‘HOLISTIC’ HYDROGEOLOGY OF THE SOUTH IRISH MIDLANDS

Field Guide

International Association of Hydrogeologists (IAH) Irish Group

2017

Cover page: *Bog and Gravel, the natural resources of Offaly* – an educational signboard at the Clara Bog Boardwalk, with the green fields of the esker in the distance.

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Programme

Saturday 21st October

9.30 Clonmacnoise

Clonmacnoise, The Esker, The Pilgrim's Path, Sand and gravel aquifers in the locality
Damien Doherty and Robert Meehan

10.15 Creevagh

The Shannon and palaeohydrology, postglacial lakes, mushroom rocks, bogs, callows, marl, navigating the Shannon
John Feehan

12.45 Lunch in Gussies, Ballycumber

13.45 Clara Bog

Clara Bog, historical hydrogeological studies
Ray Flynn

Peripheral drainage, eco-hydrology, carbon balance of intact raised bogs
Paul Johnston

Restoring Active Raised Bogs, Methods, Equipment, Goals
John Cody

16.45 Molloy Demonstration Facility

Wastewater treatment for single houses, discharge to ground, practicailities
Laurence Gill

Wastewater treatment systems, 3-D demonstration facility
John Brennan

Sunday 22nd October

09.30 Cullahill Group Water Scheme

The scheme and its history, water quality
Jimmy Walsh

10.15 Toberboe Springs

The spring source, inputs, sources and pathways of nitrates, contaminant indicator parameters
Roisin Dowd Smith, Catherine Coxon, Taly Hunter Williams

11.20 Ballykealy

Group Discussion on groundwater bodies and catchment management, and more.

Location Map

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

Preface

The Irish Midlands have always been known as a sacred landscape with long-famed sites such as Clonmacnoise, Croghan Hill and Durrow underpinning this. In reading of ancient tribes and ruling families in Ireland, landscape and their territorial boundaries have always been one of the most distinctive factors in defining their developmental trajectories. Environmental determinism, which studies how the physical environment predisposes societies and states towards certain expansionary (and contractionary) paths; has been the over-riding paradigm of our development in this country. Physical geography, and geology, has therefore had a huge part to play in our societal development and cultural heritage.

This has long been known, and is common sense in reality; towns are built with defence and practicality in mind, at summits of hills and along river fording points. People build houses where shelter is afforded; roads are constructed as straight as the landscape will allow, and across stable terrain rather than through swamps. Hidden in such principles is the importance of hydrogeology. Humans have always wanted a dry bed to lay their head upon each night (often in a cave if there is karst available), and have always needed a ready and clean source of water for drinking, cooking, washing and cleaning. We as humans have always had an inherent hydrogeological sensibility.

Taking this idea further, our history and heritage bears witness to this throughout even the ancient tales of bravery in Ireland; where battles were fought and mystical beings added fear and danger to even trivial events. In reading of druids and those held in reverence though our distant (written and verbal) history, the sacredness of the natural environment rings true. In ancient Ireland, water was sacred. In ancient Ireland, stones were sacred. Immediately it can only be concluded that the druids were the first true hydrogeologists ! Wise men with grey beards are not just a modern phenomenon within our discipline.

Through the ages hydrogeology has had such an impact. Ancient wells, latrines of various types, dry roads, high castles and churches, wet land, steep slopes, black turf, iron-rich seeps, sluggera holes, shallow soils ... how often have such topics meant drawn out conversations, deliberate musings and potential for conflict ? This is still the case today. We are all focussed hydrogeologists. Sometimes we forget how wide-reaching our discipline is, and in how many ways it affects our landscape, our people, and our society. Sometimes we do not realise that everywhere, at every point in the landscape, is hydrogeological information, hydrogeological promise, and hydrogeological wonder in some sense or other.

The idea of our field trip this weekend is to try to remember some of these matters; how wide-ranging our discipline is, and how it can be applied and seen at every scale in the countryside. I, and all on the IAH Committee, hope you enjoy it.

Robbie Meehan
IAH Field Trip Secretary
18th October 2017

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 the bus driver, for getting us around safely, and to all of the IAH Committee for help and advice.

Coran Kelly is also due thanks for the usual bouncing off of ideas, and for the mine of knowledge that he is.

1. The Clonmacnoise Esker
Robert Meehan

What is an esker?

Eskers are long, sinuous ridges of glaciofluvial sands and gravels. The term "esker" is an English rendering of the Gaelic word *eiscir* which means ridge. They range from a few tens of metres to over a hundred kilometres in unbroken length, and range locally from a few metres to over 50m in height, and from ten metres to hundreds of metres in width at their base.

Eskers have been reported from all over the mid-latitudes, and are particularly common in Ireland, Britain, Scandinavia (where they are termed *osar*), Canada, Alaska, the northeastern U.S., and Patagonia. The most extensive esker formations in the world are found in Canada, in the Districts of Keewatin in Nunavut, Mackenzie in the Northwest Territories, Manitoba, northern Quebec and Labrador; some of these eskers are up to 800 kilometres long.

How are eskers formed, geologically?

Eskers are usually the infillings of ice-walled river channels. Just as rivers on land carry and deposit sediment, meltwater that flows in the openings beneath, above and within a glacier also carries and deposits sediment. Tunnels near the base of retreating glaciers fill with transported sands and gravels, which remain as sandy or gravelly ridges that look like raised, upside-down stream beds after the glacier melts away. The ice that formed the sides and roof of the tunnel has disappeared, leaving behind sand and gravel deposits in ridges with long, winding, sinuous shapes.

Depending on the pattern of the glacier's inner tunnels, eskers can interconnect in a pattern of central ridges and tributaries, just like a branching river system. Large esker systems often radiate out from a central, core ridge, like the spokes of a wheel; this pattern therefore reflects large, once-used, complex river systems comprised of major and tributary eskers which drained the last ice sheet in that area, and trends generally in the main direction of late-glacial ice flows.

The esker forms may take the shape of single, continuous ridges of uniform cross-sectional profile, single ridges of variable height and width, single low ridges flanking numerous mounds and beads, or complex braided systems of confluent and diffluent esker ridges.

Internally, eskers are composed of a wide variety of sediment units, ranging from sorted silts, sands, gravels and boulders to sand-supported gravels to fine lacustrine silts and clays. The commonly held notion that eskers are formed completely of sand and gravel is erroneous, with sand and gravel beds often having up to 5%-10% silt and clay, and clayey or silty diamict units often forming considerable portions of single ridges.

Plate 1: The sinuous planform of the scrub-covered esker segment south of Clara, is clearly seen in this aerial photograph. Note also the disused pits in the feature.

Plate 2: The steep sided flanks of esker segment at Clonascra, near Clonmacnoise. We can imagine the surrounding ice 'smothering' the tunnel in which the sand and gravel was deposited by a river. The ridge is left upstanding after the ice melts.

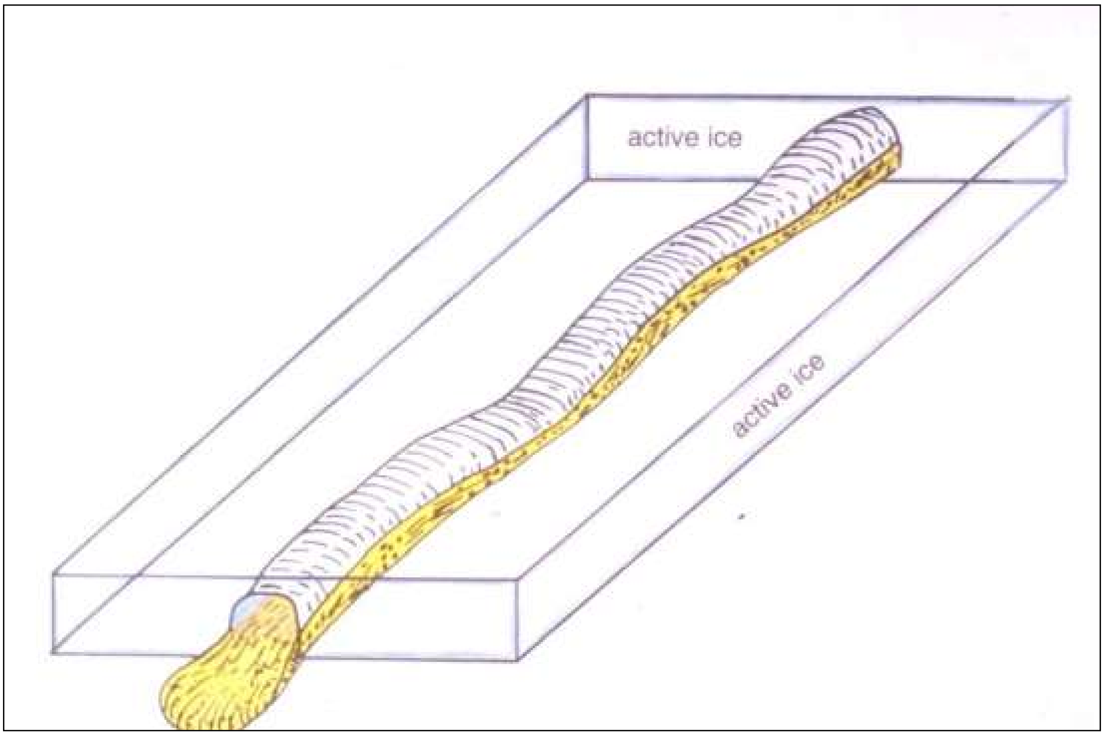


Figure 1: Esker formation in a tunnel underneath the ice. Diagram from paper by Warren and Ashley, 1995.

Plate 3: Complex esker morphology comprising anastomosing, hummocky forms at Clonmacnoise.

Eskers in Ireland.

A large system of esker landforms spans the Irish Midlands. These ridges have been the subject of geological study since the mid-nineteenth century. The eskers are composed of sorted, layered sediments but range in size, orientation and form, generally related to the movement patterns and former ice margin locations of the last ice sheet to cover the country.

