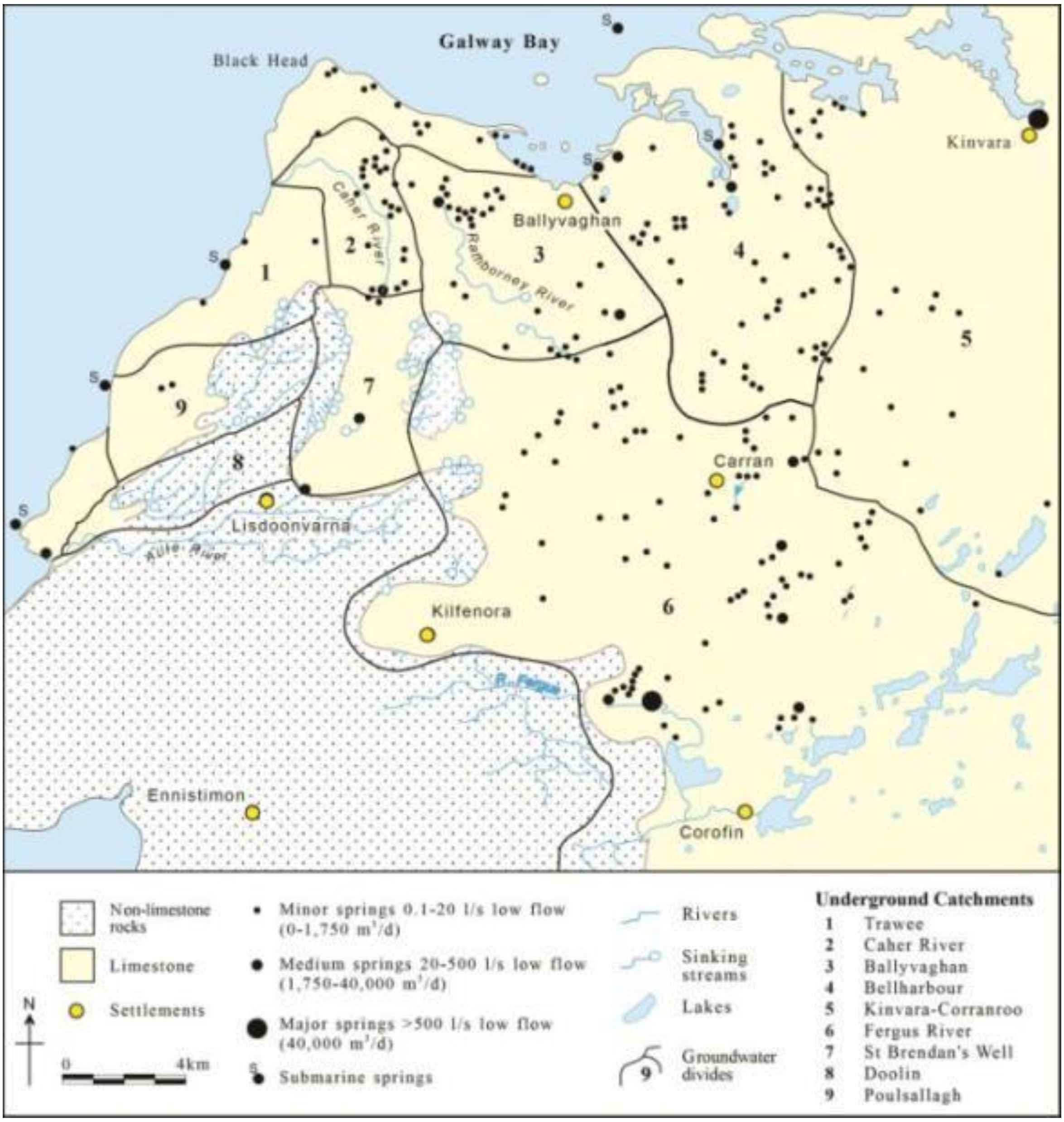

Figure 6: Burren springs and groundwater catchments.

Other 'internal' springs occur where well developed underground drainage channels were truncated by glacial erosion as for example the apparently immature springs at Oughtdarra (Pollsallagh catchment) and the Killeany spring (St. Brendans catchment) draining the northern part of Slieve Elva and Poulacapple.

The final outlet for all the Burren groundwater is via peripheral (external) springs located at hydrological lows such as the upper River Fergus valley (ca. 35 % of the total), the littoral or submarine springs on the Atlantic coast (ca. 20% of the total) and Galway Bay (ca. 35% of the total) and at the contact with the overlying Namurian rocks to the south of the Burren (ca. 10% of the total).

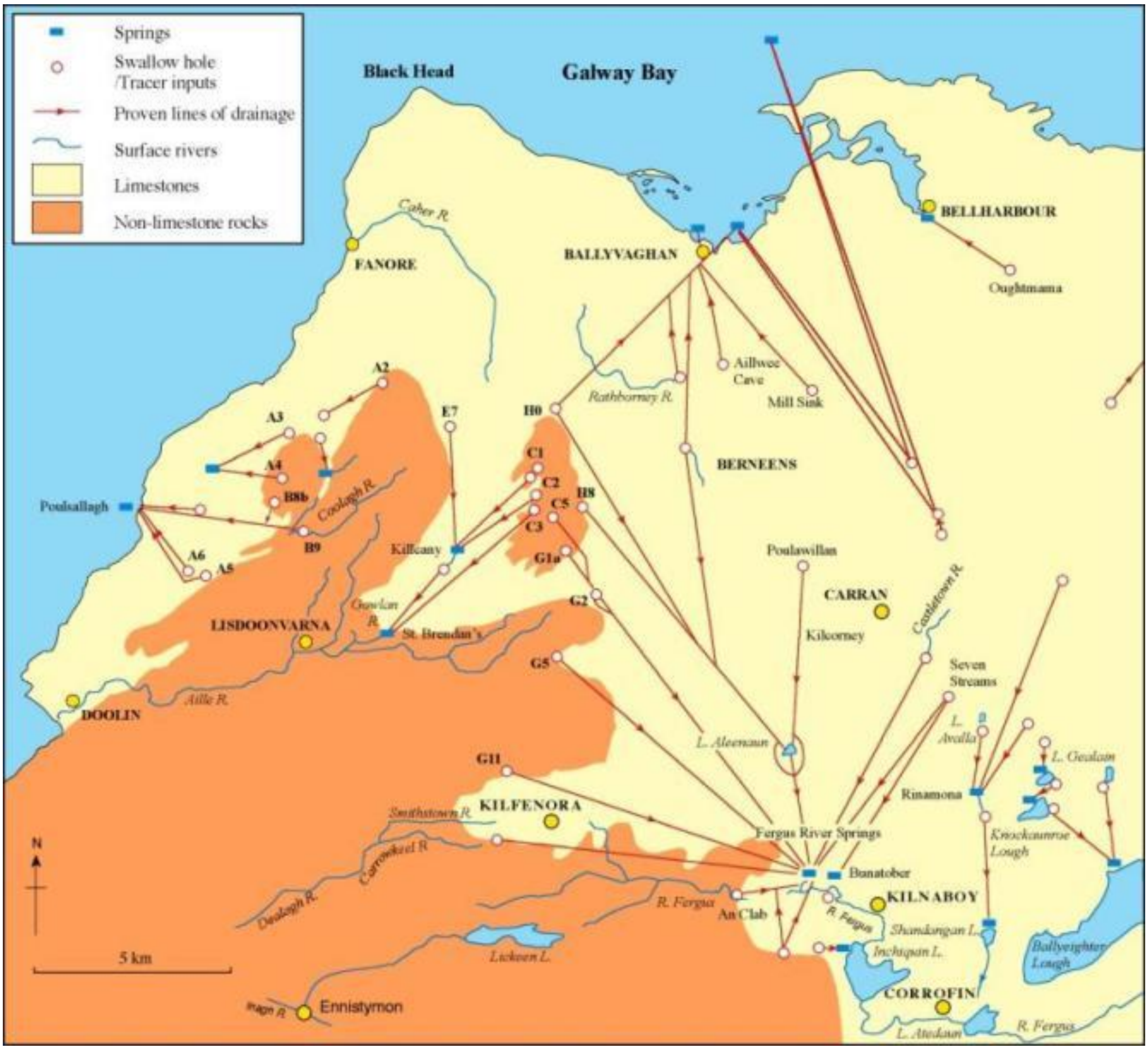

Figure 7: Burren water tracings 1960-2017.

On the north coast of the Burren (Galway Bay) the springs are associated with the major north-south embayments at Ballyvaughan, Bell Harbour-Aughinish and Corranroo. To the east of Ballyvaughan as far as Bellharbour-Aughinish, springs occur in the intertidal zone but there are also submarine springs at distances of 500-1500m offshore and at depths of up to 5m that seem to be fed from more distant sources in the central Burren. These sinks vertically traverse 250 m of limestone including numerous clay layers, possibly utilising north-south oriented vein systems as does Poll Gonzo. The flow rates, of less than 100 m/hour, are less than those recorded elsewhere on the Burren and may reflect the existence of impediments to flow.

The springs on the west (Atlantic) coast occur up to 500m offshore and at depths of up to 15 m below sea level. Cave systems such as the Green Holes at Doolin and Cliff Cave north of Poulsallagh (Mullan 2019), are or were, presumably associated with these submarine groundwater discharges.

Two large offshore springs are known along the reach of coastline between Doolin and the mouth of the Caher River to the north. They are at the Sluggagh at a depth of 12 m, offshore from Poulsallagh, and at Trawee (S5) 5km to the north, 250 m offshore and at a depth of 15 m. Little is known about the majority of these groundwater systems as water tracing to offshore springs is difficult and so the catchment areas shown in Figure 5 are only approximate. It is not obvious why groundwater outlets are graded to a level well below that of present sea level as only during the cold glacial and periglacial episodes of the Pleistocene would sea levels have been at or below this level.

Stop 1. - Coast north of Doolin

The area to be visited on stop 1 lies at the southwestern extremity of the Burren limestone outcrop, to the northeast of Doolin. Bounded by the Atlantic to the northwest and shales and sandstones to the southwest. The limestones in this area are the uppermost beds of the Aillwee Member displaying wayboards; the Balliny Member which forms a sea cliff section and the Fahee North Member with its extensive chert beds. All these beds dip to the south at the regional dip of ca. 3°. Fractures with calcite veining occur in two orientations: ca. 010° and 060°.

Small springs and seepages, often ephemeral, occur throughout the area but the outflow commonly sinks underground within a few metres. No water tracing has been undertaken in the area but presumption is that groundwater flow is to the south-southwest to submarine outlets such as those known to exist north of Doolin.

The purpose of Stop 1 is to provide an overview of the main elements of the geology and hydrogeology of the Burren and more specifically to illustrate:

- The heterogenous nature of the limestone aquifer
- Other controls (e.g. joints and veins) on groundwater
- The significance of inception horizons in localising groundwater occurrence

INCEPTION HORIZON HYPOTHESIS

From the above descriptions it can be seen that the seemingly homogenous limestone sequence of the Burren is not uniform in nature. Water will not flow through limestone until a flow path has been created, the question of how an initial flow path develops (speleogenesis) is difficult and the idea of '*inception horizons*' is an attempt to solve this problem.

> *"An inception horizon is any lithostratigraphically controlled element of a rock sequence that, by virtue of physical, lithological or chemical deviation from the predominant facies within the sequence, passively or actively favours the localised inception of dissolutional activity"* (Lowe and Gunn 1997).

Inception horizons are parts of the stratigraphy that favour early void creation. Most are strong lithological contrasts between limestone types (typically differing grain size) or between limestone and non-carbonate rocks. When deposition is cyclical then periodic regressions will cause lithostatic pressure to drive connate fluids from the sediment pile, often along contact zones between relatively porous (coarse grained) and less porous (finer grained) sediment (Figure 8). As further sedimentation occurs further slow bleeding of connate fluids continues along these embryonic inception horizons, following primitive hydraulic gradients to outputs in adjacent basins, potentially many kilometres away.

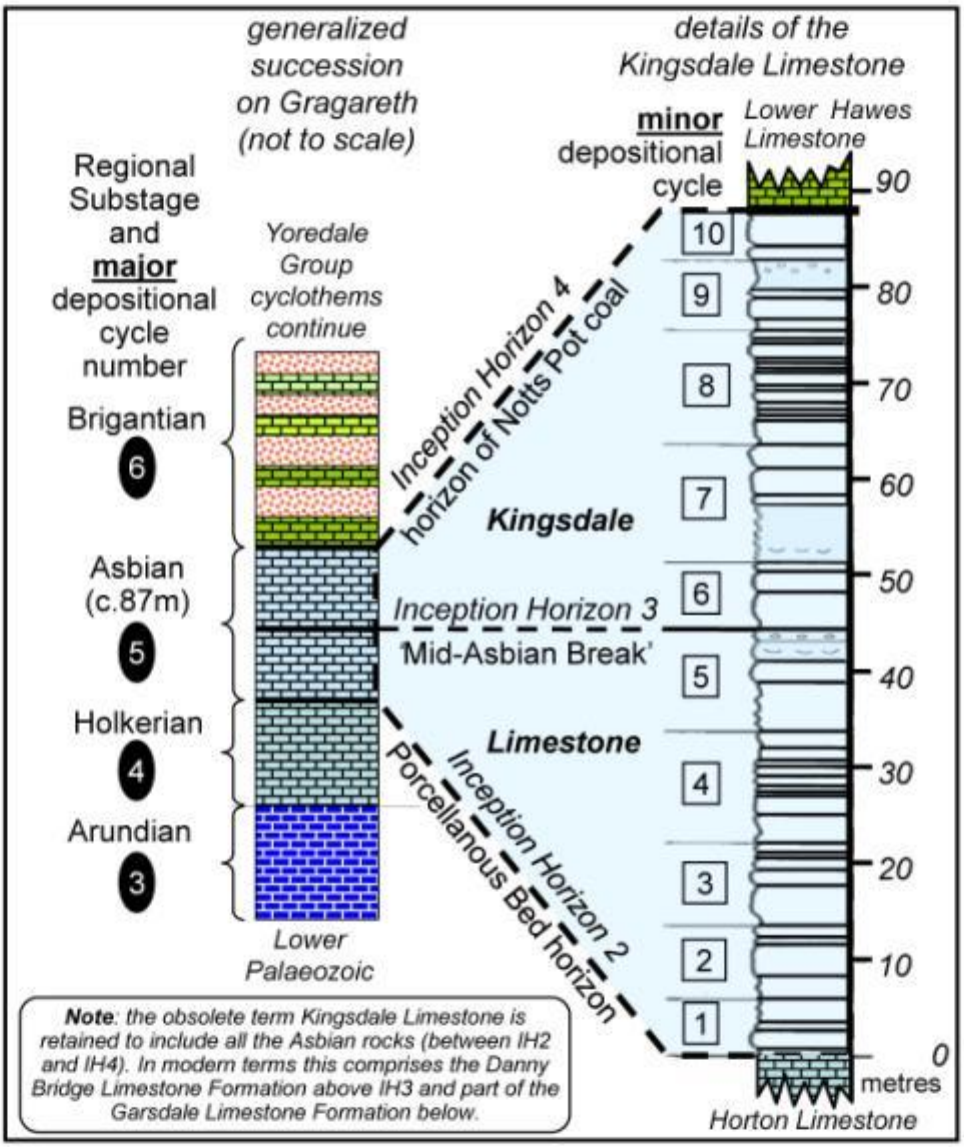

Figure 8: Example of inception horizons from Carboniferous limestones in the northern Pennines, UK (taken from Lowe and Waters 2014).

The inception stage is followed by a 'gestation' stage as increased dimensions of interconnected void systems permit extensive laminar flow. Gestation is complete for any incipient conduit when turbulent flow begins, but such conduits remain linked to extensive incipient void systems where inception conditions persist (Gunn 2004).

In the inception horizon model the role of e.g. wayboards is complex. Whereas the shale bed may act as an aquiclude, primitive void inception may be enhanced at the upper or lower contact during early dewatering; and the presence of pyrite may generate sulphuric acid.