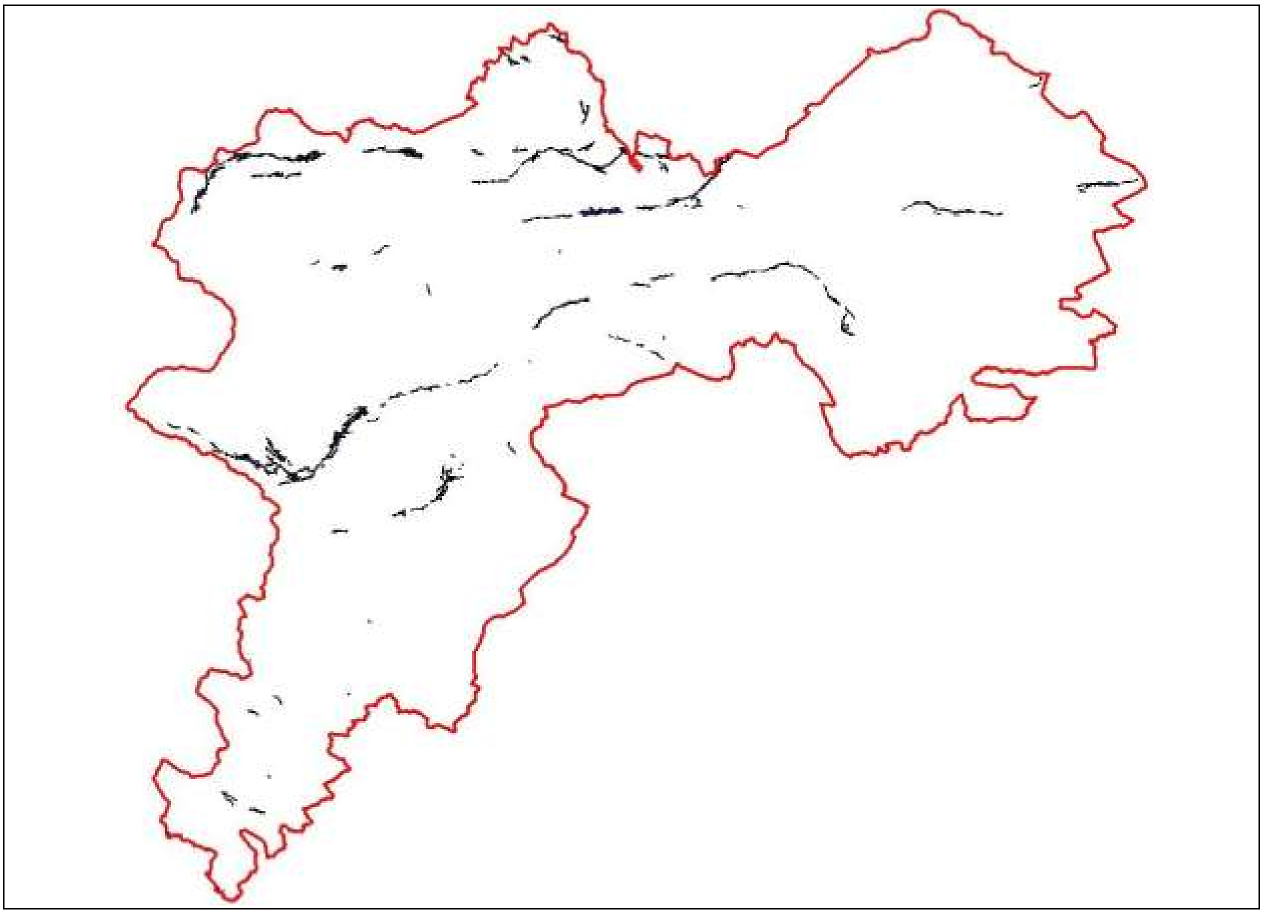


Figure 2: The eskers of County Offaly. Mapped photogrammetrically as part of EPA Soil and Subsoil mapping project (formerly FIPS-IFS, Teagasc, Kinsealy, 1998-2005).

The eskers in Offaly can be divided into two groups: a northwest-southeast oriented system of parallel-trending eskers which occurs in the southern portion of the county (and forms part of an esker system covering parts of Tipperary, Offaly, Laois, Kilkenny and Carlow); and an east-west oriented system which lies north of these and straddles the main peatland expanses of the county, and is dendritic[1].

The Clonmacnoise esker system

The largest esker system in County Offaly, and by far the most widely known, is the Clonmacnoise esker system. The esker sands and gravels of this system cover over

[1] It should be noted that many of the esker systems transgress county boundaries, so only portions of the entire system have been depicted on the map of Offaly (Figure 2).

five square kilometres (5.79 km^2, and therefore one-third of all the area of eskers in Offaly). As was seen from mapping results, the system comprises at least thirty four segments, the largest of which covers seventy hectares, and the smallest of which covers 363 square metres in County Offaly (but extends into County Westmeath also).

Further from this, seven features which are genetically classified as fans and deltas, but which form high, upstanding, steep-sided ridges, and also form part of the topographic, cultural and folklore history of the Clonmacnoise esker system, have also been included as 'esker-like' features on the GIS coverage. These are (from west to east) the complex elongate ridge immediately northwest of Fin Lough, Tullaghmore Hill, Esker or Fighting Hill, the hill just south of Mannions Crossroads, Bishops Hill, Eelweir Hill and Clavins Hill.

This gives a revised system composition of forty segments, the largest of which covers seventy hectares, and the smallest of which covers 362 square metres in County Offaly (but extends into County Westmeath also).

The legendary 'esker riada'

The Esker Riada, or Slí Mhór ('Great Road'), or Pilgrim's Path, is, by legend, a raised platform which acted as a routeway running from east to west through Central Ireland. It was used as a transport route by the earliest Irish settlers for travelling across the Midlands, and has been used through the ages since. Stories tell of pilgrims traveling the esker to Tara, and the Rath of Feerwore near Athenry [2] and even Newgrange (during the Neolithic period).

Mythological Celtic sun gods are said to have used the line of the Esker Riada as the arena for their daily battles; and the relative transients of their power struggles was displayed in terms of various strengths of light and shade along the ridge. According to legend, on evenings these fearsome conflicts would end in a blazing ball of blood-red crimson; and people would watch in amazement as the raging battlefield sank slowly into Galway Bay. By morning, when it rose again at the opposite end of the esker riada, the sun might still be showing signs of the blood-letting which took place the previous day.

Again according to legend, a battle at Maynooth around the year 123 AD led to the subdivision of Ireland politically into two parts, north and south of the esker riada. These were known as "Leath Cuinn" (Conn's Half), and "Leath Mogha (Mogha's Half). Medieval Latin texts refer to a natural mound which transversed Ireland as "*Via Magna*". Saints, the dispossessed, scholars, beggars, Celtic royalty, wandering poets, and armies, including the infamous Black and Tans of the early twentieth century, are among the many historical figures who are believed to have travelled the esker riada.

The 'esker riada' of legend consisted of one continuous raised ridge. The eskers in the Midlands are mostly discontinuous, so the feature in reality must have been a composite feature comprising several esker systems and associated gravell hillocks. Because of this, there has been much confusion over which esker, and other, features were actually part of the 'esker riada' itself. In reality, all of the raised eskers and

[2] The Rath of Feerwore is a locality in west Central Ireland where the pre-Christian, Celtic 'Turoe Stone', consisting of a large boulder hosting ornate ritual carvings, originally stood.

associated gravels would have formed dry, natural routeways, and the identification of whether features were or were not part of the legendary feature is very difficult. Esker features would have changed in transport importance in a regional sense over time, and what was an important route locally at any one time in one area may not have seemed to important to those from outside that locality. Only the longest of esker systems, such as the Clonmacnoise (Clara-Derrygolan) and Rahugh/Kiltober systems, formed long routeways that would have remained consistently important through time on a regional or national level. From this, it is these two systems that have the highest probability of forming a significant portion of the legendary 'riada' route.

The monastic settlement of Clonmacnoise is one settlement definitively on the 'esker riada' feature; this esker is part of the Clonmacnoise (Clara-Derrygolan) esker system that extends into Counties Galway and Westmeath. Founded by St. Ciaran in 548 A.D., the section of the esker to the east of the monastery is still known as the 'Pilgrim's Road'. The Shannon river provided the settlers here with an easy means of travelling north and south, so the esker riada and the Shannon therefore formed a natural 'crossroads' in the heart of Ireland, with routes radiating out from the monastery to the north, the south, the east and the west

Plate 4: The Clonmacnoise esker and Shannon River at the eastern extreme of Clonmacnoise townland, where one great routeway meets another. The monastic settlement can be seen in the distance, further along the esker/river interface.

2. The Clomacnoise Sand and Gravel Aquifer.
Damien Doherty

Geological Survey Ireland (GSI) is moving in the direction of providing three dimensional (3D) subsurface models, focusing on applying sound geological science to meet the requirements of end users: for instance, to undertake and facilitate the management of resources (such as wholesome drinking water supplies) and the environment (*e.g.*, applied data provision for integrated catchment management).

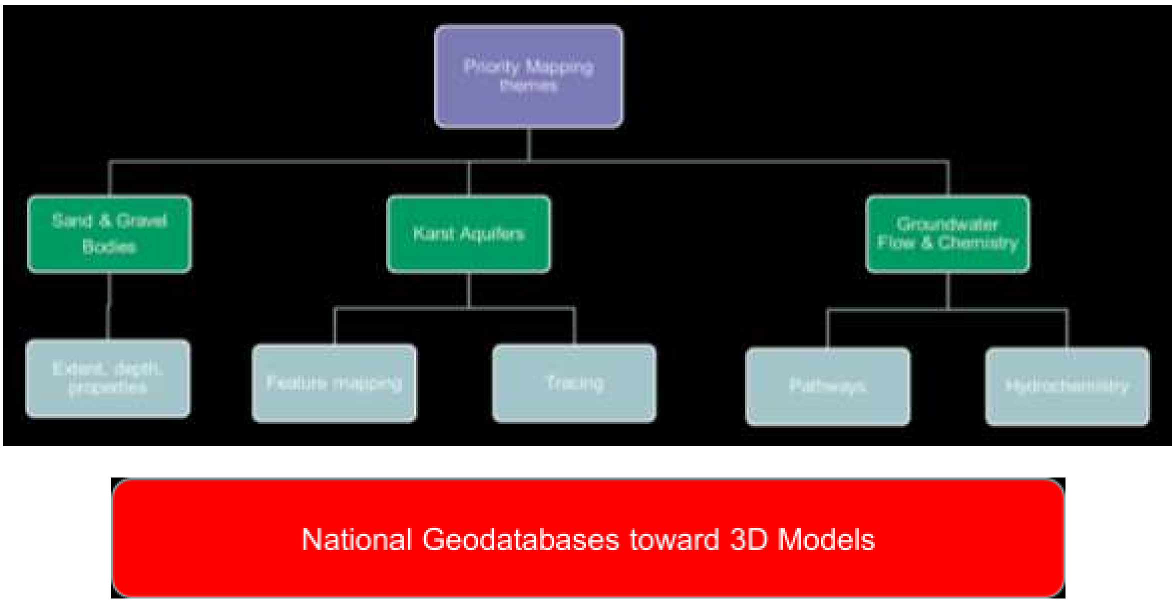
In 2015, Geoscience Initiative (DCENR) funding was allocated to this process for an initial four year term to appoint a team of eight hydrogeologists and geoscientists to this task.

Termed the Priority Groundwater Mapping project – shortened to “GW3D”, the data collection, mapping and modelling programme will address stakeholder needs and data gaps. Designed to run alongside other continued programme areas, GW3D will allow data to be collected, collated and analysed with the ultimate aim of creating 3D models that can add so much to the understanding and management of the subsurface. By the end of the four year term, the GSI will have improved the national maps and conceptual models, and will be able to provide considerably more information on groundwater systems in priority areas.

There are three main areas or themes that the Groundwater Programme has identified to pursue through the GW3D project, as follows:

- Karst
- Sand & Gravel
- Groundwater flow and chemistry.

Each of these themes comprises target elements or methods to best characterise and map them.



Given the increasing demand for accurate, higher resolution information, GSI is keen to examine areas of challenging hydrogeology at catchment and sub-catchment scales. There are ongoing issues in some of these regions, *e.g.*, pressures on water resources nationally and resource competition within areas of sand and gravel between agriculture, extraction/mining, amenity and good quality water abstraction.

Figure 3: Elements of Sand and Gravel Mapping Programme

Fieldwork consists of searching for, and subsequently assessing, exposures of sand and gravel. Target locations indicated by the desk study and accompanying field maps were visited. Exposures were often encountered in historic and active pits and quarries, golf courses, coastline, road cuttings and cut banks associated with residential, industrial and agricultural buildings, natural breaks in slope. Wells are located and dipper for water level data, and other salient information is also collected.