Vertical fractures such as veins and joints add the third dimension to water flow in the limestone, flow will be focused at the contact lines where the fractures intersect the inception horizons thus providing the prime location for conduit development.

LOCATION 1.1 Wayboard horizon - inception horizon (Figure 9)

A shale bed (or wayboard) within the Aillwee Member of the Burren Formation, this is probably the base of T9A (Figure 5b). The dark grey coloured shale bed contains pyrite and has a maximum thickness of 30cms. It is exposed in what may have been a shallow depression as the bed can be seen to "pinch-out" to the south (compare with Figure 4). A "half-tube" cave passage has developed nearby with its floor at the same level as the top of the wayboard indicating the importance of these beds as inception horizons for fluid flow, in this case an initial conduit has enlarged upwards while water filled. Exposures of these "wayboards" are difficult to locate inland as the overlying limestone collapses over the bed.

Figure 9: Wayboard exposure at location 1.1.

LOCATION 1.2 Fraggle rock - inception horizon

A bedding plane with slickenslides probably located at the base of T9B (Figure 5b), 12m below the top of the Aillwee Member. The slickenslide surface (Figure 11) appears to function as an inception horizon as the overlying bed has experienced considerable dissolutional erosion by groundwater over a considerable lateral extent. The original conduits were anastomasing channels some of which have 'captured' much of the flow and enlarged accordingly. Figure 12a shows the full extent of the enlarged bedding plane, an enlarged conduit which has extended (when water-filled) upwards into the upper bed (Figure 12b) and the most developed conduit (Figure 12c) which has extended into the underlying (slickenside) bed. This last-mentioned

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Lacklass Sea Cave before the storms. Photo by Nigel Burns

Lacklass Sea Cave after the storms. Photo by Cheg Chester

Figure 10: The impact of winter storms (2014) on the sea cliff between locations 1.1 and 1.2.

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conduit gives access to a negotiable cave (Figure 13) developed, in the third dimension, along joints and veins.

Figure 11: Slickenslides close to location 1.2.

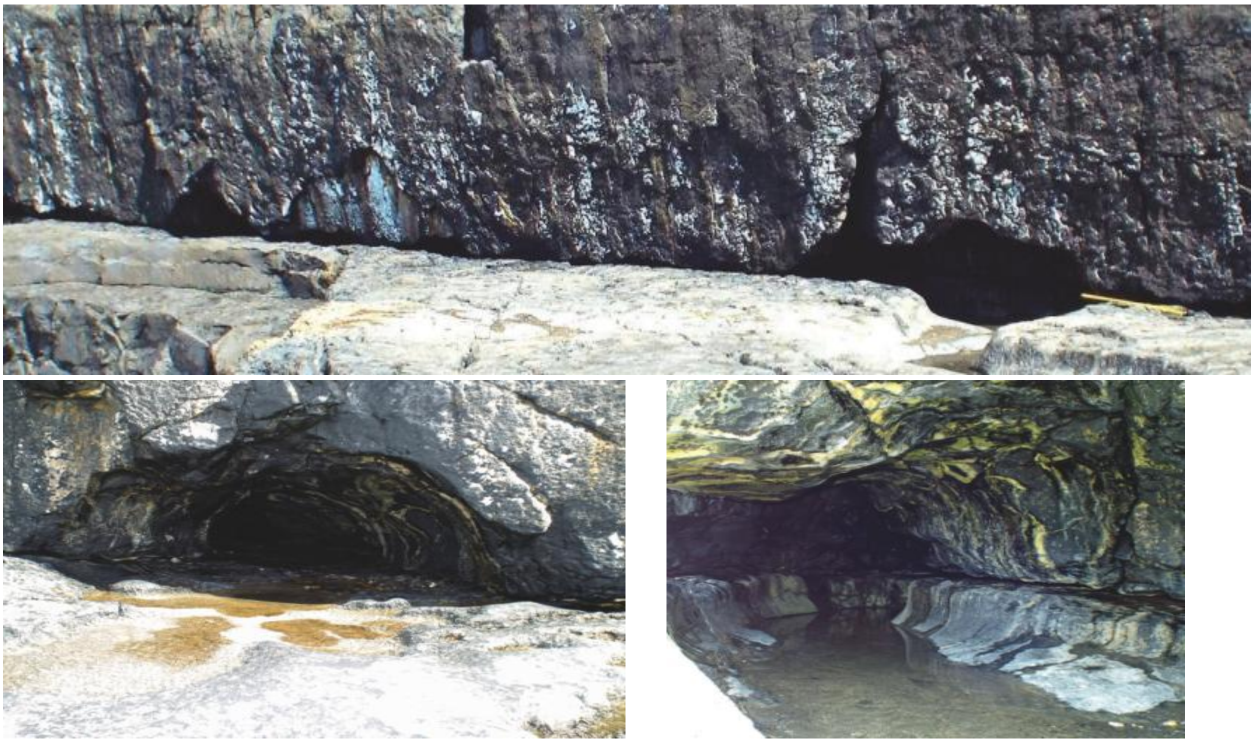


Figure 12: Location 1.2 Fraggle rock inception horizon.

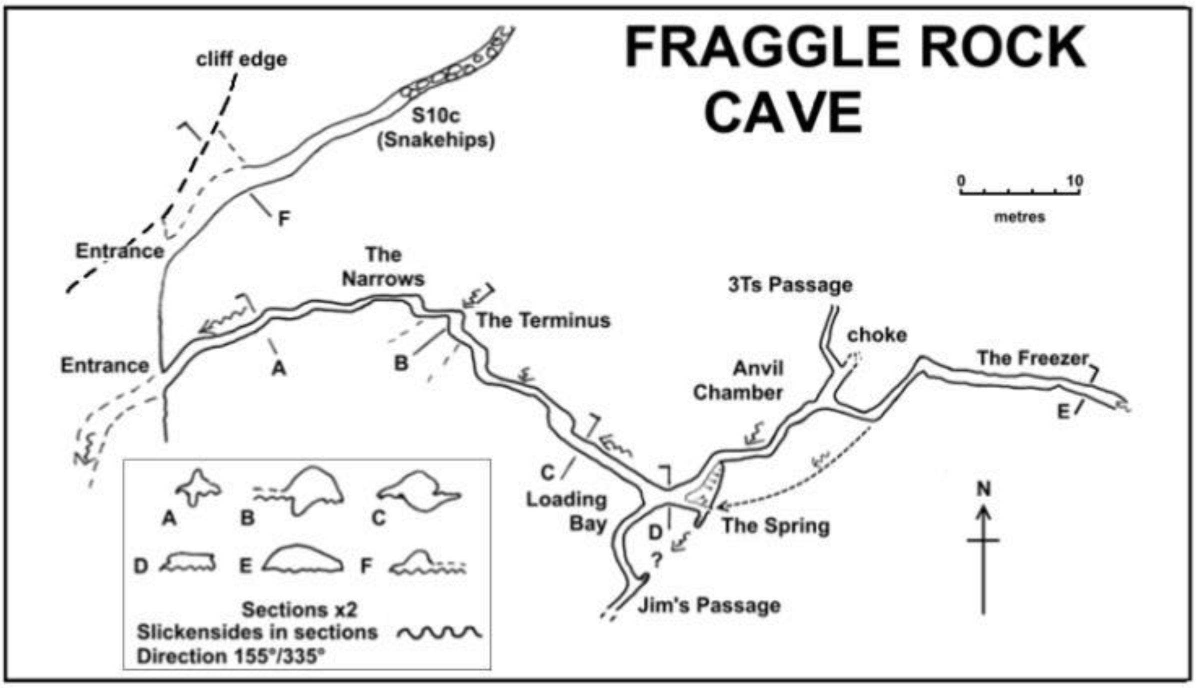


Figure 13: Plan survey of Fraggle Rock cave.

Figure 14: Location 1.3 Chert horizons in the *** Member of the Slievenaglasha Formation.

LOCATION 1.3 Chert and epikarst

A north-south vertical exposure of limestone (presumably along a vein) from the Fahee North Member (Figure 5a) of the Slievenaglasha Formation reveals a number of chert horizons. The strong lateral extent of some of these beds can be seen in the lower chert bed (Figure 14), while a higher bed is less continuous.

The top two meters of this exposure also shows the nature of epikarst. Close to the surface all the fractures become more open and available to dissolution by rainwater (Figure 15).

Figure 15:.Location 1.3 Epikarst development in the upper 2-3m of the cliff.

References

Bunce, C. A. 2010. Poll Gonzo. *Irish Speleology*. 19, 16 - 21.

Bunce, C. A. and Drew, D., 2019. The hydrogeomorphology of the Carran enclosed depression, Co. Clare Ireland. *Proc. Univ. Bristol Spelaeological Soc.* 28(1), 155-174

Davies, J.R., 1991.Karstification and pedogenesis on a late Dinantian carbonate platform, Anglesey, North Wales. *Proc. Yorks. Geol. Soc.* 48(3), 297-321

Drew, D., 1990. The Hydrology of the Burren, County Clare. *Irish Geography* 23, 69-89

Gallagher, S.J., Macdermot, C.A.V., Somerville, I.D., Pracht, M. and Sleeman, A.G. 2006. Biostratigraphy, microfacies and depositional environments of Upper Visean limestones from the Burren region, County Clare, Ireland. *Geological Journal*. 41, 61–91.

Gillespie, P.A. Walsh, J. J. Watterson, J. Bonson, CA.G. and Manzocchi T., 2001. Scaling relationships of joint and vein arrays from The Burren, Co. Clare, Ireland. *Journal of Structural Geology.* 23, 183-201.

Gunn, J., 2004. *Encyclopedia of Caves and Karst Science*. Routledge

Lowe, D.J. & Waters, CA. 2014 Geological influences on cave origin and development in the Yorkshire Dales UK. *Cave and Karst Science* 41, 13-35

Moore J.P. & Walsh J.J. 2013 Analysis of fracture systems and their impact on flow pathways in Irish Bedrock aquifers. *Irish Groundwater Newsletter*, 28-33

Mullan, G. 2019 *Caves of the Burren and western Ireland*. University of Bristol Speleological Soc., Bristol.

Pracht, M. Lees, A. Leake, B. Feeley, M. Long, B. Morris, J. McConnell, B. 2004 *Geology of Galway Bay*. Geological Survey Ireland.

Walsh, J.J. Moore, J.P. Bunce, CA. Hollis, S.P. Kelly, J. Menuge, J.F. (in review) The origin and nature of hydraulic fractures and veins within The Burren, County Clare, Ireland. *Irish Journal of Earth Sciences*

3. The geological controls on groundwater flow evident from the exposure of The Burren.

John Paul Moore and John Walsh

Introduction

The rock exposure in The Burren can provide important constraints on the geological controls on groundwater flow in limestone sequences, which are pertinent to other parts of the country where the geology is under cover and relatively unexposed. Some of these controls are highlighted in the localities visited in the morning, northwest of Doolin, and in the afternoon near Murroughtoohy (south of Blackhead, Figures 16 and 19).

Our recent work has investigated the role of geological structures on the inception and development of karst. Quantitative analysis from over 120 quarry and mine localities suggests karst conduits in the Carboniferous limestones of Ireland can only have been incepted by either conductive fractures or direct dissolution (Moore and Walsh, 2013 and refs therein). Conductive fracturing mainly arises from Cenozoic strike-slip faults and ubiquitous stress release joints, with older Carboniferous structures tending to be sealed unless karstified (Moore and Walsh, 2013). In The Burren the often non-random spatial distributions and trends of karst conduits results from a tendency for karst to localise on lithological and structural heterogeneities.

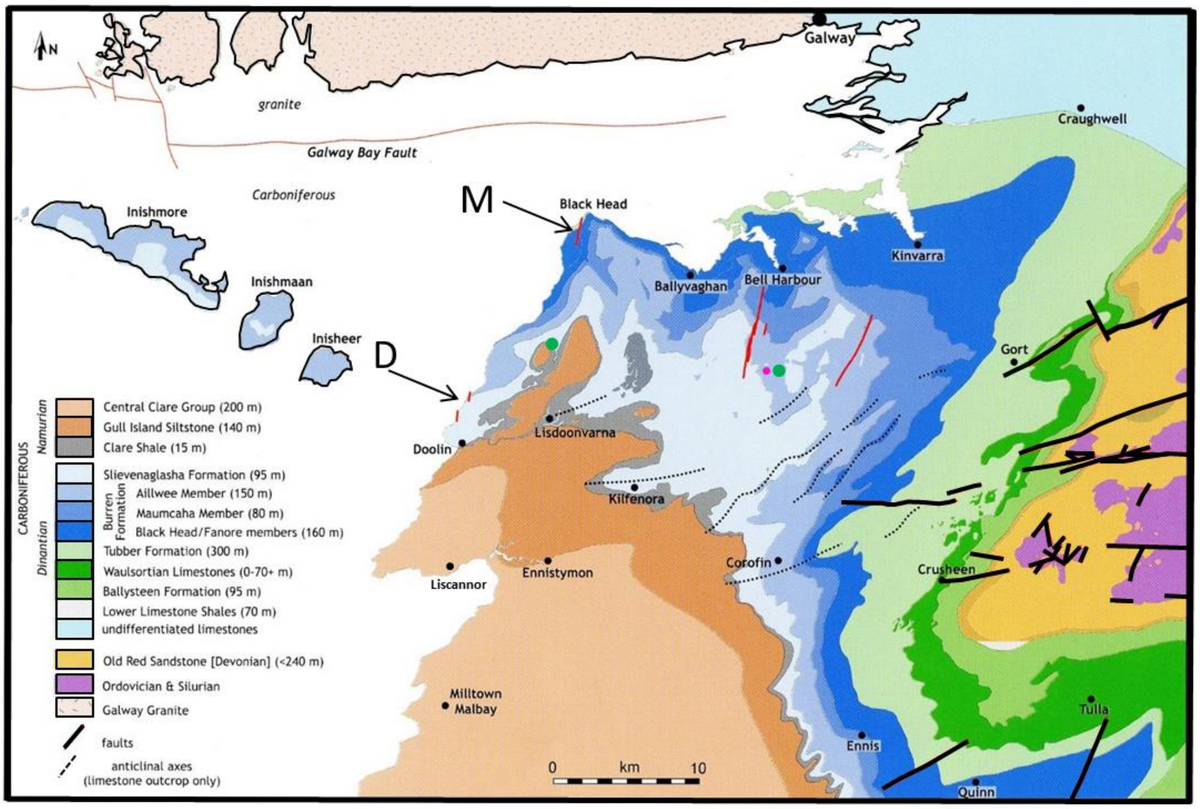


Figure 16: A simplified geology map of North Clare (Mullan 2003, after MacDermot et al. 2003, note for an up-to-date stratigraphy of The Burren cf. Gallagher et al. 2006). The two localities to be visited on the fieldtrip, north of Doolin (D) and Murroughtoohy (M) are indicated. Although not apparent on the map the coastal locality north of Doolin also exposes the Aillwee Member of the Burren Formation. The pink dot is the location of Rannagh core (GSI-15-001) referred to in Figure 17. The green dots are the locations of Poll na gCéim (west) and Poll Gonzo (east).

Major lithological heterogeneities include the laterally persistent shale or claystone layers within the Aillwee Member of the Burren Formation (Figures 16 and 17), which define the terraced nature of the exposed sequence. The most abundantly visible structural heterogeneities in The Burren (at outcrop and in caves) are intrinsically conductive joints and sealed Variscan, mainly calcite-filled, veins that are the locus for accentuated karstification. Although, the intrinsically conductive Cenozoic strike-slip faults, which have a major control on flow further east (e.g. at Lisheen mine), are not obvious at outcrop and in caves of The Burren, fresh quarry exposure east of The Burren uplands suggests associated Cenozoic fracturing has localised on clusters of Variscan veins and is therefore also likely to have done so in The Burren. This constraint is important because it implies karst inception in The Burren could have happened at much greater depths than the main impacts of stress release jointing, e.g. Cenozoic strike-slip faults have incepted cavities down to 1km in Navan, Tara mines. The Burren limestones post-date the main phase of Lower Carboniferous normal faulting and are therefore post-rift units (Walsh et al. in press). This means that relative to much of the Central Irish Midlands which comprises older syn-rift limestone sequences, including normal faults that are often inverted, the Burren sequence is structurally relatively simple (Walsh et al. in press). This scenario enhances the controlling effects of Variscan veins, Cenozoic fracturing and stress release joints on groundwater flow in The Burren compared to in limestones in the Midlands, with associated flow anisotropies controlled by karstification of the strongly N-S oriented Variscan veins in particular.

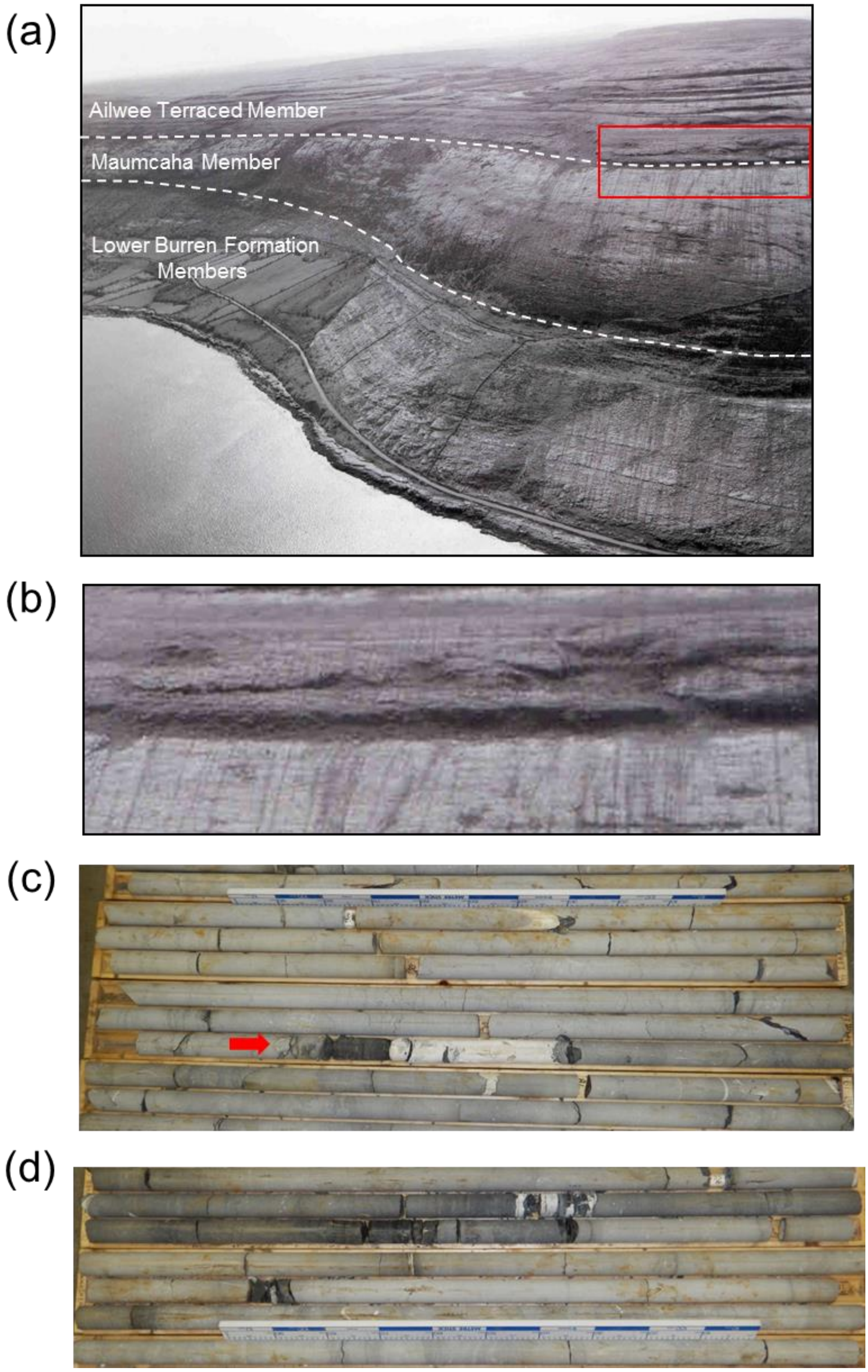


Figure 17: (a) A view southwards of the east side of Black Head, showing the exposed Burren Formation members (cf. Figure 16). Steep NNW-N-NE Variscan veins are visible in the limestones (a & b), but it is not clear how many of the veins cut the intervening shale/claystone layers. For example, in (b) (an inset of (a)) veins are visible above and below the irregular >0.5m thick shale/claystone layer, at the

boundary between the Aillwee and Maumcaha Members, but because veins also occur along the shale/claystone layers (c & d), the bed parallel veins could be linking at least some of the vertical veins visible above the shale layers, rather than the veins simply transecting the shale. This example illustrates the heterogeneous nature of Variscan veining and therefore of groundwater flow potential in The Burren. (c) A photograph of part of 207m long core (GSI-15-001 Rannagh) from the central part of The Burren (Fig.1) that extends through the Aillwee and Maumcaha Members of the Burren Formation (Fig.1), with calcite veining of 0.3m thickness above the shale layer indicated with a red arrow. Except for the top shale/claystone layer in the core all shale and claystone layers (numbering seven) have veining either above or within them. (d) Veining is evident within the unit of argillaceous limestone and claystone beds (between the red arrows) separating the Aillwee and Maumcaha Members (based on lithology interpreted by M. Pracht, 2015).

Variscan deformation in The Burren constituted broadly N-S compression under high confining pressures (with km-scale burial depths) and elevated fluid pressures (Gillespie et al. 2001). This resulted in predominantly gentle folding, with local monoclines and ubiquitous veining (Walsh et al. in press and refs. therein). The veining mainly occurs as steep NNW-N-NE veins (Figure 18), but often as bridging veins that link up steep veins and bed parallel veins, such as those formed by flexural slip during folding e.g. along shale or claystone layers (Figures 17 and 18).

Veining is characterised by hydraulic fracturing and brecciation, processes attributed to the valving of overpressured pore fluids within underlying basinal sequences. Variscan veins are clustered at different scales, providing zones with high frequencies of veins that are more likely to be connected laterally and vertically, via vein bridges and bedding plane parallel veins. Since larger vein clusters comprise wider and longer clusters of veins with thicker and longer veins, they have a strong localising effect on groundwater flow.

The persistence and connectivity of veining promotes the localisation of conductive fracturing and karst, and the flow connectivity of associated groundwater flow systems. This factor is demonstrated by the common occurrence in caves of vertical and horizontal passages localised along veins and wayboards respectively (e.g. Poll Gonzo; Drew, 2018; Walsh et al. in press). At the Murrooghtoohy field location, we will look at the attributes and impacts of a larger vein cluster. The impact of larger vein clusters on groundwater flow ranges from the localisation of subsurface cave systems through to the localisation of valleys and collapses on a range of scales. It is the localisation of caves and valleys on vein clusters as well as the localisation of karst along lithological interfaces that are some of the most important constraints provided by looking at the geological controls on flow evident in The Burren. The next two sections summarise some of the features examined on the Saturday morning and early afternoon field stops, illustrating how geological observations can provide important constraints on groundwater flow response.

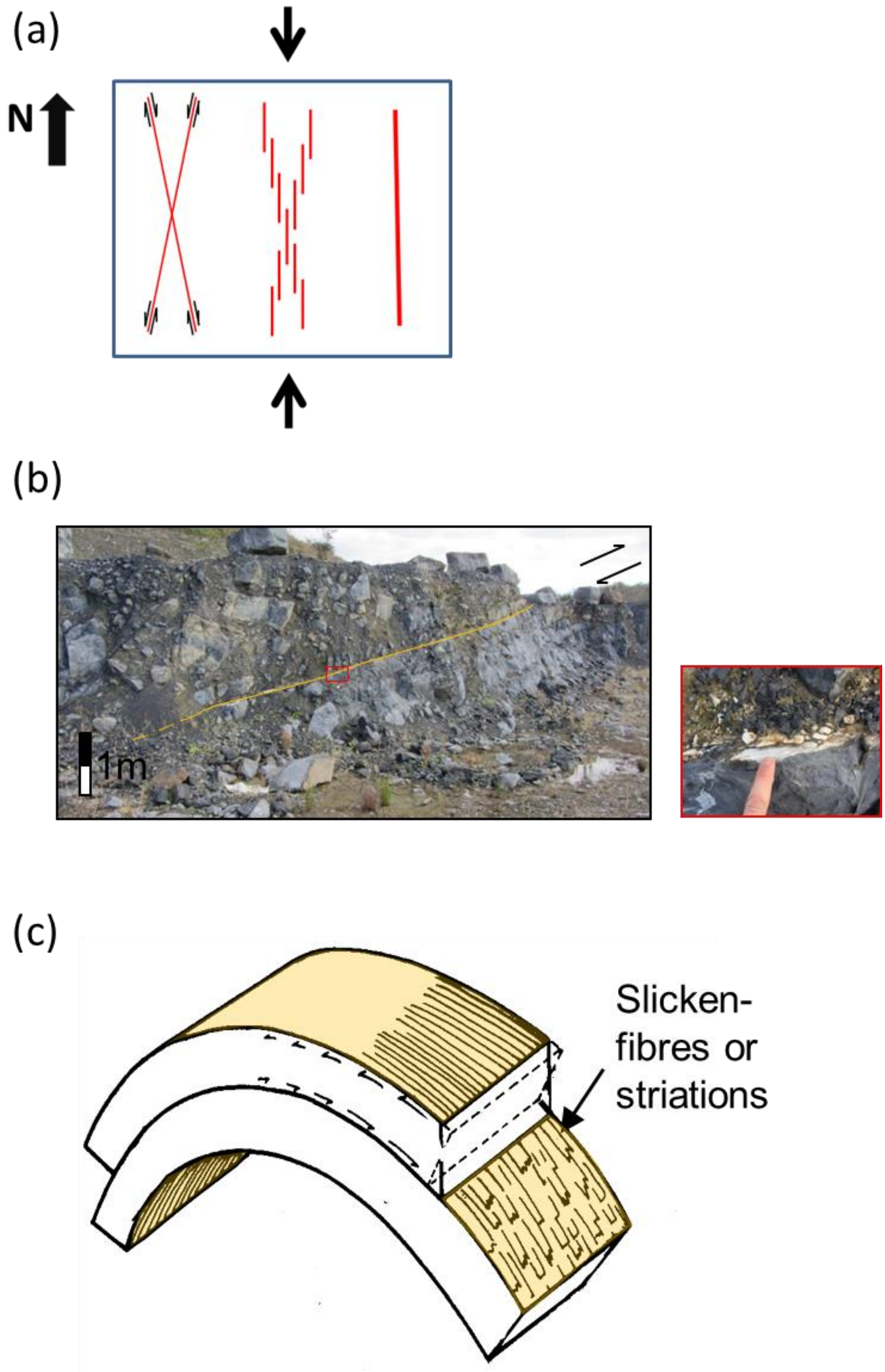


Figure 18: A schematic of the dominant steep vein trends in The Burren (Moore and Walsh, 2013). (b) A veined flexural slip surface (with sense of slip in black arrows) and, inset, a close-up of the slicken-sides on the vein which also shows the vein has localised later conductive fracturing and is infilled by later sand due to groundwater flow (Moymore Quarry, Clare). (c) A schematic showing how flexural slip and associated veining occurs where there is folding of thicker stronger layers, with intervening lower cohesion material that localises slip e.g. along limestone-shale interfaces.

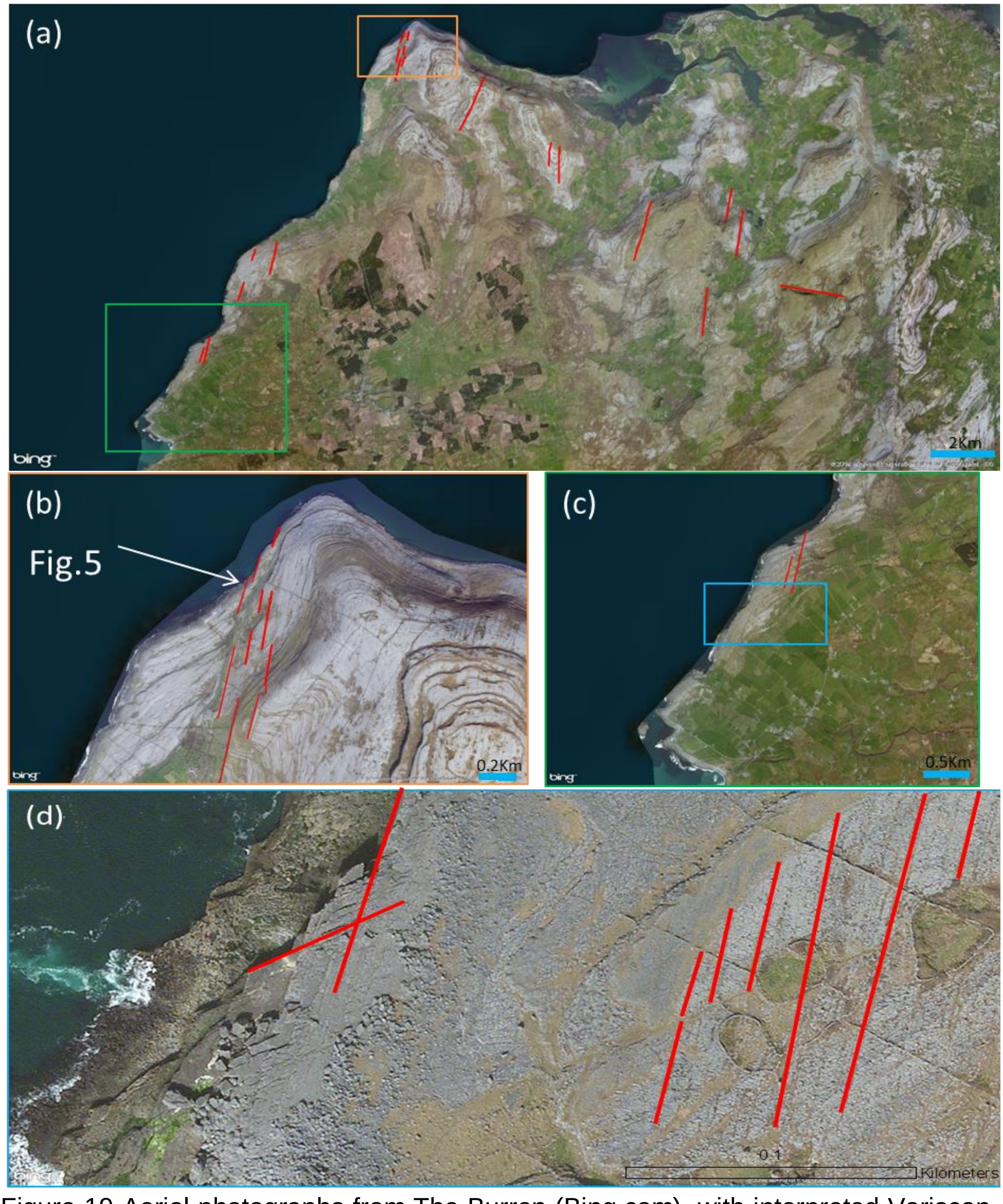


Figure 19 Aerial photographs from The Burren (Bing.com), with interpreted Variscan veins and vein clusters (red) based on persistent topographical features, formed by karstification and collapse along individual Variscan veins or vein clusters, some of which were ground-truthed. The outline of (b, orange) and (c, green) are shown on (a). Some of the veins of the cluster arrowed in (b) are shown in Figure 20. (b) A close up of the NW western corner of The Burren (Murrooghtoohy). (c) The coastal outcrop north and west of Doolin. (d) A close up of the same coastal outcrop, showing NNE and NE Variscan veins which are parallel and sub-parallel to parts of the cliff. The NE and NNE vein trends form the sides of blocks that are being weathered and eroded from the cliff, illustrating the importance of the veins in localising later conductive fracturing and/or dissolution.