The data collected at a sand and gravel exposure included:

- Location on map and tablet
- Height/thickness
- Width
- Clast lithology
- Evidence of sedimentary structure
- Evidence of water/dampness
- Material classification to BS5930 standard
- Geotagged photograph of material exposed

Clonmacnoise Sand and Gravel Aquifer: Summary of Initial Characterisation.

<table>
<tr><th colspan="2">Hydrometric Area
Local Authority</th><th>Associated surface water features</th><th>Associated terrestrial ecosystem(s)</th><th>Area (km^2)</th></tr>
<tr><td colspan="2">26 – Upper Shannon
Offaly Co Co.
25 – Lower Shannon
Offaly Co Co.</td><td>Rivers; Suck (26), Dalgan (30)
Streams; n/a
Lakes; n/a</td><td>Fin Lough SAC, Mongan Bog SAC, River Shannon Callows SAC, Pilgrim’s Road Esker SAC.</td><td>10.11</td></tr>
<tr><td>Topography</td><td colspan="4">This sand and gravel aquifer occupies a considerable portion of the Clonmacnoise esker complex at elevations between 30 m and 80 m OD (Figure 1). The aquifer is a quasi-linear, ridged body that stretches for 12 km in a general west - east direction, but is usually only a few hundred metres to a kilometre wide. The body is hummocky and the west – east ridge stands proud above the surrounding, peat dominated landscape. The western margin of the body terminates at the River Shannon.</td></tr>
<tr><td rowspan="5">Geology and Aquifers</td><td>Aquifer categories</td><td colspan="3">The sand and gravel aquifer occupies an area of just over 10 km². Data for four geotechnical boreholes were identified in the aquifer outlining depth to bedrock of 14.6 m to 21.9 m (Figure 4). These data, along with the presence of a sand and gravel pit in the centre of the body, proves that there is sufficient depth of sand and gravel in that locality to qualify as an aquifer. This area is then extended using geomorphological mapping, and the assumption that the hummocky terrain co-incides with sand and gravel, to define the area of the body. It is inferred therefore that a significant proportion of the body has depths greater than 10 m (see Cross Sections 1 and 2, in Figure 2). Based on its areal extent, inferred thickness, saturated thickness and position in the landscape the deposit qualifies as a Regionally Important Sand and Gravel Aquifer (Rg), but owing to the fact that the groundwater body is as yet poorly understood, the body has been classified as a Locally Important Sand and Gravel Aquifer (Lg) (DELG/EPA/GSI (1999)).</td></tr>
<tr><td>Main aquifer lithologies</td><td colspan="3">Glaciofluvial sands and gravels derived from limestone, with interfingering esker sands and gravels which are dominated by gravels of basic reaction.</td></tr>
<tr><td>Key structures</td><td colspan="3">n/a</td></tr>
<tr><td>Key properties</td><td colspan="3">A number of water level localities were recorded across the aquifer extent during field work. The water levels recorded range from 0 m to 12.86 m below ground level. This has allowed basic assumptions and inferences to be made on the depth of water levels and degree of saturation within the sand and gravel deposits themselves.
Sand and gravel aquifers generally consist of unconsolidated coarse grained material, usually containing less than 8% fines (O’Suilleabháin, 2000). Groundwater is considered to be unconfined in this aquifer body. When analysing the water level data groundwater gradients were identified to be in the order of 0.001 – 0.009.</td></tr>
<tr><td>Thickness</td><td colspan="3">The thicknesses of sorted sands and gravels are likely to be greater than 10 m over much of the aquifer extent.</td></tr>
<tr><td rowspan="4">Overlying Strata</td><td>Lithologies</td><td colspan="3">Significant portions of the fringes of the aquifer are overlain by thin strips of cutover raised peat, with smaller pockets and areas covered with lake sediments and alluvium, with sands and gravels assumed to be underneath (see Figure 2 and Figure 4).</td></tr>
<tr><td>Thickness</td><td colspan="3">The cutover raised peat is assumed to generally be less than 3 m thick where it appears on the edges of the sands and gravels, and in pockets within the aquifer.</td></tr>
<tr><td>% area aquifer near surface</td><td colspan="3">A cutover raised peat covers approximately 14% of the mapped sand and gravel aquifer (Figure 4).</td></tr>
<tr><td>1 Vulnerabili ty</td><td colspan="3">The groundwater vulnerability of the sand and gravel aquifer is ‘Extreme’ where the water table is inferred to be < 3 m from the surface, whereas in all other areas where the water table is at > 3 m from surface, the vulnerability is classed as ‘High’ (Figure 3).</td></tr>
<tr><td rowspan="2">Recharge</td><td>Main recharge mechanisms</td><td colspan="3">Diffuse recharge occurs via rainfall percolating through the unsaturated sand and gravel. Due to the high permeability of sand and gravel, a high proportion of the available recharge will percolate down to the water table.</td></tr>
<tr><td>Est. recharge rates</td><td colspan="3">The groundwater recharge rate has a maximum recharge value of 467 mm/year.</td></tr>
<tr><td rowspan="3">Discharge</td><td>Large springs and large known abstractions (m^3/d)</td><td colspan="3">There are three small springs along the western flank of the complex which discharge groundwater into the River Shannon. There are no known large abstractions in the aquifer however there are a number of private wells which supply dwellings and farming enterprises in the area.</td></tr>
<tr><td>Main discharge mechanisms</td><td colspan="3">Groundwater is likely to discharge to a number of small streams that surround, originate and flow through the aquifer.</td></tr>
<tr><td>Hydrochemical Signature</td><td colspan="3">Raw water samples taken from a sand and gravel pit in the aquifer, in April 2008. The key hydrochemical parameters which were averaged from the three samples are; pH 7.39; Electrical Conductivity @25°C 604 µS/cm.</td></tr>
</table>

Groundwater Flow Paths	The length of flow paths depend on the extent of the sand and gravel deposit. In general, locally important sand and gravel aquifers are expected to have relatively short flow paths *i.e.*, up to several hundreds of metres. In a Regionally Important sand and gravel aquifer, flow paths are likely to be longer, perhaps up to several kilometres. Generally the drainage density is low over sand and gravel bodies, and such is the case in the localities underlain by sands and gravels around Clonmacnoise.
Groundwater & Surface water interactions	Groundwater is expected to discharge to the streams that surround the body and the three springs along the western flank of the body. Hydraulic connections between the groundwater in the aquifer and the three springs along the western flank of the complex, is assumed to be high.
Conceptual model	• The sand and gravel aquifer consists of glaciofluvial sands and gravels derived from limestone, interfingering with esker sands and gravels, with 14% of the body overlain with cutover raised peat, assumed to be less than 3 m thick. • The deposits stand proud above the surrounding, low-lying, and relatively flat areas, with depth to bedrock proven to be up to 21.9 m below ground level at one locality within the sands and gravels. • Diffuse recharge occurs *via* rainfall percolating through the unsaturated sand and gravel. • The presence of a deep sand and gravel pit in the centre of the body, geotechnical borehole logs with > 10 m to bedrock, as well as the overall regional geomorphology, suggests that this is a deep (> 10 m) sand and gravel deposit.
2 Attachments	Figures 1, 2, 3 & 4.
Instrumentation	**Stream gauges:** None present. **EPA Water Level Monitoring boreholes:** None present. **EPA Representative Monitoring points:** None present.
Information Sources	DELG/EPA/GSI (1999) *Groundwater Protection Schemes.* Department of the Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland. EMS Consulting Ltd., Extension of Gravel Extraction Operations at Carrowkeel and Clonfinlough Townlands, Clonfinlough, Co. Offaly. Offaly County Council. EPA map viewer. http://gis.epa.ie/Envision Feehan, J. (2013). The geology of Laois and Offaly. Offaly County Council, 400pp. NPWS viewer. http://webgis.npws.ie/npwsviewer/ Offaly County Council Planning. http://www.offaly.ie/eng/Services/Planning/Planning-Search/ O'Suilleabháin, C., (2000). *Assessing the boundary between high and moderately permeable subsoils.* Unpublished MSc., University of Dublin. Department of Civil, Structural and Environmental Engineering, Trinity College Dublin. Tubridy, M. (1987). The Heritage of Clonmacnoise. Environmental Sciences Unit, Trinity College, 136pp.
Disclaimer	Note that all calculation and interpretations presented in this report represent estimations and assumptions based on the information sources described above and established hydrogeological formulae. Figure 1, 2, 3 & 4 are used for illustrative purposes only.