On the coast, north of Doolin

At the coast, exposures of the Slievenaglasha and the Burren Formation (down to the Aillwee Member) provide a 3D view of the stratigraphic sequence and the vein/fracture network, and their impact on groundwater flow and topography (Figures 16 and 19d). Karstification and conductive fracturing along shale/claystone layers of the Aillwee Member has formed the upper and lower surfaces of blocks of limestone being eroded into the sea, while dissolution and conductive fracturing along NNE and 060 striking Variscan veins formed the sides of the blocks (Figure 19d). The impact of shale/claystone layers on vertical persistence of steep NNW-N-NNE Variscan veins is also evident at this locality. The locality illustrates how the localisation of karst and conductive fracturing along shale/claystone layers (both veined or un-veined) provides important pathways for flow and connects up the karst along ubiquitous steep veins.

Murrooghtoohy

At Murrooghtoohy we track a cluster of veins which can be seen on aerial photography to extend over 1Km along strike (Figure 19a, b), but is likely to extend further given the width of the cluster. In addition, features indicate both the lateral and vertical persistence of the vein cluster: (i) MacDermot, (2016) mapped silica veins within this vein cluster and these are visible on inland outcrop and on the coast. Isotopic evidence suggests that some of the more exotic veins, including sulphide and silica, were sourced from greater depths in the sequence, maybe down to the depths of Lower Carboniferous normal faults or lower to basement (Walsh *et al.* in press); (ii) a concentration of calcite at least 6m high and 10-15m long (in the first locality at Murrooghtoohy) is indicative of greater dilations within the cluster than away from it; (iii) along strike to the NNE, on the coast, a rapid thickness change from a >1m thick vein to a number of veins with thicknesses of cm scale, some of which are bridging veins, is attributed to sinistral shearing during vein formation, a feature indicative of greater deformation than the straighter veins in The Burren; (iv) the vein cluster is along strike and 6Km north of Poll na gCéim cave (Figure 16), the deepest cave in The Burren and one which penetrates the shale/claystone layer between the Slievenaglasha and Aillwee Member, a layer considered an aquiclude because it is rare for caves to go below it in The Burren (Judd & Mullan, 1994). Only one other cave is known to have penetrated this layer - Poll Gonzo cave (Boycott et al. 2011; Fig.16)). All this evidence supports the notion that the vein cluster mapped from aerial photography at Murroughtoohy (Figure 19a, b) is a large vein cluster in three dimensions, with substantial vertical and lateral persistence.

The significance of a larger vein cluster for today's groundwater flow is evident through impact of the veins on topography. Valleys occur along veins and vein clusters due to the localisation of conductive fracturing and karst along the veins. Larger vein clusters result in greater groundwater flow connectivity, greater rates of weathering and wider and longer valleys. Our work in the central Midlands indicates the presence of very similar vein systems, and we suggest that associated NNW-N-NE valleys in the more poorly exposed limestones of the Midlands may also be localised along associated veins and vein clusters.

Figure 20: Photo viewing NNE along a >1m thick Variscan vein (just left of the yellow notebook) and thinner veins (left foreground and in the background are NE and NNE cliff faces), features consistent with dissolution and collapse localised along the NNE and NE veins.

References

Boycott A., Bunce C., Cowper Q. and Cronin P., 2011. Cave notes Co. Clare and Co. Galway. Proceedings of the University of Bristol Spelaeological Society, 25(2), 233-248.

Gallagher, S.J., MacDermot, C.V., Somerville, I.D., Pracht, M. and Sleeman, A.G., 2006 Biostratigraphy, microfacies and depositional environments of upper Viséan limestones from the Burren region, County Clare, Ireland. Geological Journal 41, 61-91.

Gillespie, P.A., Walsh, J.J, Watterson, J., Bonson, C.G. and Manzocchi, T., 2001. Scaling relationships of joint and vein arrays from The Burren, Co. Clare, Ireland. Journal of Structural Geology 23, 183-201.

Judd, B. and Mullan, G., 1994. Poll na gCéim Co. Clare, Ireland. Proceedings of the University of Bristol Speleological Society, 20(1), 3-13.

Moore, J.P and Walsh, J.J., 2013. Analysis of fracture systems and their impact on flow pathways in Irish bedrock aquifers. Geological Survey of Ireland (GSI), Groundwater Newsletter, 51. ISSN 0790-7753. Accessed at: https://www.gsi.ie/documents/GWNewsletterNo51.pdf

Mullan, G.J., 2003 The caves of County Clare and South Galway. Bristol. University of Bristol Speleological Society, 259pp.

MacDermot, C.V., McConnell, B. and Pracht, M., 2003 Bedrock Geology 1:100,000 Scale Map Series, Sheet 14, Galway Bay. Geological Survey of Ireland.

MacDermot, C.V., 2016. The 6” field sheets (i.e. 1:10560), showing the occurrence of siliceous and other mineralised veins in The Burren, are available GSI online digital archive (GOLDMINE): secure.dcenr.gov.ie/goldmine/index.html. Accessed June 2016.

Pracht, M., 2015. Unpublished lithological log of Rannagh core (GSI-15-001).

Walsh, J.J., Moore, J.P., Bunce, C., Hollis, S.P., Kelly, J. and Menuge, J.F., in press. ‘The origin and nature of hydraulic fractures and veins within The Burren, County Clare, Ireland’. Irish Journal of Earth Sciences.

4. Holy Wells in north County Clare.
Bruce Misstear

Poll Insheen

By way of an introduction, the writer of this field note is currently carrying out a study of Irish holy wells with the aims of investigating their hydrogeological settings and water chemistries (Misstear *et al*., 2018). There are – or perhaps it is better to say there were – at least 3,000 holy wells in Ireland (Logan, 1980; Ray, 2014). These include more than 200 holy wells in Co Clare (Houlihan, 2015), one of which we will visit during this field trip.

Poll Insheen is located in Gleninsheen townland at Grid Reference M 22993 02947 (OSI Discovery Map 51). This is an example of a well formed within a solution-enhanced hollow (kamenitza) in epikarst (a second Burren example is St Fachtna's well in Termon, at M 30042 00472). The karstified limestone bedrock at Poll Insheen belongs to the Aillwe member (Upper) of the Burren Formation (part of the Dinantian pure bedded limestone unit; Figure 21). Poll Insheen has a reputation for curing toothache (Rackard and O'Callaghan, 2001; Doolan, 2002): toothbrushes can sometimes be seen at the well (Figure 22).

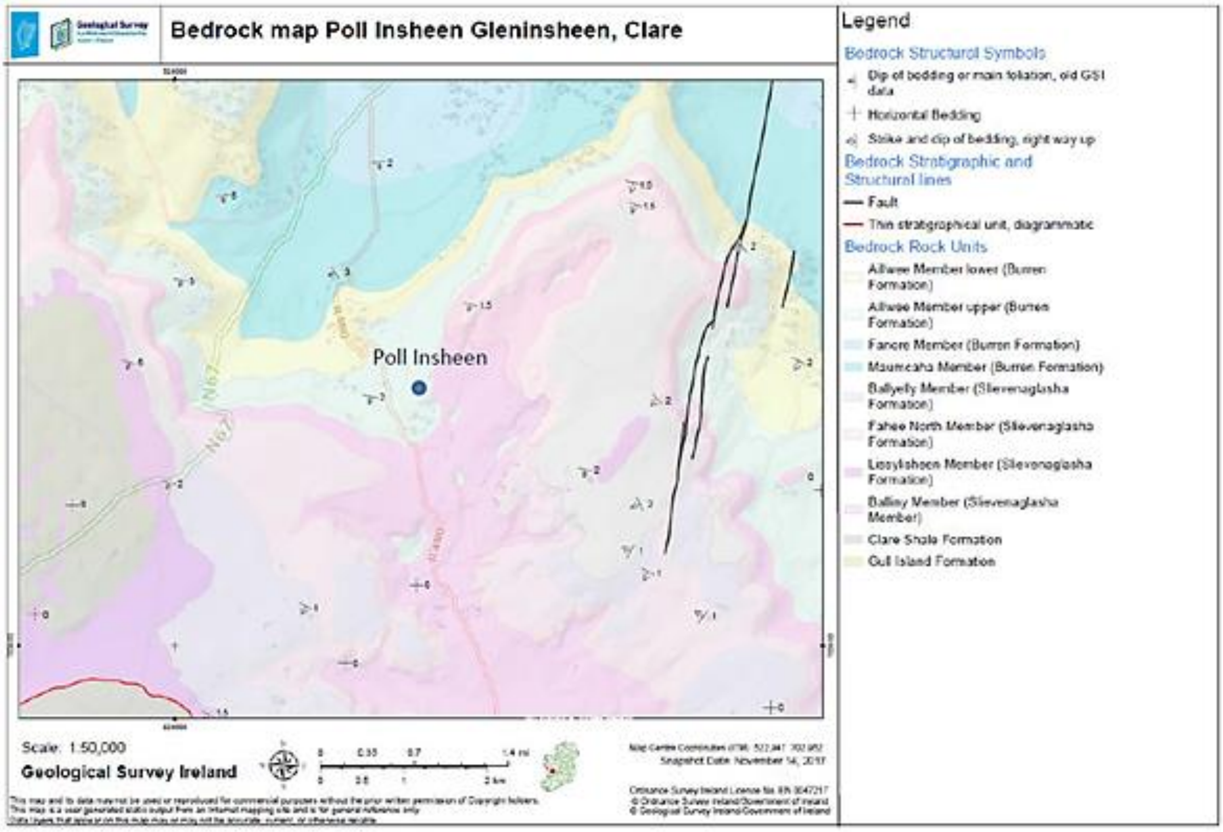
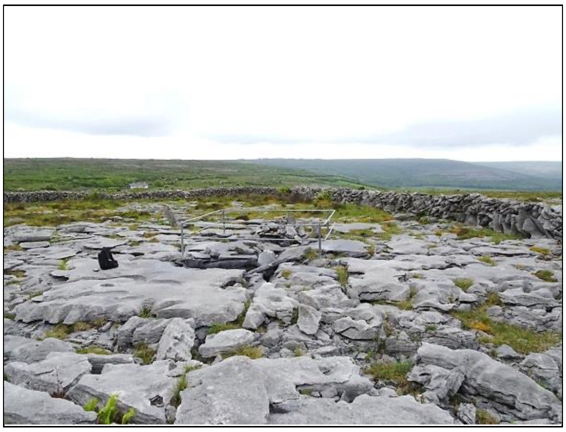


Figure 21: Bedrock geology map for the area around Poll Insheen (Map prepared using GSI Groundwater Data Viewer).

The small circular hollow in the limestone pavement (*poll* = hole), which forms the well, is covered by a stone cairn between 0.5 and 0.6 m high. The well is 0.25 m in diameter and typically contains about 0.1 m of water. The well area is surrounded by a simple two-bar metal fence. Nearby, but outside the fence, there is another circular water-filled kamenitza similar to Poll Insheen, but without a cairn over it. This well is 0.2 m in diameter and contains about 0.2 m of water.



Metal fencing around Poll Insheen

The stone cairn above the well, including a lintel with many coins

The circular rock hollow that forms Poll Insheen

Toothbrushes at the well, an indication of its reputation for curing toothache (23/4/19)

Figure 22: Poll Insheen Gleninsheen (photos by Bruce Misstear).

Poll Insheen appears to be in a relatively isolated block of limestone, and the source of its water is not obvious. (We will discuss this during the field visit).

The well was sampled by the author in May 2017. The EC was 237 µS cm^{-1}, with a Ca-HCO_3 water chemistry. Elevated values of trace metals including zinc, copper and nickel may relate to the large number of coins at the well.

There is short video of the well on YouTube: https://www.youtube.com/watch?v=gXbBOdeidRc.

Lisdoonvarna spa wells

In addition to carrying out hydrogeological surveys of more than 200 holy wells, the writer has also visited and sampled a number of spa wells, including those in Lisdoonvarna. Lisdoonvarna developed as a spa town in the middle of the 19th century and reached its peak popularity in the period from the 1880s to the 1920s (Foley, 2010). The pump room was built in 1867 and baths were added in 1875; the current bath house was built in the 1930s and 1940s. There is now a visitor centre containing an exhibition about the history of the spa and of the town more generally
The main spa centre is on the south side of the town, at the confluence of the Gowlaun and Aille rivers (Figure 23). There were originally six spa wells in Lisdoonvarna, of which the Sulphur well at the main spa centre is the only one in use (Figure 24). The well, which is inside the Pump room, is approximately 0.6 m in diameter and lined with brick. It is covered with a glass see-through top, and the interior of the well is lit. The well is reportedly about 3 m deep, with silt at its base. There is a tap from the well in the Pump room.

Figure 23: OSI Digital Globe image showing locations of the extant spa wells in Lisdoonvarna.

Of the other five wells, there was a copper-rich (copperas) well behind Tivoli terrace, on the west side of the main street, but this is apparently covered/lost.

The so-called Double wells are located on the left bank of the Killoon river, just upstream of where it crosses below the R67 off the main street (Figure 23). The old pump house here is now used as a library (Figure 24). The two wells are 30 m apart and are inside stone-arched well buildings with iron gates (locked). Both wells have wooden covers. The well houses are partly overgrown. There are two outside taps in alcoves on the exterior wall of the library (i.e. the old pump house); these are presumably fed by the two wells. The Double wells are known as the magnesia and chalybeate (i.e. iron) wells; iron staining was visible around the well closest to the library, so this may be the chalybeate well.

The spa centre, with the pump room to the right, the bath house behind and the Gowlaun River in the foreground.

The Sulphur well inside the pump room

The old pump house near the Double wells, which is now a library (note the two external taps in the alcoves on the tower like entrance to the building).

The Double well closest to the pump house: iron staining is visible on the ground near the well, so this may be the chalybeate well.

The 'Twin wells': the sulphur 'well' to the left (note the white precipitate) and the iron 'well' to the right (with the ochre deposit).

Outcrop of highly weathered shales alongside the path leading to the Twin wells.

Figure 24: Lisdoonvarna spa wells. Photos by Bruce Misstear.

The Twin wells (known for sulphur and iron) are located about half a km downstream of the main town, near the confluence of the Killoon Stream with the Aille River (the wells are about 5 m from the right bank of the Aille River), at the west end of Town park (Figure 23). The Twin wells are, in fact, two small seepages from rock outcrop (Figure 24), about 0.6 m apart, one of which (with the larger 'flow') collects in a small circular 'well', 0.2 to 0.3 m in diameter, which is covered by a white precipitate (probably calcium sulphate). The seepage to its right (really just an intermittent dripping) has given rise to an ochre deposit, after which the water trickles towards the first 'well'. The rock face with the seepages is covered by a concrete shelter and by a wooden railing. Both the sulphur-rich and the iron-rich seepages seem to originate from below the same hard bed (which occurs within a mainly shale sequence – this bed looks like a sandstone and may be part of the hard, compact Phosphate Shale referred to in the geology description below).

The main Sulphur well and the Twin wells (sulphur and iron) were considered effective against gout, rheumatism, consumption and liver problems (Foley, 2010). The magnesia and iron-rich Double wells were used 'as blood tonics and for weak stomachs', whilst the copperas well was used for treating diseases.

The geology and hydrogeology of the Lisdoonvarna Spa wells has been described by Drew (2001). The town lies on the Namurian Clare Shale Formation, comprising shale, sandstone and siltstone beds with a total thickness of about 20 m. The Clare Shales have been cut into by the rivers that run through the town (the Gowlaun, Aille and Killoon Rivers), and beds of the underlying Visean Burren Limestone Formation are exposed along the river beds. According to Drew's account, the bedrock geological sequence in Lisdoonvarna, from youngest to oldest, consists of: a) ribbed beds of sandy black shales; b) Goniatite Shale (8-14 m of black shale); c) Phosphate Shale (0-3 m of hard dark grey black shale with calcite and dolomite); d) Cahermacon Shale (0-3.5 m of black shale with phosphate and pyrites – where this latter unit is absent, the Phosphate Shale lies directly on the Burren Limestone. Outcrops of soft, highly weathered shale outcrops can be observed along the access path down to the Twin wells (Figure 24).

The springs and seeps that give rise to the various spa waters issue from near the base of the Clare Shales, especially at the hard Phosphate Shale bed (Drew, 2001). Drew reported that the outflows from each of the wells are modest: 400 l $hour^{-1}$ (Sulphur well); 80 l $hour^{-1}$ (chalybeate well of the Double wells); 40 l $hour^{-1}$ (magnesia well). The flows from the Twin wells, as mentioned above, and observed by this author, only amount to a very small trickle. The Clare Shales are classed as a Pu aquifer.

Regarding the water chemistry, Drew (2001) noted that the none of the springs is highly mineralised, but rather show elevated concentrations of particular parameters such as iron (4.5 and 3.0 mg l^{-1} in the chalybeate and magnesia wells, respectively), sulphate (150 mg l^{-1} in the chalybeate well) and total hardness (344 and 300 mg l^{-1} [as $CaCO_3$?] in the chalybeate and magnesia wells, respectively). The Sulphur well has low TDS, as indicated by the EC measurement of 527 µS cm^{-1} made by the present author, which is typical of Irish groundwaters and does not indicate a high degree of mineralisation. A sample collected from the Sulphur well in August 2018 showed a Ca-Mg-Na-HCO_3 chemistry; the SO_4 concentration was 32 mg l^{-1}, which is not particularly elevated compared to many other (non-spa) wells. The sulphur well of the Twin wells was also sampled, and found to be slightly more mineralised, with an EC of 718 µS cm^{-1}, but with lower SO_4 (14 mg l^{-1}). In terms of minor ions and trace elements, both the Sulphur well and the Twin wells showed elevated levels of strontium, barium and caesium, whilst the Sulphur well also had elevated lithium. Iron concentrations for the two wells were 106 and 198 µg l^{-1}, respectively. It was not possible to sample the chalybeate and magnesia wells (i.e. the Double wells).

A certificate available at the Spa centre (given to visitors to confirm that he/she has drunk a glass of the sulphur water) reports that Charles Lucas was the first person to sample the Sulphur well (or at least the original spring) in the early 18th century, and his example was followed with later analyses by Sylvester O'Halloran in 1751 and John Rutty in 1757. All these analyses apparently showed high concentrations of iron and sulphur.

A curious feature about the Sulphur well water is that the tap and water are hot at the beginning of each day. The water was certainly hot for the first few seconds after the electric pump was switched on during this author's visit in August 2018, and then cooled rapidly to a normal groundwater temperature. Is this due to some exothermic biogeochemical reaction leading to a build-up of heat overnight? Or is it related to the type of pump and pumping arrangement (the details of which were not available)?

References

Doolin, L, 2002, Lores and Cures and Blessed Wells. In: O'Connell J, Feehan J & Korff A (eds) 'Book of the Burren'.

Drew, D., 2001. Lisdoonvarna Springs and Spa Wells, County Clare, Ireland. In: LaMoreaux PE and Tanner JT (eds) 'Springs and Bottled Waters of the World: Ancient History, Source, Occurrence, Quality and Use', Springer-Verlag, Berlin Heidelberg, pp 152-153.

.

Foley, R., 2010. Healing waters: Therapeutic landscapes in historic and contemporary Ireland. Ashgate, Farnham, UK, pp213.

Houlihan, M., 2015. The holy wells of County Clare. Walsh Colour Print, Castleisland, Ireland.

Logan, P., 1980. The Holy Wells of Ireland. Colin Smythe Ltd, Gerrards Cross, UK.

Misstear, B.D.R., Gill, L.W., McKenna, C. and Foley, R., 2018. Hydrology and Communities: A Hydrogeological Study of Irish Holy Wells. In Proc. Irish National Hydrology Conference, Mullingar, 20 November 2018, 39-47. http://hydrologyireland.ie/2018-irish-national-hydrology-conference-papers/

Rackard, A. and O'Callaghan, L., 2001. Fish, Stone, Water: Holy Wells of Ireland. ATRIUM, Cork

Ray, C., 2014. The Origins of Ireland's Holy Wells. Archaeopress Archaeology.

5. A pipe network model for the catchment of Bell Harbour.

Philip Schuler, Lea Duran, Paul Johnston and Laurence Gill

Background and study area

Trinity College have been developing pipe network models for karst aquifers using the urban drainage software InfoWorks CS for over 15 years, initially focussing on the Gort Lowlands (Gill, et al., 2013), and then other catchments in Ireland, including Bell Harbour (McCormack, et al., 2017; Schuler, et al., 2018; Morrissey, et al., in press), Ballindine and Manorhamilton (Schuler, et al., 2019b). This approach has also started to be used by other teams in other European karst systems, namely in Germany/Austria (Chen and Goldscheider, 2014), Slovenia (Kaufmann, et al., 2016) and Switzerland (Vuilleumier, et al., 2019).

Trinity College has been conducting research in the groundwater catchment of Bell Harbour since 2014 (one post-doc and PhD project) with the means of a high resolution hydroclimatic monitoring network of 12 stations sampling data in ≤ 1 h interval. The aim of the research has been to develop a conceptual understanding of this complex coastal aquifer system, and then translate this numerically into a pipe network model which can be used to gain further insights into the system.

The groundwater catchment of Bell Harbour (Figure 25) forms the north-eastern part of the limestone Burren Plateau. The entire catchment is underlain by Lower Carboniferous well-bedded and pure limestones ranging between the Tubber formation (early Viséan), the Lower Burren and Upper Burren formation (mid-Viséan, Asbian), and the Slievenaglasha formation (late Viséan, Birgantian). The first catchment boundaries of a “Bell Harbour catchment” were delineated by Drew (1990) which were then applied in succeeding studies (Perriquet, et al., 2014; McCormack, et al., 2017). However, uncertainty with regards to a southern boundary persisted which, as indicated by Bunce and Drew (2017), may extend further towards the south. This assumption was confirmed by successfully tracing the underground river in Poll Gonzo (PG, Figure) to Galway Bay (Schuler, et al., in print); the southern boundary was therefore moved south of PG to cover an area of 56 km^2. In addition, it is believed that the polje Carron adds some contribution towards flow to the north (Schuler, et al., 2019a), at least seasonally, adding an area of 6 km^2 to the south.

Groundwater flow within the delineated catchment is towards the north. The general flow dynamics characterise a relatively long ‘high flow period’ during autumn to spring, and a relatively short ‘low flow period’ in summer (Figure 16). Within the catchment, no perennial surface water features exist. Intermittent flooding occurs in upland Carron (Carron North, CAN and Carron South, CAS) as well as in the low lying turloughs T1 and T2 (Figure 25). Groundwater flow was confirmed up to a depth of 176 m below sea level at the open borehole BH1 (Figure) using single borehole dilution tests (Schuler, et al., 2018).

Groundwater discharge occurs via submarine and intertidal springs in Bell Harbour Bay, as well as via submarine springs in Galway Bay. The shallow discharge into Bell Harbour Bay has been estimated using a tidal prism approach based on continuous observation of EC within the outlet of Bell Harbour Bay (BHB, Figure). During low flow periods, the turloughs are empty and ‘deep’ groundwater flow dominates discharging SGD into the Atlantic Ocean (Figure 16a). In turn, during flood conditions, the piezometric level rises, activating the shallow karst network and discharge into Bell Harbour Bay (Figure 16b).

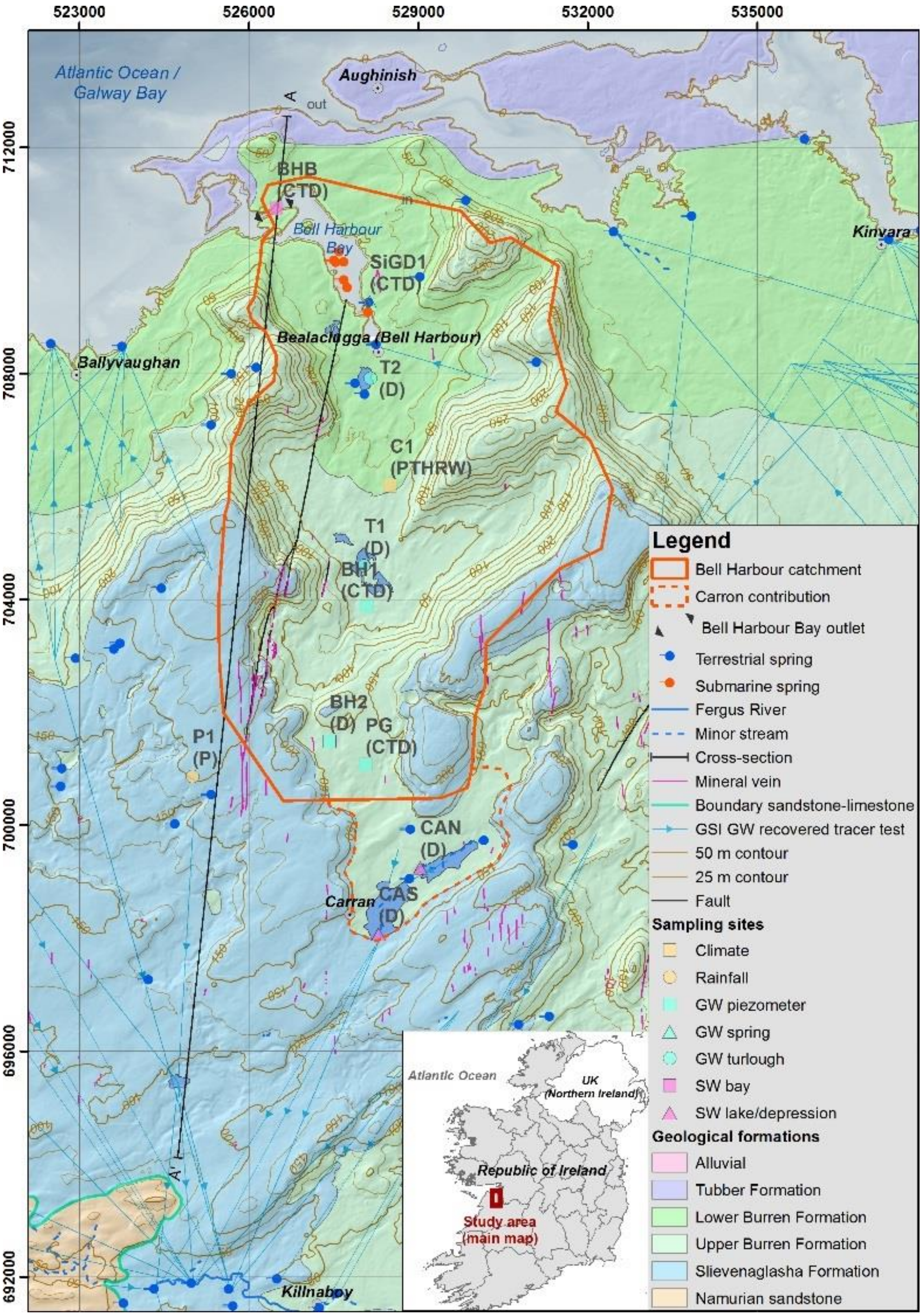


Figure 25: Geology and sampling locations in the groundwater catchment of Bell Harbour.

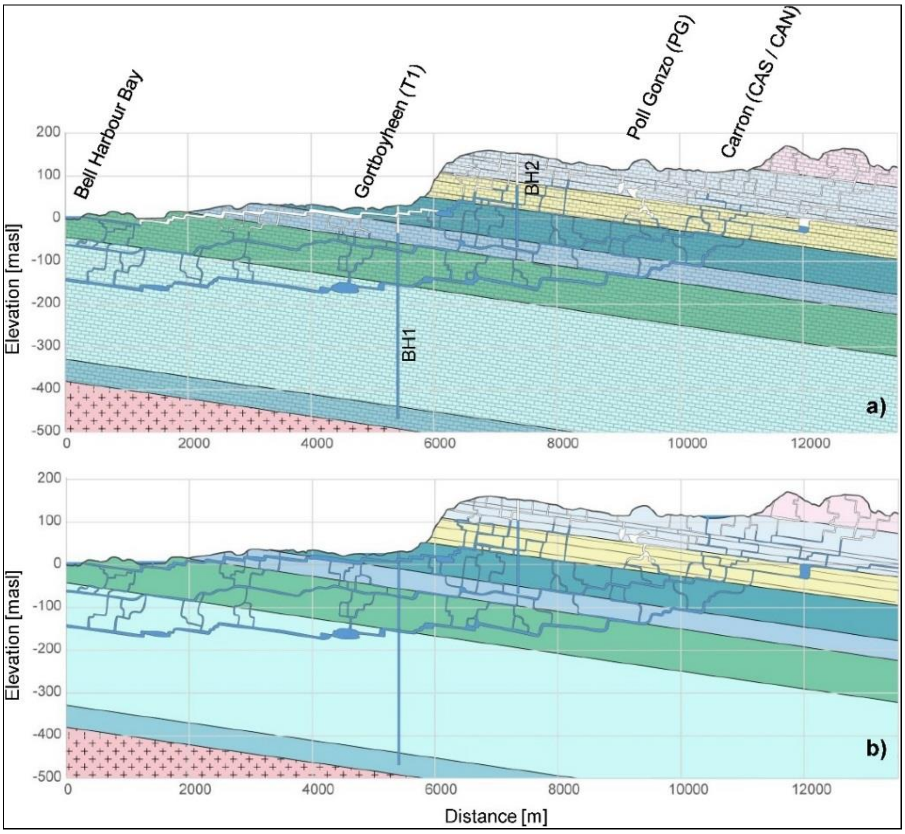


Figure 16: Conceptual model of the karst aquifer of Bell Harbour (left – N; right – S), described by a multi-level conduit dominated system: a) during summer, a low piezometric state of the aquifer causes less SiGD than in b) autumn to spring, when a higher piezometric state causes turloughs to be flooded and increased / activates SiGD into Bell Harbour Bay.

Pipe network model

The pipe network modelling approach adopted consists of a distributed network of pipes that solve the flow equations following Darcy's law for laminar flow (Figure 27, blue) and the Saint Venant equations for open channel and pressurized pipe flow (Figure 27, green). The pipe network is fed by inflow from sub-catchments that generate different more damped flow contributions on the basis of a series of different reservoirs that simulate the rainfall-runoff process, soil storage and more diffuse flow through the aquifer (Figure 27, red).

In plan view, the entire catchment was sub-divided into nine sub-catchments according to landcover (soil or bare outcrop) and elevation (lowland or upland): four high elevated sub-catchments with bare outcrop; three low lying sub-catchments with a soil cover; one sub-catchment for Bell Harbour Bay and one sub-catchment for Carron (Figure 28). The lowland sub-catchments are modelled as draining into permeable pipes (Darcy flow) accounting for a diffuse flow component. In turn, the upland sub-catchments are modelled to drain into an empty pipe (open channel flow and pressurised pipe flow), representing direct recharge and fast-flow.