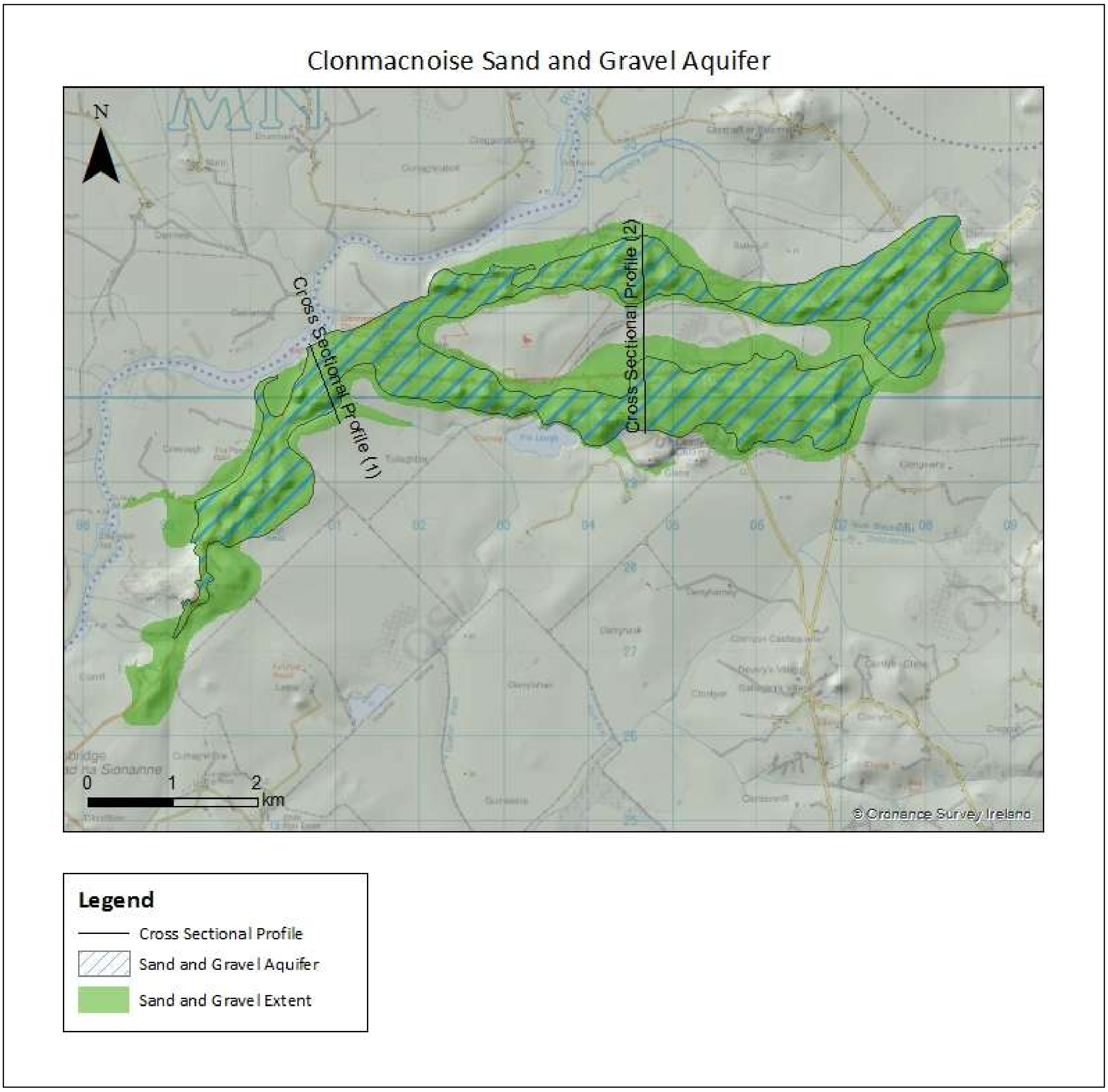
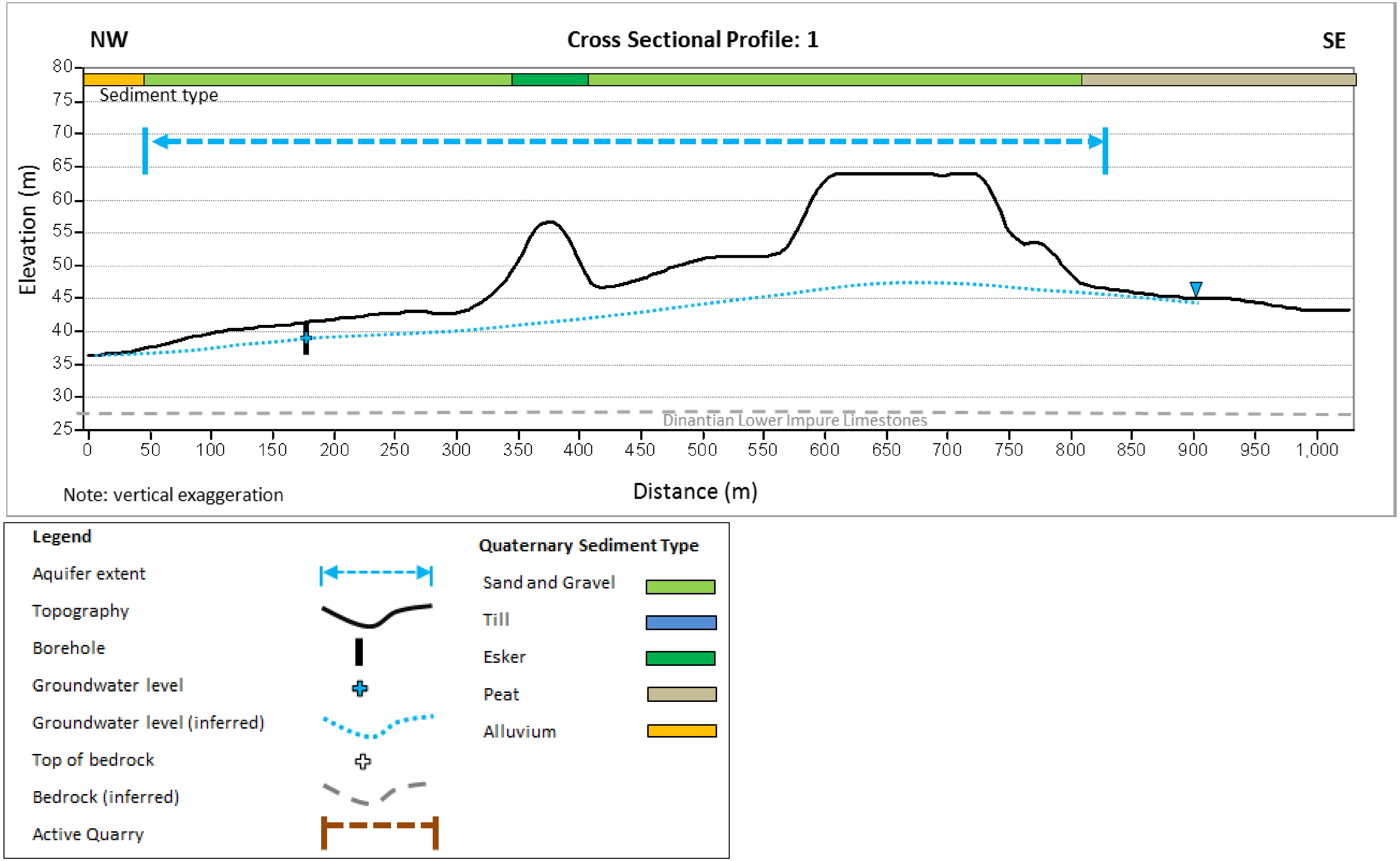
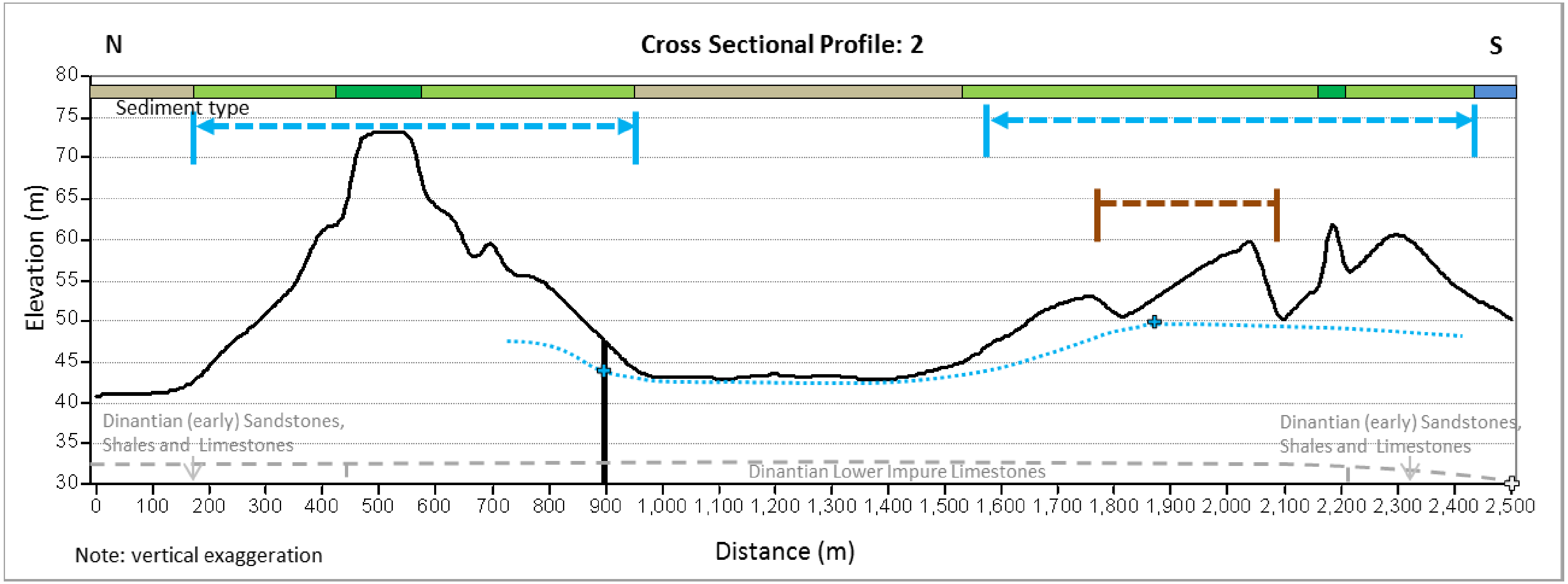


Figure 4. Clonmacnoise sand and gravel aquifer extent and cross section locations.


NW
Cross Sectional Profile: 1
SE
Sediment type
Elevation (m)
80
75
70
65
60
55
50
45
40
35
30
25
Dinantian Lower Impure Limestones
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1,000
Distance (m)
Note: vertical exaggeration
Legend
Aquifer extent
Topography
Borehole
Groundwater level
Groundwater level (inferred)
Top of bedrock
Bedrock (inferred)
Active Quarry
Quaternary Sediment Type
Sand and Gravel
Till
Esker
Peat
Alluvium



Figures 5 a and 5b: Cross sectional profiles 1 and 2 through the Clonmacnoise sand and gravel aquifer.

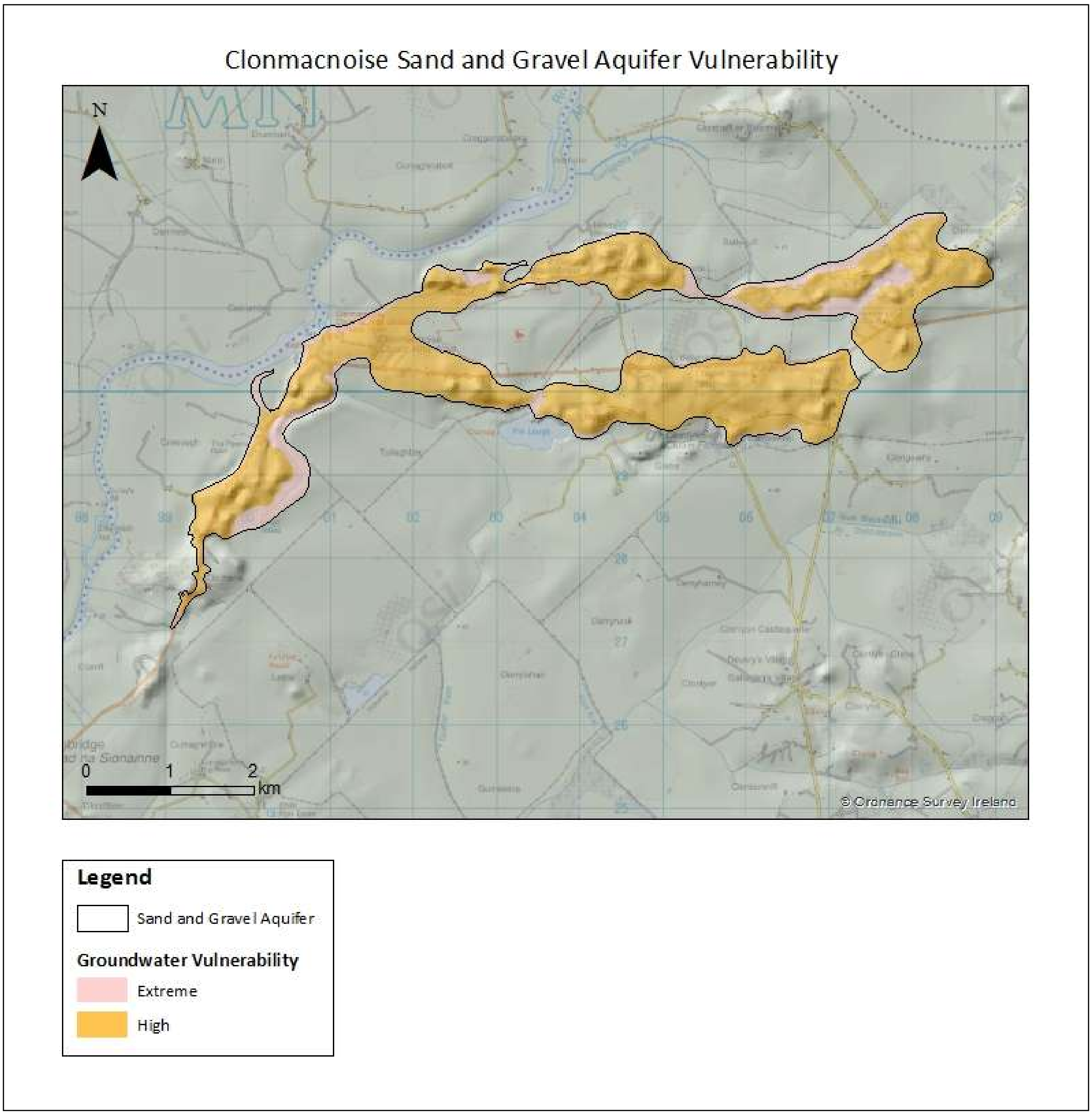


Figure 6. Groundwater vulnerability across the Clonmacnoise sand and gravel aquifer.

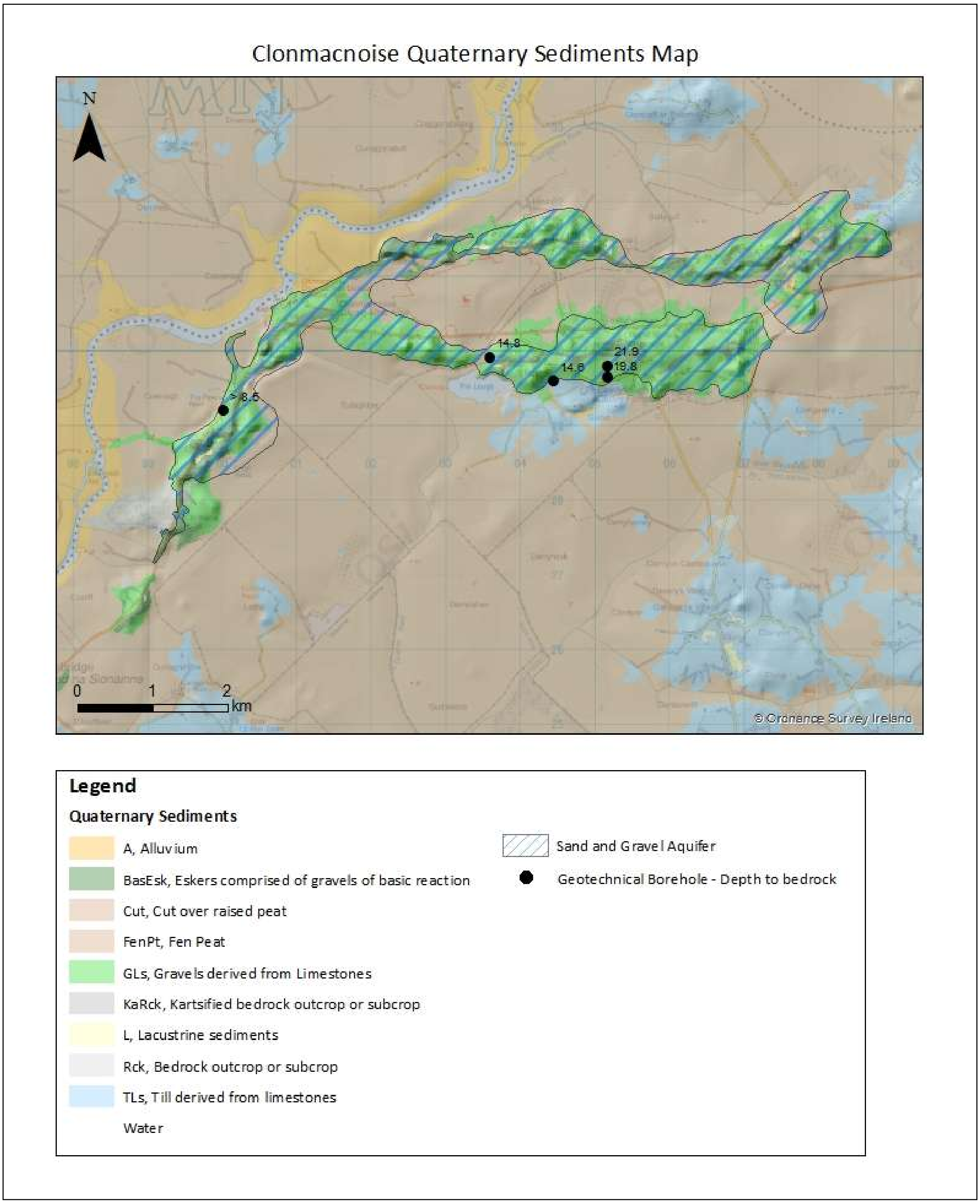


Figure 7. Quaternary sediments map and borehole locations in the Clonmacnoise locality

3. Clonmacnoise: an excursion in palaeohydrology.
John Feehan

At the end of the Ice Age the River Shannon as we know it today did not exist. A great sheet of water occupied what is now its floodplain and the water level was several metres higher than it is now. Only much later did it acquire its deep sediment infill and come to occupy its present channel. The raised bogs – which are such a feature of the Irish midlands today – did not exist at this time, and a combination of these two factors meant that the water extended much further inland than it does today – even when the river is in full flood – except where such glacial features as eskers and moraines rose above its level. All of the areas along the river now occupied by bog were embayments of a Greater Shannon Lake, and formed one continuous sheet of water, the outlines of which we can reconstruct in some detail.

As far back as 1835 the engineer Samuel Nicholson pointed out the vast extent of this Great Shannon Lake. He recognised that the surface of the marl in the callows (the winter-flooded grasslands of the floodplain) and bogs was nearly always level with the summer water level of the Shannon, 'thus proving that the Shannon must have occupied in former times a much greater area and rose higher than it does at present.'[3]

For many several millennia the landscape remained like this. The cold waters of the Great Lake lapped against margins that were up to several kilometres inland of the present river. Here and there on these shores there were isolated limestone boulders left by the melting ice, on which the persistent erosive action of the waves carved a bench mark recording their action and level over all those centuries. And then, suddenly, the water in the Great Lake dropped to a lower level: twice, with a long time interval between, so that the waves had time to carve a second, lower bench mark on some of the boulders.

There are numerous wave-sculpted boulders on the east side of the Shannon below Clonmacnoise; they also occur on the far side, but less frequently. The biggest concentration is in Clorhane (the townland south of Clonmacmnoise), including a superb mushroom-like one near the old village of Creevagh, and many others further north in Creevagh townland of which the most striking is one known as the Piper's Rock.

As well as the wave-worn boulders, the limestone bedrock has also been wave-eroded at the western edge of Clorhane wood, and also around the Creevagh mushroom stone, showing that this was an island at the time: indeed, was probably one of an archipelago of small offshore islands surrounded by very shallow water.

Numerous mushroom stones occur on the edge of the Lough Ree floodplain (mainly on the western side) and are also found in smaller numbers elsewhere in Ireland.

[3] Appendix D: the Report of Samuel Nicholson upon the nature and value of those Lands which lie along that portion of the River Shannon, extending from Lough Derg to Lough Ree. *Third Report of the Commissioners for the Improvement of the Navigation of the River Shannon* (1838), page 56.

Plate 5: One of the impressive Moyvannan Mushroom stones, County Roscommon.

Plate 6: A second, anvil-shaped stone at Moyvannan.

When conditions became warmer plant and animal life began to flourish in the nutrient-rich waters. The white *marl* found under many of the raised bogs today consists largely of the remains of stoneworts and shells belonging to the many species of freshwater snails that lived in the water.[4] With the further passage of time reeds colonised the lake margins, giving rise to large areas of reedswamp, in which the partially decomposed remains of generations of these plants accumulated over time, often to a depth of several metres, This caused a gradual shrinking inwards of the area of open water, and helped give rise to conditions suitable for the development of *fen*. The transition to fen was catalysed by the sudden drop in the level of the Shannon recorded by the lake-edge mushroom stones, which drained much of the open water from the shallower lake margins.

Fen peat accumulated in some instances for hundreds of years, but in time the growing thickness of peat raised the surface beyond the reach of groundwater and its nutrient supply, giving an advantage to new communities of plants that could thrive without that source. These new communities of bog plants now replaced those of the fen. To begin with, the bogs were confined to the lake basins in which the fens had formed: but the dominant plants in them were sphagnum mosses, which are nourished entirely by rainwater, so they could grow upwards indefinitely. At this time the slopes of the islands of moraine around the bogs were covered in woodland. The upwardly-expanding bog engulfed these woods, whose remains can be seen when the peat is stripped away in these areas.

The unimpeded upward growth of the bogs at the centre enabled them to develop a domed profile in time. For this reason they were called *raised* bogs. Many of the moraine hills were entirely overrun by bog. Others kept their summits above the sea of rising peat like gigantic whales. In due course these were claimed for agriculture, to become the *cluain* townlands that are such a distinguishing feature of the cultural landscape.

The making of the callows

In the beginning – at the end of the Ice Age – the area of what are now the Shannon Callows was occupied by a deep lake, whose margins we are able to map out at intervals by the lake edge markers of the mushroom stones, and the general topography in between. The scant vegetation cover at the time – and the low rate of evaporation – meant that the level of runoff and erosion was very high, especially in the immediate post-glacial period. As a result great quantities of silt and clay were washed into the lake: the characteristic grey silts and clays that are found in the lower part of the stratigraphy of the callows and bogs. Measured thicknesses of these clays range from 6m at Clonmacnoise to 13m along the Little Brosna callows. Herds of giant Irish deer grazed and browsed on the tundra surrounding this Great Midland Lake in the early postglacial period around 13,000 years ago, in the company of all the other animals with which they shared the landscape: reindeer and elk, bear and wolf, lemmings, foxes and hares. The remains of giant deer are found often entombed in the clays under the raised bogs (which were laid down mostly between 14,700 and 12,700 years ago) and in the callows. A brief, sharp return to

[4] Marl continues to form in the small, shallow lakes of the Upper Shannon basin; in some places the marl deposit is as thick as 9m.

glacial conditions between 12,800 and 11,000 years ago (the period known as the Younger Dryas) led to the extinction of the giant deer.

The dramatic drop in the level of the lake recorded for us by the mushroom stones is also seen in the sediments that floor the callows, where a ‘wash-layer’ of fine sand occurs at two levels in the stratigraphy. The lower layer of this ‘lacustrine sandy clay’ is generally between 2 and 4cm and never exceeds 8cm. These layers of sand reflect a redistribution of sediment in the lake as a result of *isostatic uplift* the finer material being washed away by the currents generated by that uplift.[5]

The deposition of shell marl begins almost immediately after the second drop in the level of the lake, and the transition is quite abrupt. The pollen record at the base of the marl tells that there was a sudden change in climatic conditions about 11,600 ago: away from the periglacial tundra that had prevailed until then. This allowed the development of a continuous vegetation cover, which reduced erosion greatly, limiting the input of sediment to the lake. Pine forest began to spread over a surrounding landscape hitherto dominated by juniper and willow. The marl lakes survived for millennia, but by 5,200 years ago fen was replacing open water nearly everywhere and the bogs had begun to spread across the landscape. It is possible that raised bog once covered the entire floodplain except for a narrow zone along the river channel. At Clonmacnoise marl deposition ceased early on (sometime between 9,200 and 5,200 years ago, and gyttja was being deposited for some time before fen peat began to accumulate.[6]

The open water of the Great Lake of the early postglacial landscape had almost disappeared by between 4,000 and 4,500 years ago, and there are indications that the modern river course was being incised at this time. Alder carr dominated much of the floodplain between 4,300 and 4,150 years ago, after which it was replaced by raised bog where conditions were suitable. The pollen record shows that by this time agricultural activity had begun on the callows.