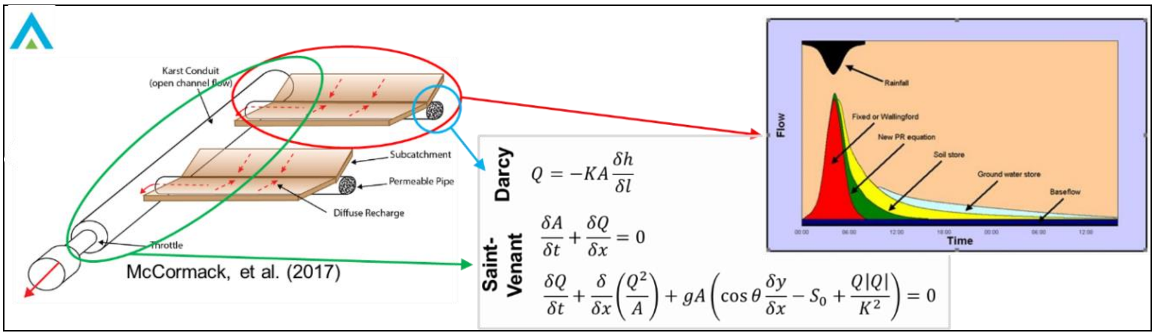


Figure 27: Concept of pipe network models.

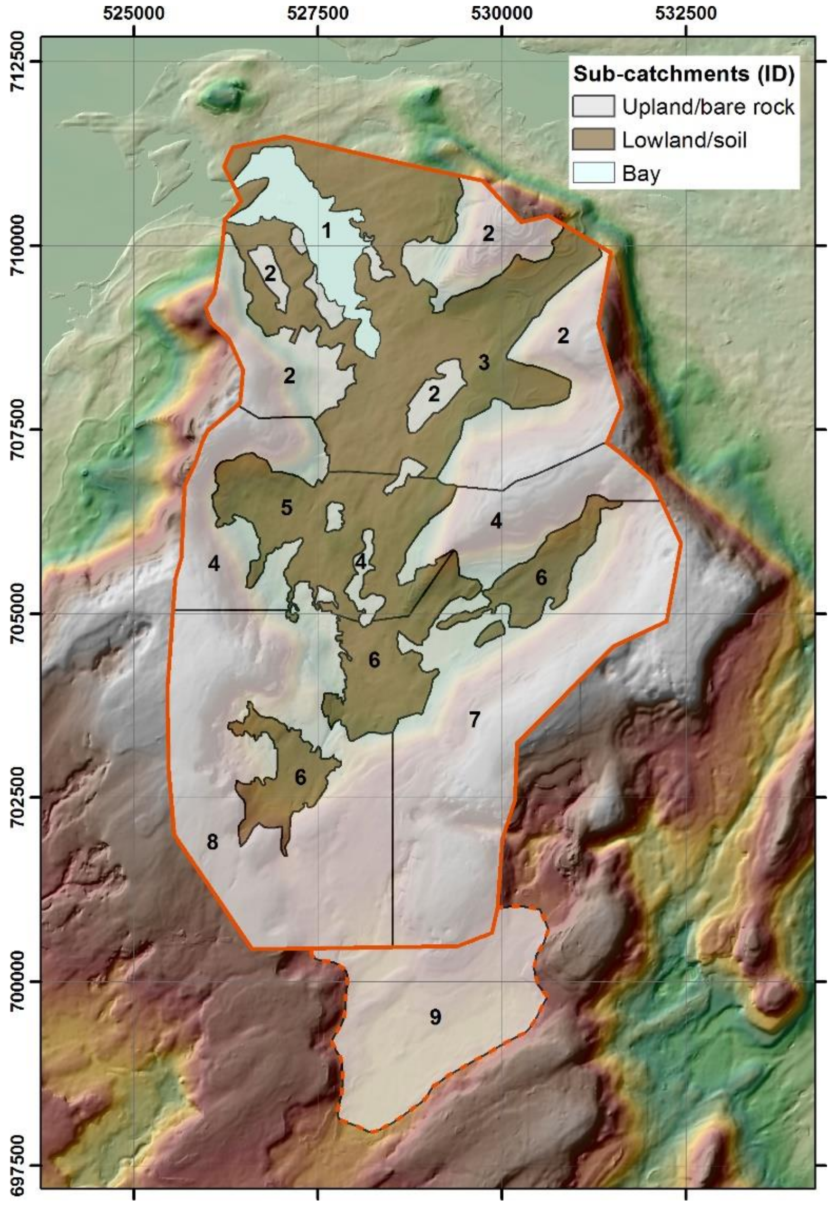


Figure 28: Bell Harbour sub-catchments as modelled in InfoWorks ICM.

The previously identified characteristic of shallow and deep groundwater flow was represented by two levels of conduits shown in the conceptual model in Figure 29.

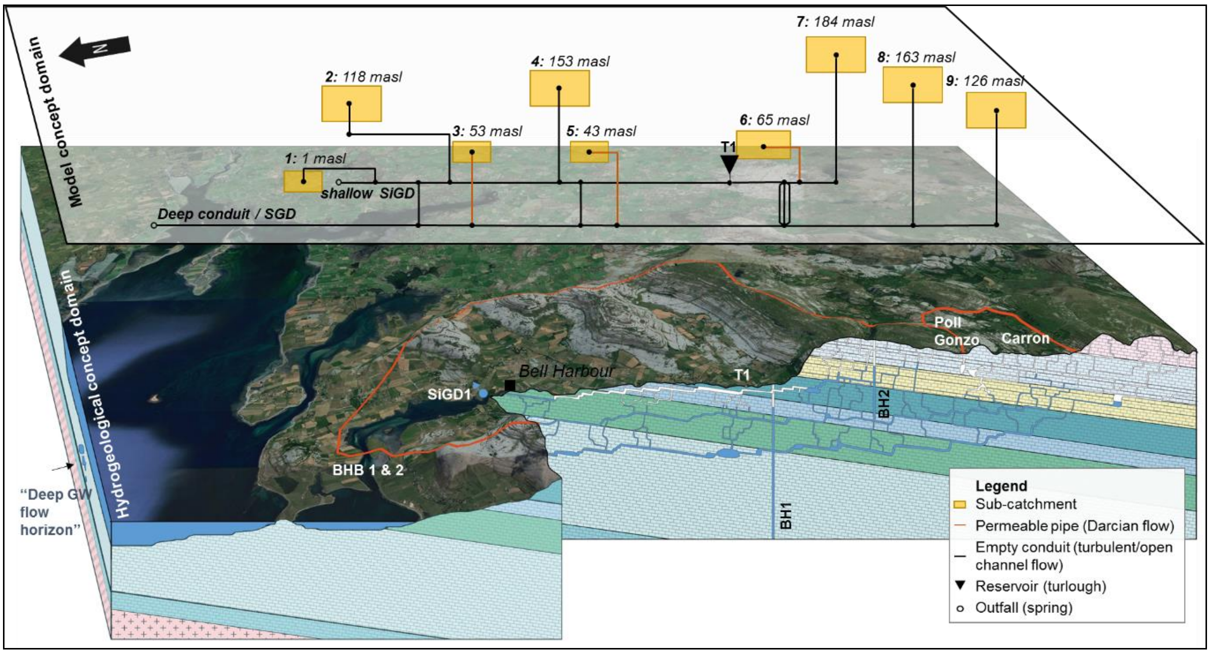


Figure 29: 3D conceptual model of the hydrogeology of the Bell Harbour catchment. Yellow boxes represent conceptually sub-catchments with sub-catchment number and mean elevations.

The shallow conduit system ranges between 10 and 0 m above sea level and discharges periodically as overflow SiGD into Bell Harbour Bay compared to the deep conduit system at ~ 65 m below sea level (~95 m below ground level) that discharges as SGD into Galway Bay, bypassing Bell Harbour Bay. Both conduit levels are connected via vertical pipes to allow upwards and downwards flow.

The upper most sub-catchment of the model domain is resembled by the sub-catchment of Carron (CAS) which is integrated as a 'pond node'. The drainage of Carron enters the conduit network: the major share flows towards the north and Bell Harbour Bay/Galway Bay while a minor share flows towards an outfall representing discharge into the Fergus River in the south. The percentage split, determined during the calibration procedure by the overall water balance, was 36.9% (towards the Fergus River) to 63.1% (towards Bell Harbour). Similarly to CAS, also the turlough T1 was represented as a 'pond node'.

Modelling results

The modelled head is plotted together with the observed head along with rainfall for the calibration and validation period (Figure 30). Periods of missing observations are illustrated by using horizontal double arrows. All flood events are matched by the model. During calibration, the model performance reaches a Nash-Sutcliffe efficiency (NSE) of 0.946, which deceases slightly to 0.883 during validation.

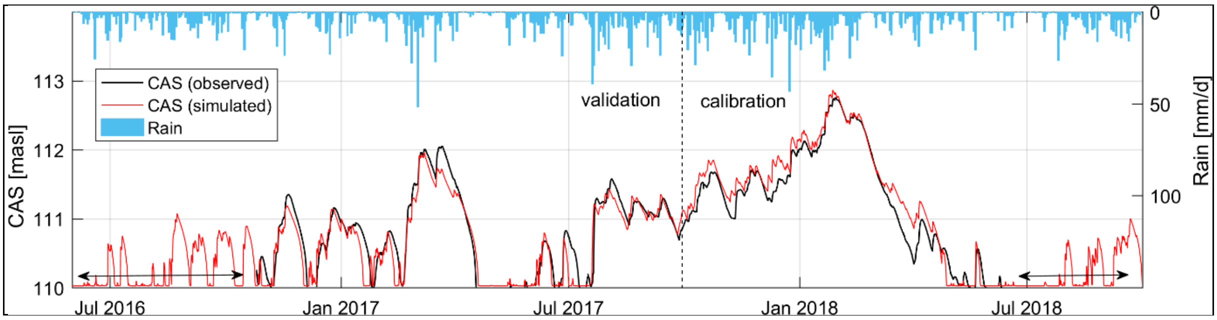


Figure 30: Observed vs. modelled head in Carron South (CAS) along with rainfall during the validation period 01 Jun 2016 to 30 Sep 2017 and the calibration period 01 Oct 2017 to 01 Oct 2018.

The simulated head in the upper level of the pipe network upstream of the pond node T1 was also compared to the observed head in the borehole BH1 (Figure 3131).

Overall, the model matches the pattern of high-flow and low-flow periods with single surges in head very well matched by the model, and the simulated recessions generally following the observed time series. However, the simulated absolute levels deviate from the observed hydrograph.

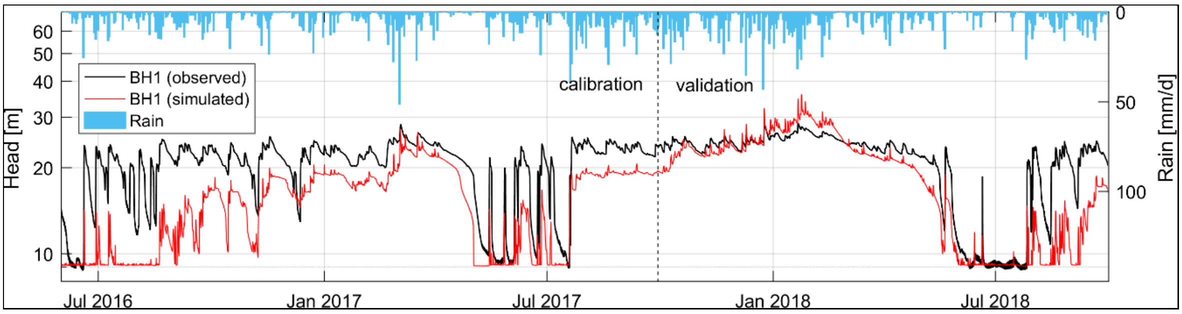


Figure 31: Observed head in BH1 and simulated head upstream of the pond node T1 ('BH1 simulated') during calibration and validation.

Figure 32a shows the observed (estimated) and simulated SiGD during the calibration and validation period, along with daily rainfall. Figure 32b shows the cumulative discharges. The total discharge is the 'overflow' of the upper outfall representing SiGD into Bell Harbour Bay.

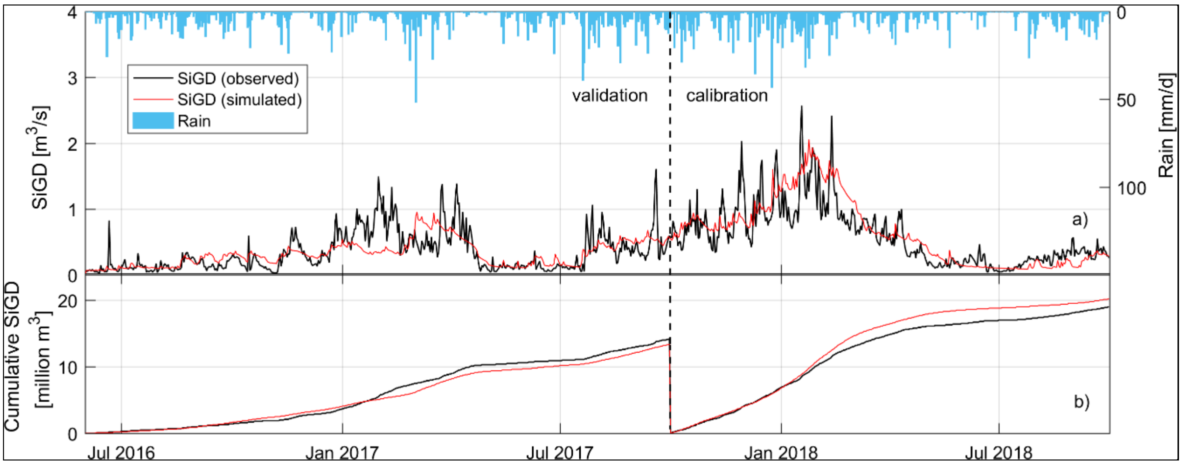


Figure 32: Simulated and observed (estimated) SiGD draining Bell Harbour Bay during calibration and validation: a) averaged daily discharge (m^3/s), and b) cumulative discharge (million m^3).

During calibration (01 Oct 2017 to 30 Sep 2018), the model matches the pattern of the estimated SiGD relatively well - the estimated SiGD was 19.0 million m^3 compared to a simulated SiGD of 20.2 million m^3. The simulated SiGD matches the pattern of the estimated SiGD relatively well.

During validation (1 Jun 2016 to 30 Sep 2017) the estimated SiGD was 14.2 million m^3, while the simulated SiGD is 13.4 million m^3 and there are two periods of clear mismatch: first, between 10 Jan and 24 Feb 2017, when the simulated SiGD is too low; and secondly, between 24 Feb and 24 Mar 2017, when the simulated discharge is too high. The deviation of modelling results in these periods remains unclear. However, it should be noted that the tidal prism method of estimating SiGD is susceptible to errors according to the assumptions made, for example, the calculation time step of each ‘tidal cycle’ of ~12 h which acts to smooth out any discharge peaks occurring in between.

The performance of the simulated discharge during the validation period is low, yielding a NSE of 0.36, compared to the calibration period which achieved an NSE of 0.65.

References

Bunce, C. and Drew, D., 2017. Water tracing in the Carron depression and River Fergus valley, Burren, Co Clare. Irish Groundwater Newsletter: 13-18.

Chen, Z. and Goldscheider, N., 2014. Modeling spatially and temporally varied hydraulic behavior of a folded karst system with dominant conduit drainage at catchment scale, Hochifen–Gottesacker, Alps. Journal of Hydrology 514: 41-52 DOI http://dx.doi.org/10.1016/j.jhydrol.2014.04.005

Drew, D., 1990. The Hydrology of the Burren, County Clare. Irish Geography 23: 69-89.

Gill, L.W., Naughton, O. and Johnston, P.M., 2013. Modeling a network of turloughs in lowland karst. Water Resources Research 49: 3487-3503 DOI 10.1002/wrcr.20299.

Kaufmann, .G., Gabrovsek, F. and Turk, .J., 2016. Modelling flow of subterranean Pivka river in Postojnska jama, Slovenia. Acta Carsologica 45 DOI 10.3986/ac.v45i1.3059.

McCormack, T., O'Connell, Y., Daly, E., Gill, L.W., Henry, T. and Perriquet, M., 2017. Characterisation of karst hydrogeology in Western Ireland using geophysical and hydraulic modelling techniques. Journal of Hydrology: Regional Studies 10: 1-17.