The grassland that characterises the callows today only came into being between 1500 and 1900 AD, replacing the carr woodland that had been widespread before this, and was now cleared of its trees and drained to allow mowing and grazing. It continued to flood during the winter, but the annual input of fertile silt gave them a natural fertility that guaranteed good crops. They required careful management however to prevent a return to scrub. This was easier under the labour-intensive farming of an earlier time, and with the hardier breeds of grazing and browsing animals of a bygone age.

The clay in the upper part of the stratigraphy reflects the arrival and spread of farming in the Shannon catchment. Forest was cleared to make fields, exposing topsoil and allowing it to be washed away in the floodwaters, to settle out finally as an annual fertilising layer on the callows. Annual flooding is the price that has to be paid for this free gift, however.

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[5] Aljosja Hooijer (1996). *Floodplain hydrology. An ecologically oriented study of the Shannon Callows, Ireland*. Thesis, Vrije Universiteit Amsterdam
[6] Gyttja (pronounced ‘yit-cha’ is lake mud that is rich in organic matter.

The work of the Shannon Navigation Commissioners

> *It is, indeed, in this district a noble river independent of its lakes, and as regards magnitude and natural capabilities of being rendered completely navigable, all other rivers in the empire are insignificant compared with it.*
>
> Samuel Nicholson, *Report upon the General State of Agriculture in the District of Country adjoining the Middle Shannon* (1841), page 4.

A survey commissioned by the government in the early 1830s resulted in a report by the engineer Thomas Rhodes in 1833,which laid out a detailed schedule of the works that would need to be carried out in order to provide a channel for navigation and at the same time reduce flooding. This was followed in 1838 by an optimistic report by Samuel Nicholson on the implications for agriculture.[7] Before the works of the Shannon Commission (1839-46) the callows could be under water for six months of the year, and fields that rarely flood today for three months. Shoals were removed, field drainage improved and new flood-relief cuts made, lowering the level of the river by a foot at Clonmacnoise.

The Commissioners issued their 11th and Final Report in 1850, by which time the entire length of the river from Limerick to Boyle and Lough Allen, a distance of 144 miles in all, was navigable for public traffic. The optimism of the 1830s and 40s was short-lived however. Although navigation was greatly facilitated, flooding continued – and was exacerbated in some areas, giving rise to a flood of complaints. Five great autumn floods occurred between 1840 and 1866, the most disastrous of them in August of 1861; where the River Suck meets the Shannon below Shannonbridge the flood rose by an average of 4 inches a day for ten days running, resulting in a loss of crops worth £20,000 along the Shannon and a further £30,000 along its tributary. There were floods of complaints. A further survey was commissioned in 1866, resulting in a further set of recommendations … [8]

4. A Historical Hydrogeology of Clara Bog

Ray Flynn

To those of us who have studied geology as undergraduates, the concept of historical geology should be familiar. In brief, we can use information from deposits to deduce what environmental conditions were like in an area in the past. Strangely this idea is not normally extended to hydrogeology, even though the principles underlying hydrogeological processes are intimately controlled by the deposits through which groundwater flows. Historical hydrogeology can thus provide us with a useful insight into the role of groundwater in an area, both in the past and in the present.Perhaps more critically, use of historical hydrogeology can provide useful information that can help us deduce how particular natural processes or human activities have influenced groundwater.

The stops in the vicinity of Clara Bog will attempt to investigate this issue further by examining how the diverse range of (mainly unconsolidated) deposits in the area can

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[7] Appendix D to the Third Report, 1838, 55-62.

[8] *Report of Mr. J. Lynam on the Rivers Shannon and Suck*. House of Commons (1867).

interact with one another to give the hydrogeological phenomena we observe. In doing so, we will need to draw not only on hydrological concepts, but also those derived from sedimentology/ Quaternary geology, ecology and geotechnics, to mention a few. This approach is often neglected in conventional models of bog development, but which I hope to show is helpful in understanding their genesis and conservation.

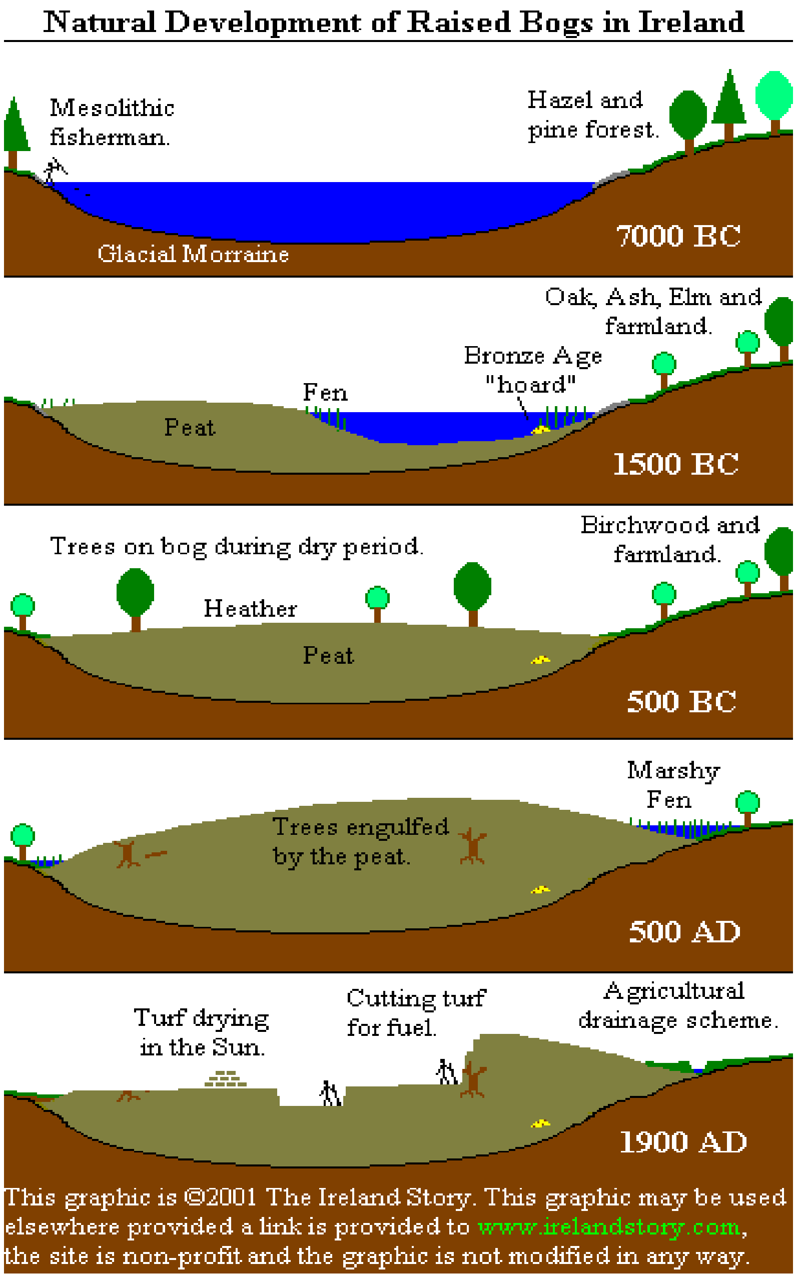


Figure 8: Illustration of the conventional view of raised bog development.

The two stops are scheduled for this part of the trip, illustrated on the GSI Quaternary geological map in Figure 9.

STOP 1 – Ballinlough / Lough Cuitch.

The middle of a sand and gravel complex may appear an unusual place to stop for a field trip to a bog. However, conditions in the area provide us with a useful insight into the hydrogeology of the deposits, encountered along (the north side) of the bog margins and in some cases (on the northwestern side) the materials that immediately underlie the peat.

A. Boulder sequence (Plate 7). Looking at the geological map, one may be tempted to consider geological formations as homogenous. Hopefully this exposure will put an end to any such ideas, particularly when it comes to Irish sand and gravel deposits. The predominance of boulders in this exposure provides an indication of both the immense energy that must have been present at the time of their deposition and the contrasts that may be expected in hydraulic conductivity (and drilling conditions) that can occur over short distances in this area. A borehole drilled in the complex approximately 400m to the south west of this location revealed a thick sequence of sand overlay a coarse bed of pebbly gravel resting on clean , slightly karstified limestone bedrock.

   Comparable sequences of sand and gravel occur in the gravel pits dotted all along this ridge complex. It may come as a surprise to some that the same deposits directly underlie the peat along the north-western margin of Clara Bog. Conventional models, if they consider the role of non-peat deposits in peat bog genesis view the substrate as a very low, if not impermeable material. However, observations at Clara and elsewhere show that this is not necessarily the case.

   Drilling, grain size analysis and pumping test data, completed in the 1990's as part of the Irish Dutch Raised Bog Conservation Project, reveal the sand and gravel deposits to have elevated hydraulic conductivities (10s m/day), while the groundwater had a distinctive high conductivity, calcium bicarbonate signature. This contrasts markedly with less conductive Na-Cl signature waters encountered in the samples collected from the Clara Bog.

B. Lough Cuith (Trans. *Lake in a hollow*). That the enclosed damp depression at the bottom of the field has an Irish name (Cuith-trans Hollow) may come as a surprise to some, and suggests a significant long term landscape feature. Looking at historical Ordnance Survey Maps from the 1830s , 1870s and 1913 reveal a body of open water, albeit much reduced in size in more recent maps (Figure 10).

   Moving forward to the 1970s, aerial imagery continues to show a small body of open water, which by the 1990s had disappeared. This has made an intermittent comeback in more recent years, but repeated aerial imagery suggests this rarely persists.

   Specific electrical conductance (SEC) measurements of water samples collected from Lough Cuitch reveal it to have consistently elevated values, comparable to water samples collected from wells in sand and gravel deposits, rather than low SEC values associated with rainfall or bog water. This points toward the lough's water balance predominantly receiving groundwater, rather than acting as a focus for intermittently accumulated rainwater.