Morrissey, P.J., McCormack,T., Naughton, O., Johnston, P.M. and Gill, L.W. (in press). Modelling Groundwater Flooding in a Lowland Karst Catchment. Journal of Hydrology.

Perriquet, M., Leonardi, V., Henry, T. and Jourde, H., 2014. Saltwater wedge variation in a non-anthropogenic coastal karst aquifer influenced by a strong tidal range (Burren, Ireland). Journal of Hydrology 519: 2350-2365 DOI http://dx.doi.org/10.1016/j.jhydrol.2014.10.006

Schuler, P. Duran, L., Johnston, P.M. and Gill, L., 2019a. Quantifying submarine and intertidal groundwater discharge and linearity of the coastal karst aquifer Bell Harbour. Irish Groundwater Newsletter: 22-26.

Schuler, P., Duran, L., Johnston, P.M. and Gill, L.W., 2019b. A multi-method approach to quantify and simulate groundwater flow components in karst aquifers using pipe-network models. Paper presented at the 46th IAH Congress, Malaga, Spain, 22.09.2019 - 27.09.2019 2019b.

Schuler, P., Duran, L., McCormack, T. and Gill, L., 2018. Submarine and intertidal groundwater discharge through a complex multi-level karst conduit aquifer. Hydrogeology Journal 28: 2629-2647 DOI 10.1007/s10040-018-1821-3.

Schuler, P., Stoeckl, L., Schnegg, P-A., Bunce, C. and Gill L (in print). A combined method approach to trace submarine groundwater discharge from a coastal karst aquifer. Hydrogeology Journal.

Vuilleumier, C., Jeannin, P-Y. and Perrochet, P., 2019. Physics-based fine-scale numerical model of a karst system (Milandre Cave, Switzerland). Hydrogeology Journal DOI 10.1007/s10040-019-02006-y

6. The impact of on-site wastewater effluent on karst springs.
Luka Vucinic

Introduction

In Ireland, more than one third of the population (approximately 500,000 dwellings) use domestic wastewater treatments systems (DWWTSs), of which more than 87%

are septic tanks, while on a global scale at least 2.8 billion people are relying on septic tanks, latrines and other improved on-site wastewater treatment systems.

Karst aquifer systems are exceptionally vulnerable to pollution from such potential contamination sources as a result of predominantly rapid recharge of water from the surface and strong aquifer heterogeneity in karstic regions. These karst network characteristics and multiple different pollution sources make it complex to trace the origins of pollution using conventional methods whereby targeted pollutants in groundwater can be linked to their specific sources and quantified at the same time. This is particularly important in karst aquifer systems where numerical modelling of the fate and transport of pollutants from prevailing contamination origins is extremely challenging and yet increasingly necessary for the implementation of appropriate management strategies at a catchment scale.

The main aims and objectives of Luka's PhD work are related to the assessment of analytical (microbiological and chemical fingerprinting methods and techniques) and monitoring tools for investigating DWWTSs impacts on karst aquifer systems and the assessment of the actual DWWTSs impacts on these aquifers and linked risks to human health by establishing links between subsurface wastewater effluent contaminants movement and contaminant transport to karst springs.

A range of microbiological and chemical fingerprinting methodologies and techniques have been used, trialed and evaluated across the west of Ireland at 9 different karst springs (in Co. Clare, Co. Galway and Co. Mayo) on a monthly basis throughout the hydrological year or longer. Additionally, event-based sampling/analysis/monitoring at selected springs at catchments with contrasting groundwater vulnerabilities, karst systems and with different densities of DWWTSs has been conducted and is still in progress.

The results from this PhD project so far show that detection and quantification of source specific chemicals such as fluorescent whitening compounds (FWCs), fluorescence-based investigations of organic matter using the excitation-emission matrices (EEMs) and PARAFAC analysis, specific anion ratio signatures, faecal sterol and stanol profiles and ratios, and several microbial fingerprinting methodologies in parallel can provide sufficient information for decision making processes and adaptive management strategies. Notably, whilst some of the techniques tested are not capable of being able to link pollutants directly with any particular pollution source, they can still quantify specific pollutants, in some cases to a very high accuracy, thereby determining the overall impacts of contaminants on groundwater quality at karst springs. Furthermore, it has been found that techniques for advanced investigation of microbial populations may be very advantageous for numerical modelling of the fate and transport of contaminants of DWWTSs effluent origin through karst aquifer systems.

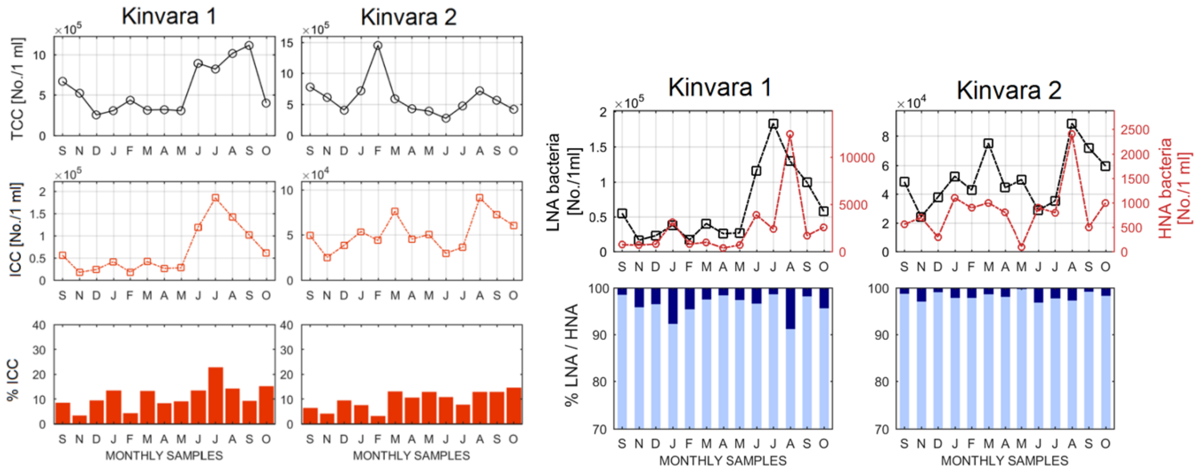


Figure 33: Flow cytometric microbiological fingerprinting of groundwater samples taken at two Kinvara springs. TCC – Total Cell Count, ICC – Intact Cell Count, LNA – Intact Bacteria with Low Nucleic Acid content, HNA – Intact Bacteria with High Nucleic Acid content

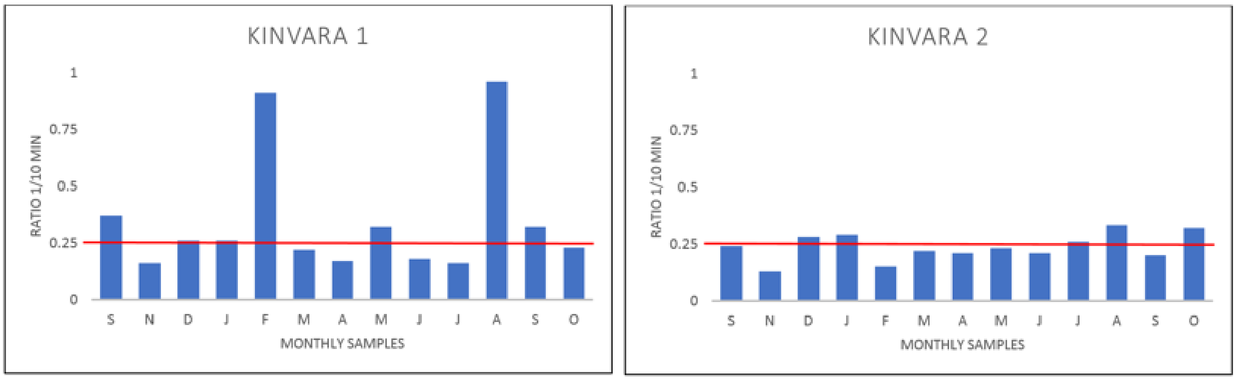


Figure 34: Analysis of fluorescent whitening compounds (FWCs) signal at two Kinvara springs. Values ≥ 0.25 indicate the detection of FWCs in groundwater samples.

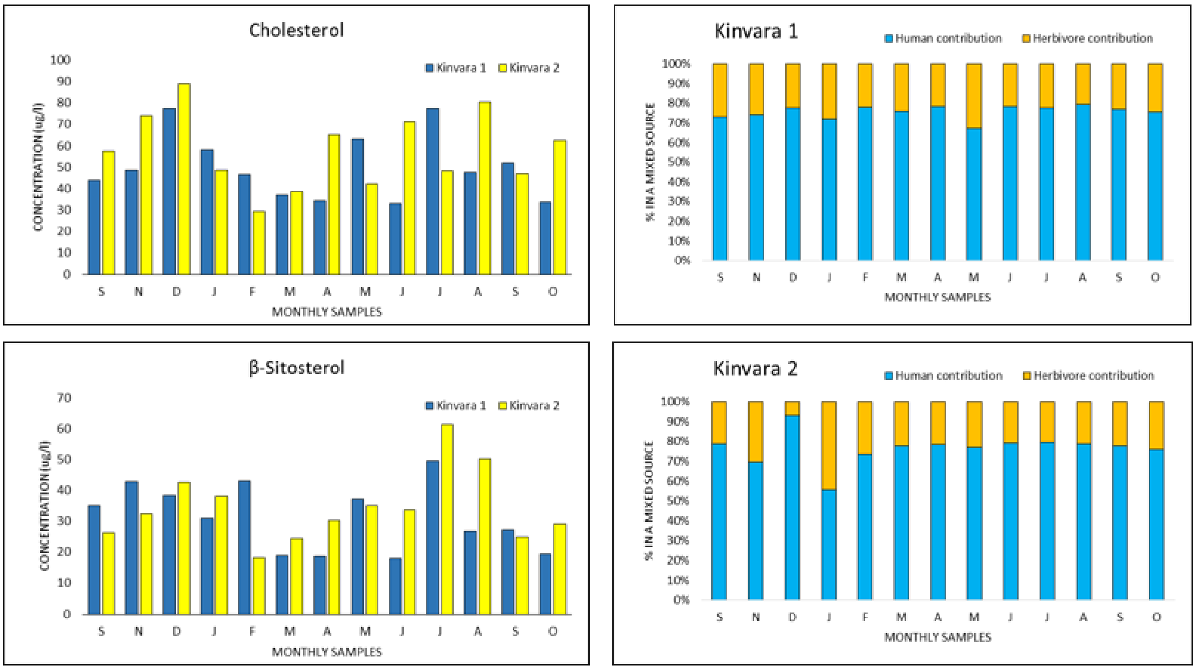


Figure 35: Analysis of domestic wastewater indicators and human vs. agricultural impact on groundwater quality at Kinvara springs; cholesterol and β-sitosterol (some of a few known domestic wastewater indicators). Also shows sterol and stanol ratios for quantification of human and herbivore contribution in a mixed source.

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7. Groundwater Flooding in the Gort Lowland Karst .

Patrick Morrissey

What is Groundwater Flooding?

Groundwater flooding events in Ireland predominantly occurs within the lowland karstified limestone areas of the west of the country (Coxon, 1987b, Goodwillie and Reynolds, 2003) in low-lying basins and valleys. The flooding is inherently linked to the underlying bedrock geology where extensive interactions between ground and surface waters predominate, with sinking and rising rivers/streams common with surface water features absent completely in many areas (Drew, 2008). The dominant drainage path for many catchments is through the karstified limestone bedrock; however, the limited storage within such secondary porosity dominated rocks, means that the fractures or conduits within the limestone are unable to convey the recharge fast enough during intense or prolonged rainfall, the result being surcharging of groundwater above the surface. This flood water is usually contained within low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Coxon, 1987a, Coxon, 1987b). In Ireland, the most susceptible region to groundwater flooding is the Gort Lowlands in South Galway which is a lowland karst catchment covering an area of approximately 500 km^2 – see Figure 36 (Naughton *et al.*, 2018).

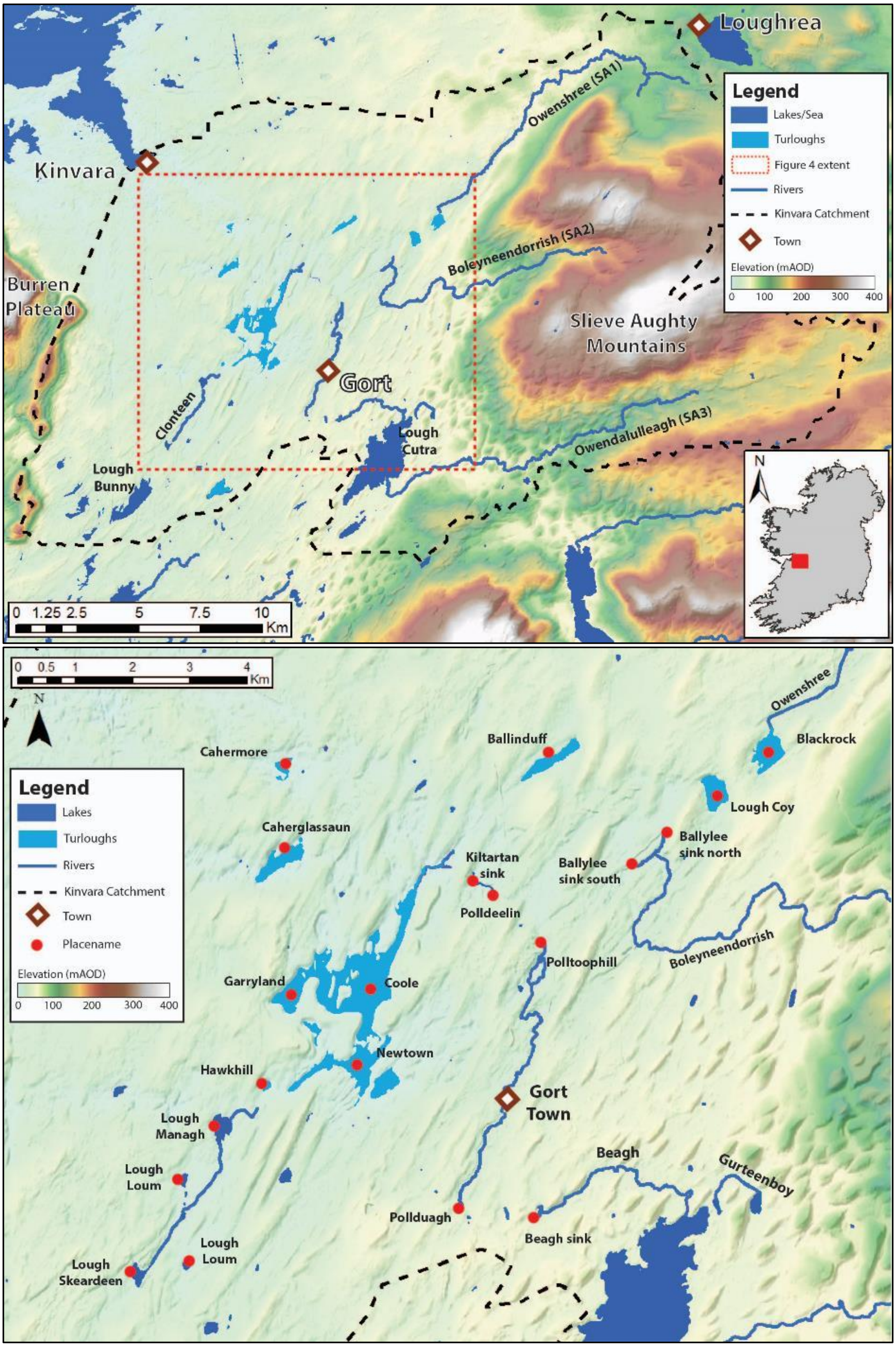

Figure 36: Location map of the catchment (top) and plan showing main surface water and turlough features in the catchment (bottom) (Naughton et al., 2018).