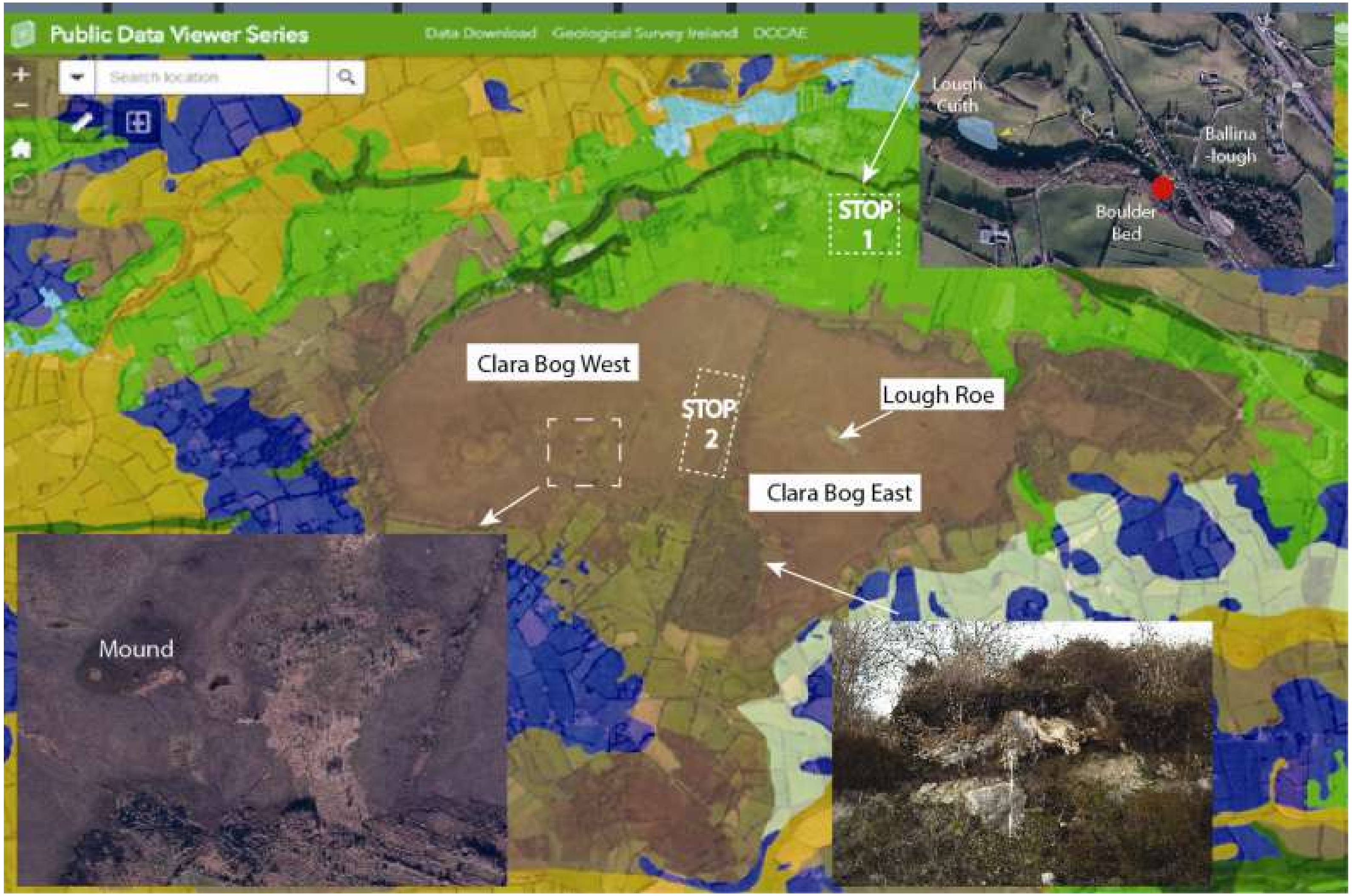


Figure 9: Quaternary Geological Map of Clara Bog and its Immediate Surroundings. Insets: Top right: Stop 1: Lough Cuitch and BallinaLough; Bottom right: Ancient tree stump on silty till, covered by peat; Bottom left: Bing maps aerial image of the mound and surrounding ponds on Clara SW. Base Map: Courtesy of GSI.

Plate 7: Boulder bed encountered in central part of sand and gravel complex, Ballingalough, County Offaly.

The more extensive coverage by open water at Lough Cuitch in historical maps is indicative of a higher water table in the past. This is borne out by surveys revealing dry hand dug wells across the esker, as well as the loss of Ballinalough between the 1830s and the 1870s. (Figure 10)

Coring at the lough has revealed peat over 1.5m thick in places underlain by silty and sandy deposits. C14 dating of this peat base showed that it was over 6000 years old and began accumulating at a comparable time to much of the early peat encountered at the base of Clara Bog..

The origin of the Lough Cuith has proven a bit more puzzling. The presence of an enclosed hollow in a sand and gravel sequence points to dead ice and a feature such as a kettle hole, with the presence of the fine grained substrate suggesting an intermittently perched system resting on top of the gravel (lying on rock). However, an earlier visit this year revealed a new drain at the edge of the lough, constructed as a water source for cattle (that doesn't always provide water). The materials in the trench showed that the silty deposits underlying the peat rested on a much firmer silty diamictic unit containing subangular erratic boulders. This proves surprising, given the presence of the boulder unit nearby and reflects very diverse deposition (and erosion) processes over short distances.

The lateral extent of the till unit may prove critical not only in protecting bedrock water quality from contaminants contained in the overlying sand and gravel, but also in explaining the development of Clara Bog to the south.

Peat coring at Clara Bog suggests that the level of lacustrine clay that forms the substrate of much of the lower lying part of the bog basin, occurs at elevations that are 2-3m below the level of the Brosna River, flowing through Clara to the north of the sand and gravel complex. Given that both the sand and gravel complex and the underlying Waulsortian Limestone have proven quite permeable, they could be expected to allow river water to flow through them to the lake that was the precursory of Clara Bog to the south. The presence of a layer of lower permeability glacial till would help limit this loss.

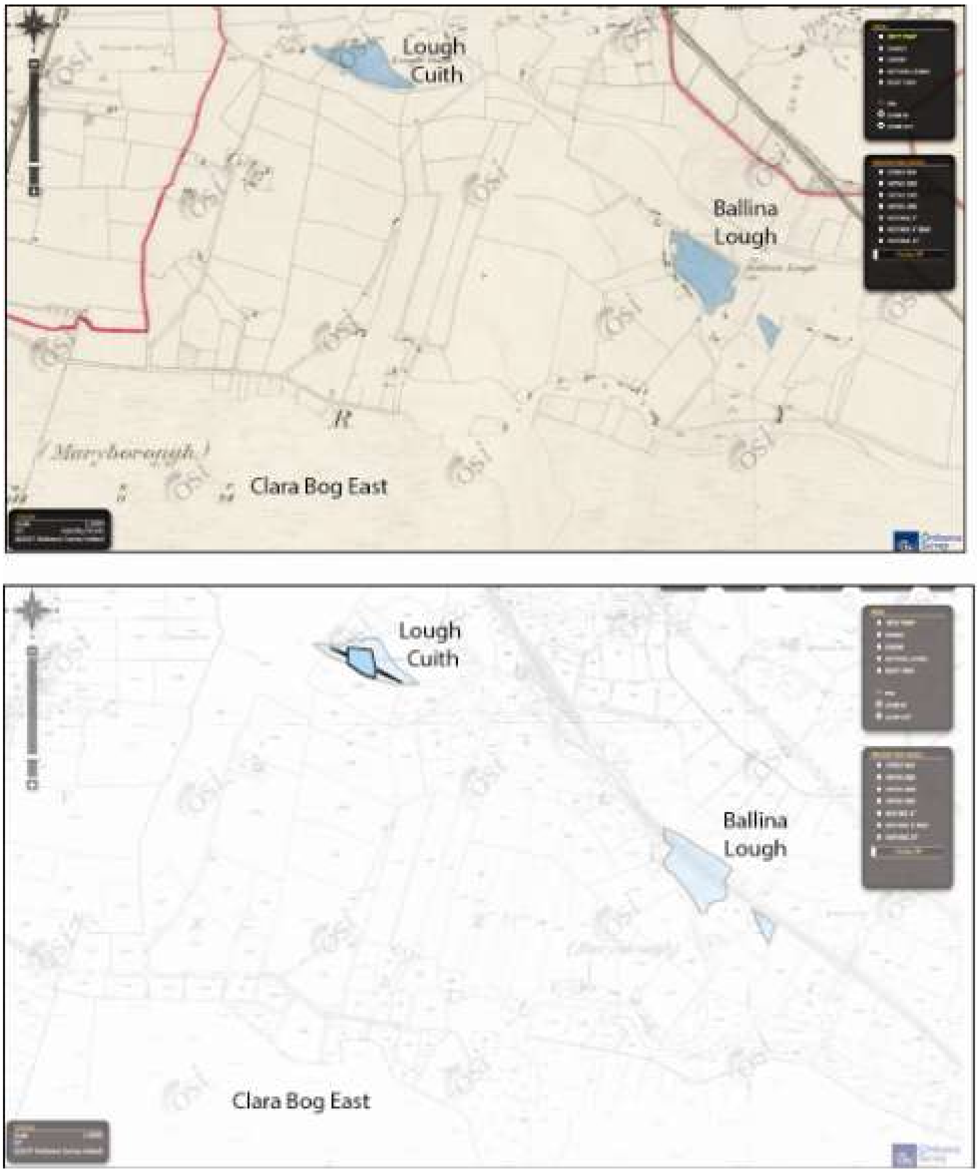


Figure 10: Historical topographic maps of the North-eastern margin of Clara Bog. The 1830s map (above) shows a number of open water bodies. By the time the second map was completed in the early part of the 20th century these had either diminished in area (Lough Cuitch), or disappeared (cf. Ballina Lough).

By contrast as peat began to accumulate to the south groundwater discharge, which had flowed to the south from the sand and gravel complex, proved increasingly difficult, leading to a rise in groundwater levels. This was accompanied by the development/expansion of open water in the sand and gravel complex. This in turn lead to the discharge of water on the north side of the bog into the sand and gravel complex. It is only with the advent of human interventions and associated drainage that this trend has reversed. This includes the road that now crosses the bog and takes discharge from the north side of the bog southwards to the Silver River, rather than to the Brosna.

Stop 2 - Clara Bog Boardwalk

Stop 2 brings us south of the esker sand and gravel complex to the Centre of Clara Bog. Although the area is very flat, this belies a complex geology underlying the peat, as suggested by deposits shown in the Quaternary geological map surrounding the bog. As noted, the lacustrine clay (and locally shell marl) immediately underlie the peat to in the central part of the bog's depositional basin. At higher substrate elevations these deposits are absent and the peat base comes into direct contact with more permeable glacial and glaciofluvial deposits.

Both coring and geophysical data reveal significantly greater relief in the peat substrate, compared to the overlying bog surface. That is except in the vicinity of the road, where more significant relief is apparent on the bog surface. Although the bog topography proves significantly flatter than the surrounding landscape, notable depression , corresponding to the route of the road is apparent. Historical maps show that the road was constructed between 1780 and 1810, although it was possible that it corresponded to an existing dip in the bog surface. However, investigations by Bell and Samuels from Imperial College London in the early 1990s, have shown that this occurs as a consequence of roadside drainage. Indeed study findings challenged the view that the impacts of drainage on bogs extended in no more than 30m, but actually could extend considerably further due to declines in head and pore water pressure.

This results in peat deformation (strain) due to the increase stress acting on the peat. Impacts are greatest near drains (and the road) giving rise to increases in slope approaching drains. The increase in slope has significant ecological consequences. Water which would have otherwise ponded on the very flat raised bog surface now flows off to a greater degree, resulting in reduced water levels in peat and the die back of the Sphagnum species that allow for peat accumulation. Hydrological modelling of the bog surface, assuming a dominance of surface hydrological processes , and comparing flow patterns with the distribution of plant communities has revealed that peat accumulating vegetation generally dies off on slopes greater than 0.3% on Clara (More Generally across Ireland this ranges between 02.% in the east, and 0.5% on raised bogs further west). (Figure 11)

Modelling results in Figure 11 show some discrepancies with observed vegetation distribution. These discrepancies occur principally in areas where peat substrate is sufficiently permeable to permit significant vertical losses of water (not accounted for in the hydrological model). As a consequence vertical losses from the peat to the substrate become a significant element of the local water balance. As losses to the substrate operate continuously, where these draw the water table to depths of greater than 15-20cm BGS for significant period of time, peat accumulating die back may occur, even though conditions are topographically suitable for its survival.