Three rivers flow off the Slieve Aughty Mountains onto the Gort lowland karst and upon contact with the limestone disappear into the bedrock where flow occurs within caves / conduits – see Figure 36. A fourth river also flows onto the karst from the southwest, however represents much more modest discharges given the smaller catchment area it drains. The rivers reappear for short intervals at a number of locations in the catchment before discharging to the sea through a submarine groundwater discharge (springs located at the intertidal zone of the bay) at Kinvara Bay (Gill et al., 2013b). Groundwater surcharges to the surface through estavelles and springs following periods of sustained heavy rainfall when sufficient capacity is not available in the bedrock to store and convey water to the sea. This surface water discharge forms numerous turloughs across the region.

The dramatic nature of the flooding associated with these turloughs has led to considerable groundwater flooding events in recent years beyond their established upper seasonal boundaries following exceptional rainfall events, causing considerable damage and disruption. An extreme groundwater flooding event took place in the Gort lowlands catchment during the winter of 2015/2016; this represented the most extensive groundwater flooding ever recorded. A number of homes and farmyards were flooded with extensive damage caused by floodwaters. The nature of groundwater flooding gives rise to lands being inundated for extended periods of time in the order of many months; during the 2015/2016 flood, many homes and farms were cut off for extended periods of time due to roads becoming impassable – see Figure 37 below. Large areas of farmland were flooded impacting on agricultural activity and causing livestock welfare concerns.

Figure 37: Groundwater flooding in the vicinity of the Coole Complex during January 2016 (Image courtesy OPW).

During extreme events (such as 2015/2016) these turloughs exceed their established maximum bounds and overflow their natural basins in dramatic fashion often joining together to form enormous swathes of inundated lands covering many square kilometres. An example of such an extreme overflow is shown in Figure 38 below where Coole Turlough can be seen spilling into Caherglassaun Lough through agricultural lands at Crannagh.

Figure 28: Coole Turlough overflowing into Caherglassaun Turlough at Crannagh (January 2016 – Image Courtesy OPW)

A semi-distributive model representing the complex karst system of the Gort Lowlands was recently developed by Morrissey et al. (2019) based upon previous work by Gill et al. (2013a). The model consists of a complicated pipe network built within the Infoworks Integrated Catchment Management (ICM) software package with pipes representing conduits/fractures in the karst bedrock. A total of 15 storage nodes were connected to the pipe network representing surface flooding in the catchment at turloughs and floodplains. The stage-volume relationship of these turloughs/floodplains was determined using high accuracy LiDAR and survey data and provided the input for each storage node in the model. The full model domain represents 159.2 km^2 of the lowland karst within the South Galway catchment. Meteorological data (rainfall and potential evaporation) was obtained from climatological stations or rain gauges located within the catchment. Autogenic recharge to the karst bedrock was determined by the software using a Ground Infiltration Module calibrated using field observed data (Morrissey et al., 2019). The boundary conditions at the catchment outfall were represented by the tide level at Kinvara Bay and data were obtained for same from the Irish Marine Institute from a buoy located at Galway Port. The model receives inflow from the four rivers described above. The model was calibrated using observed stage (flood level) data at all 15 storage nodes between 2016 – 2018 and further validated using historical stage data at five turloughs for the period 2007 – 2018 (Gill et al., 2013a, Mccormack et al., 2014). The model successfully simulated the observed flood level (stage) at each of the fifteen storage nodes during the calibration and validation periods with Nash Sutcliffe model efficiencies (NSE) ranging between 0.87 – 0.98 and Kling Gupta (KGE) model efficiencies ranging between 0.87 – 0.97 generally achieved – see Figure 39 for sample calibration plot and Figure 40 for a longer term sample validation plot

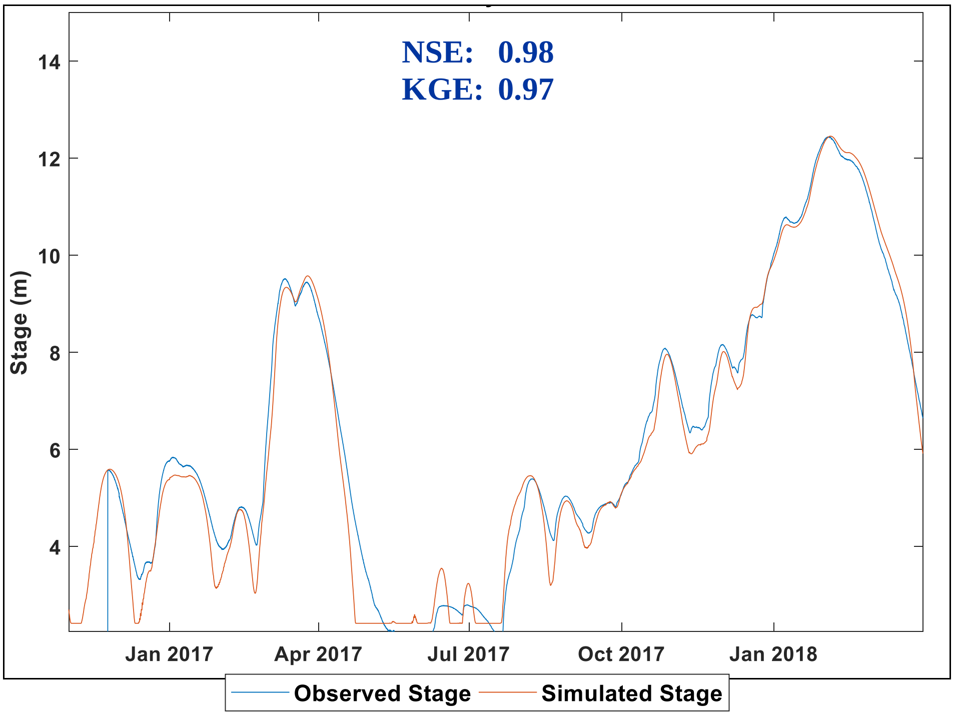

Figure 39: Model calibration plot for Garryland Turlough in the period November 2016 to February 2018.

The calibrated model was used to carry out numerous novel and interesting analysis with respect to groundwater flooding including:

- Flood level frequency analysis – establishing return periods for peak groundwater flood levels at all locations within the catchment;
- Flood duration frequency analysis – establishing return periods for groundwater flood durations which is a key aspect in assessing the hardship and disruption caused by such flooding (which can then feed into cost-benefit assessments of potential flood alleviation schemes);
- Land use assessments within the catchment – determining the potential relationship between changing land uses within the catchment and the associated impacts in terms of groundwater flood risk.

The calibrated model is also currently being used to inform the Gort Lowlands Flood Alleviation Scheme being progressed by Galway County Council and the OPW and their consultants Ryan Hanley Engineers. As part of the TCD/GSI research project, overland flood relief channels have been simulated using the calibrated model as shown in Figure 6 below (Ol1 – OL6). The simulated data regarding the timing and quantity of discharges through such channels are being used to inform the development of a suite of flood alleviation measures throughout the catchment which is an on-going body of work.

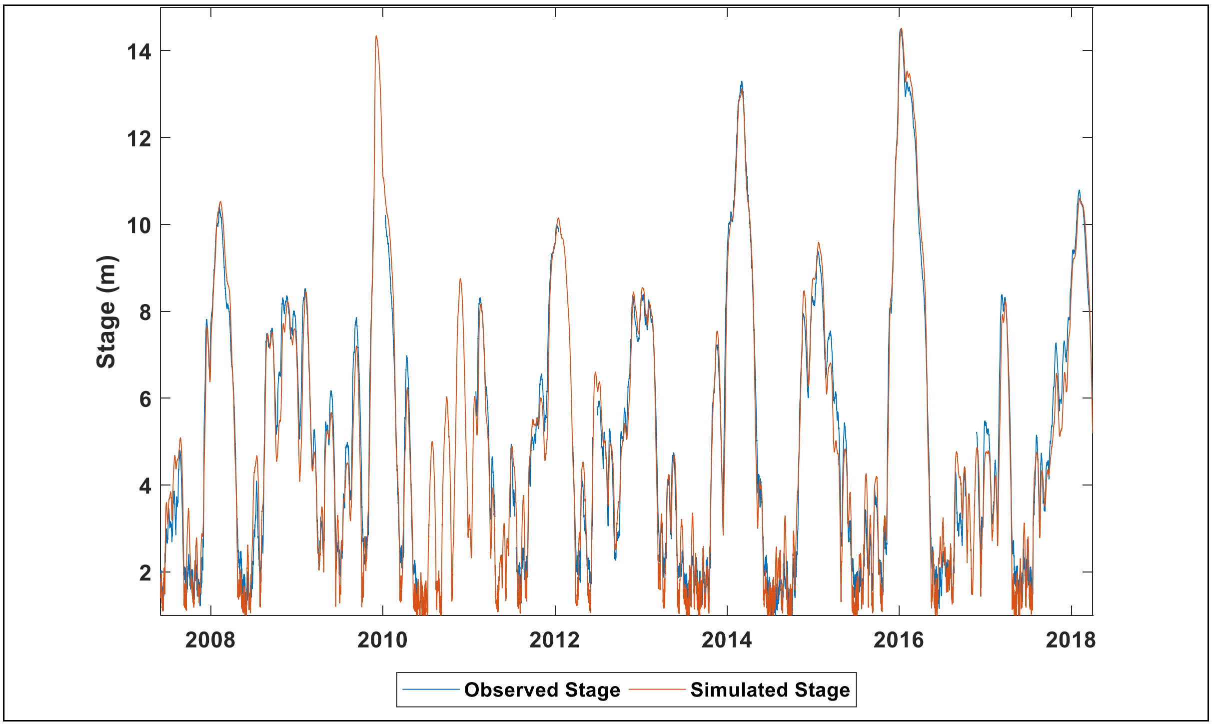

Figure 40: Model validation for Caherglassaun Lough (2007 – 2018).

In addition to informing engineering solutions to groundwater flooding, this work is also considering the potential impacts of such works relating to eco-hydrology. For example, the potential impacts on salinity within Kinvara Bay with the introduction overland flood relief channels resulting in accelerated water transfer to the bay are being considered. Similarly, the ecological impact on the protected wetland habitats within the turlough basins is being considered. Any potential reduction in inundation duration below what is considered to be a "normal" flooding range could have a negative impact on established wetland habitat zones.

References

Coxon, C. E., 1987a. An Examination of the Characteristics of Turloughs, using Muitivariate Statistical Techniques. *Irish Geography,* 20**,** 24-42.

Coxon, C. E., 1987b. The spatial distribution of turloughs. *Irish Geography,* 20**,** 11-23.

Drew, D. P., 2008. Hydrogeology of lowland karst in Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology,* 41**,** 61-72.

Gill, L. W., Naughton, O. and Johnston, P. M., 2013a. Modeling a network of turloughs in lowland karst. *Water Resources Research,* 49**,** 3487-3503.

Gill, L. W., Naughton, O., Johnston, P. M., Basu, B. and Ghosh, B. 2013b. Characterisation of hydrogeological connections in a lowland karst network using time series analysis of water levels in ephemeral groundwater-fed lakes (turloughs). *Journal of Hydrology,* 499**,** 289-302.

Goodwillie, R. and Reynolds, J., D., 2003. Turloughs. In: Otte, M.L. (Ed.), Wetlands of Ireland: Distribution, Ecology, Uses and Economic Value. pp 130–134.

McCormack, T., Gill, L. W., Naughton, O. and Johnston, P. M., 2014. Quantification of submarine/intertidal groundwater discharge and nutrient loading from a lowland karst catchment. *Journal of Hydrology,* 519**,** 2318-2330.

Morrissey, P., J., McCormack, T., Naughton, O., Johnston, P., M. and Gill, L., W. 2019. Modelling Groundwater Flooding in a Lowland Karst Catchment. *Journal of Hydrology***,** Article in press.

Naughton, O., Gill, L. W., Johnston, P. M., Morrissey, P. J., Regan, S., McCormack, T. and Drew, D. 2018. The hydrogeology of the Gort Lowlands. *Irish Journal of Earth Sciences,* 36**,** 1-2

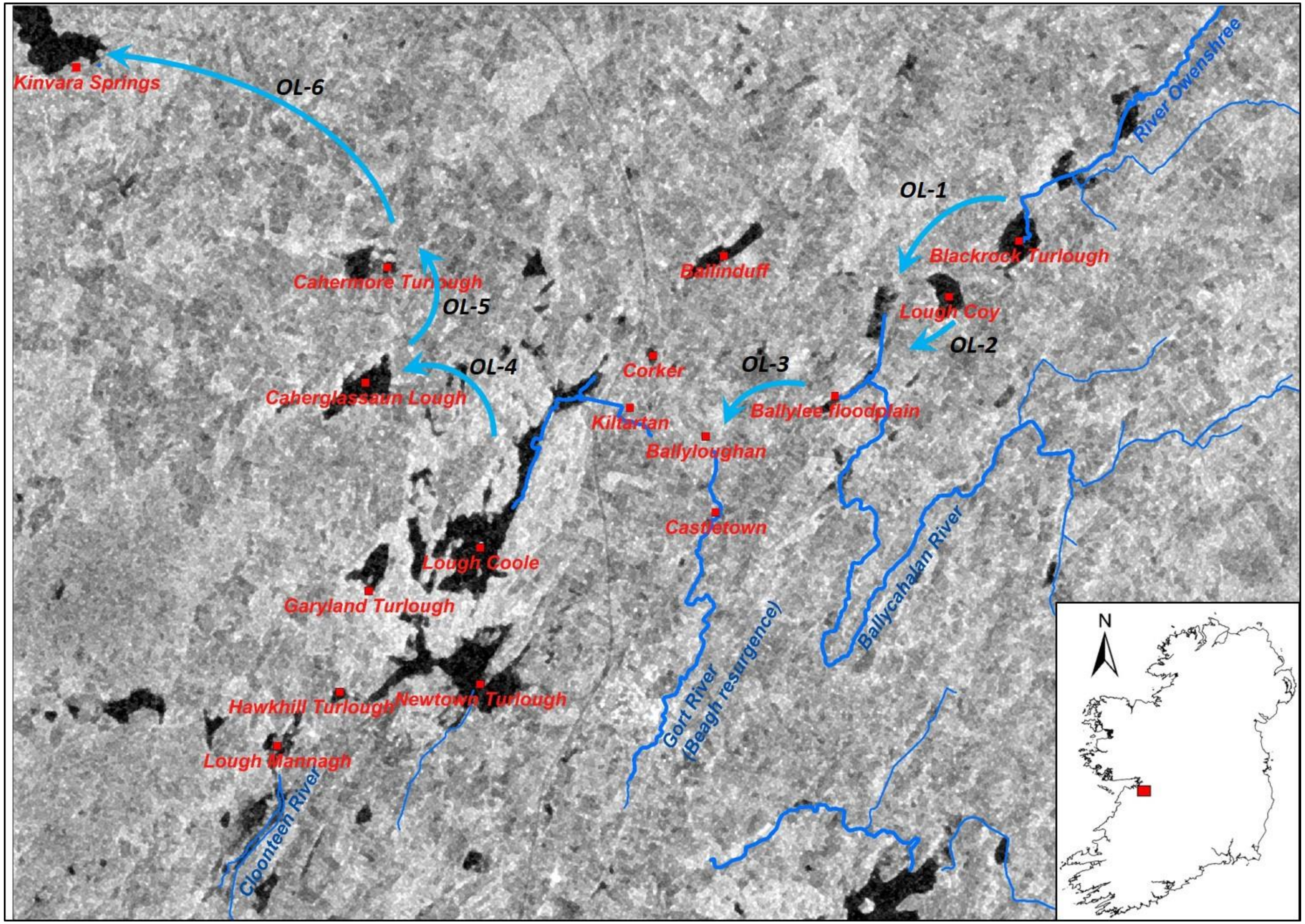

Figure 41: Sentinel Satellite Imagery (SAR) of the catchment under normal winter flood conditions flooded areas show up with darker shading based on the SAR imagery bandwidth. Turlough/floodplain nodes within the model are shown in red with proposed overland flood alleviation routes identified by blue arrows.