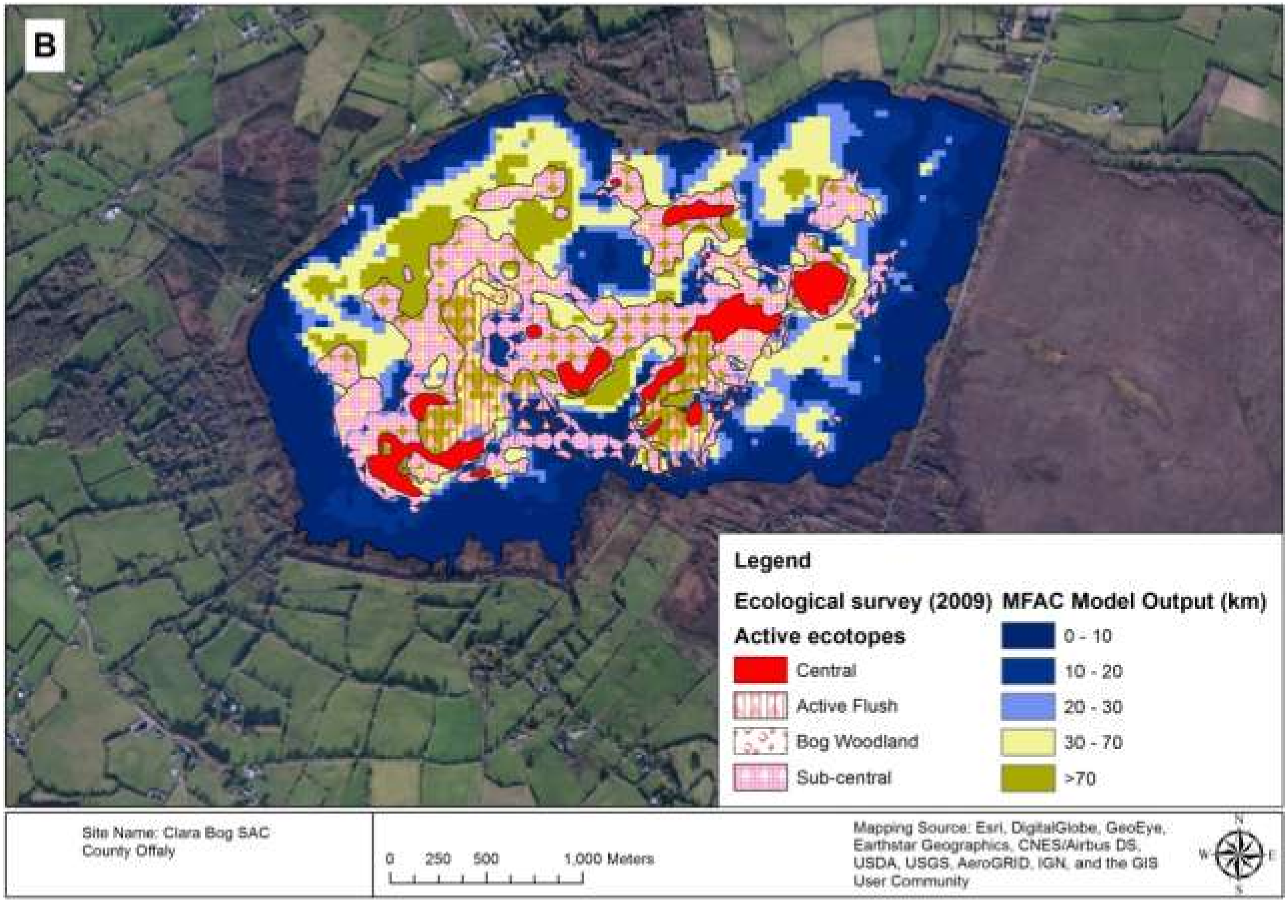


Figure 11: hydrological modelling output for Clara Bog West. Observed peat accumulating vegetation (in pink) generally corresponds well with simulated occurrence (in green/yellow) apart from the northern and southwestern sides. (Image: Mackin et al (2017)

Simulations, incorporating the geotechnical and hydrogeological properties of the peat, have provided a means for better understanding the impact of drainage and subsidence processes. In fact integration of compressibility measurements with groundwater flow modelling can generate the topography observed in the immediate vicinity of the road. Moreover, adaptation of the model to irregular substrates can actually result in drainage causing some areas of uncut (high) bog from subsiding to generate localised water-logged hollows: (See Figure 11). Put another way, drainage can result in some areas of bog becoming wetter. As it turns out comparable phenomena have been observed in the vicinity of peat resting on a mound of glacial till close to the southern margin of Clara Bog West (See Plate 7). Since the 1980s, the area immediately surrounding the mound has seen the development of a number of open water bodies (although the bog as a whole continues to dry out).

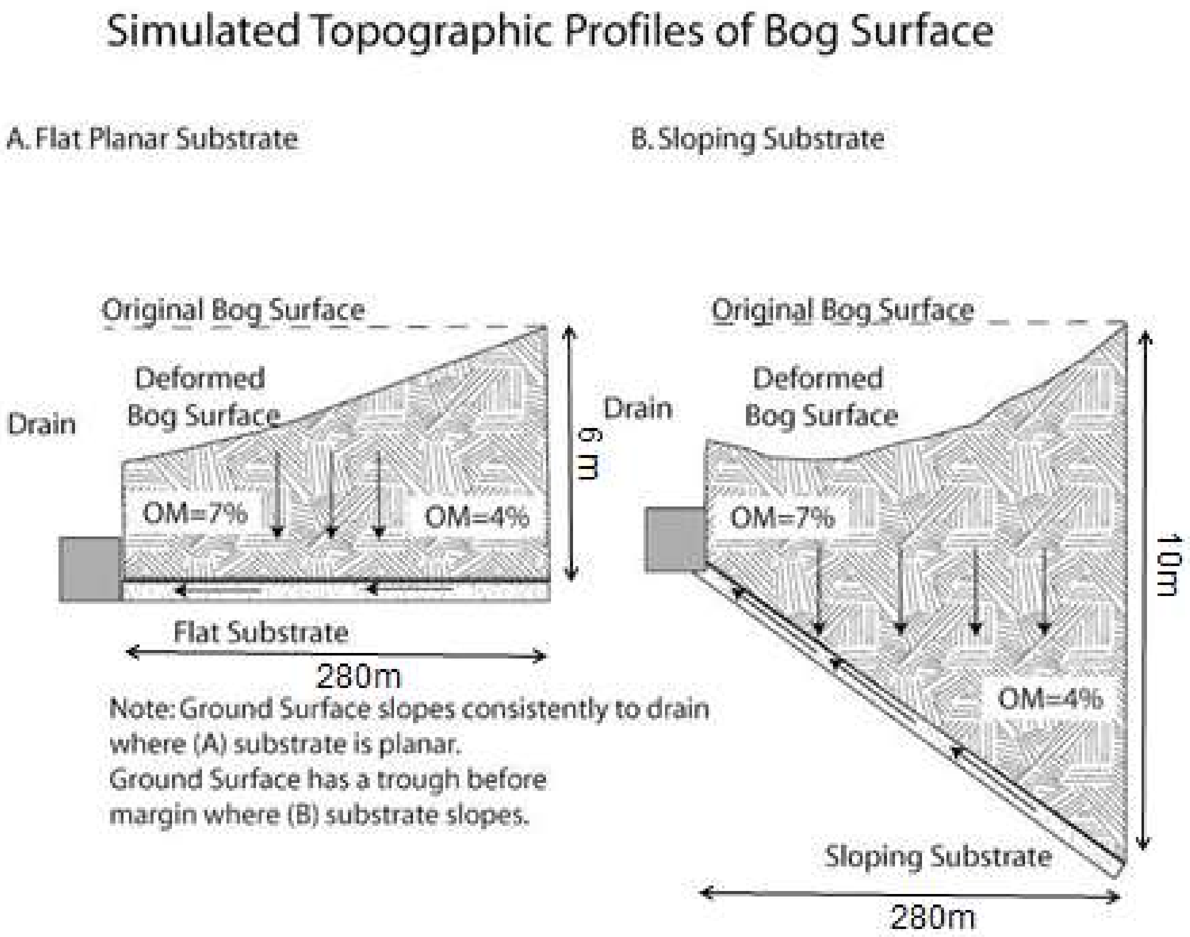


Figure 12: Simulated impacts of marginal bog drainage on bog topography (and organic matter content). Although drainage of a bog with a flat substrate results in consistent sloping toward the bog margins, when an irregular sloping surface is introduced localise hollows can develop which may become water logged.

Overall, studies have shown that Clara Bog can have a significant, if localised, groundwater dependency. More critically, the research completed at Clara has demonstrated the intimate relationship between hydrogeological conditions in the bog and in the surrounding area. At the same time the study has further highlighted the need for an interdisciplinary approach, incorporating hydrology and hydrogeology, if peatland conservation is to succeed in Ireland.

Findings of the work completed at Clara have provided a strong scientific basis for better understanding the ecohydrology of Irish Bogs. Models arising from the study now underpin management measures across the Irish Raised Bog Special Area of Conservation (SAC) network, while these results in turn provide a conceptual basis for on-going EPA funded research into the quantification of blanket bog ecosystem services (QUBBES).

5. Long-term impacts and controls of peripheral drainage on the eco-hydrology and carbon balance of an intact raised bog

Shane Regan, Paul Johnston and Laurence Gill

Introduction

Clara Bog, located in the centre of Ireland, is Ireland's premier raised bog wetland. It has high conservational importance, being a designated Special Areas of Conservation (SAC) under the Habitats Directive, and has been the subject of eco-hydrological research since the late 1980's. To put its importance into perspective, in the past 100 years two thirds of Europe's wetlands have been lost, and those that remain are often heavily degraded. The scale of wetland losses in Ireland has been less than in other European countries, but significant losses occurred and between 1990 and 2006 (approximately 10%). Despite this, Ireland still contains one of the highest concentrations of wetlands in Western Europe and key habitats, such as raised bogs, which have been almost completely lost in the European Union (EU) Member states. Indeed, Ireland has approximately 60% of the remaining raised bog habitat remaining in Western Europe, making conservation of the remaining examples paramount.

Raised Bogs

A raised bog is a wetland composed of peat-masses in deep (> 10m) sub-surface hollows, etched into the landscape following the retreat of the last major glaciers that masked Ireland ca. 10ka. They are hydrological features of the landscape, being located in areas with great drainage impediment, and often serve as the headwaters of streams and rivers. The distinguishing feature of a raised bog is the presence of vegetation, primarily rootless *Sphagnum* species, which are adapted to anoxic environmental conditions that occur due to persistent shallow water tables. The lack of oxygen in the shallow subsurface means vascular plants are uncommon in 'natural' conditions and that decomposition of the *Sphagnum* species vegetation exceeds primary production. This results in the accumulation of organic material (and thereby carbon), which later becomes peat (organic soil). Whilst there are a number of different peat wetland typologies, the term 'raised' bog refers to a peatland that has become separated from regional groundwater flows in a low-lying part of the catchment (almost all raised bogs originated as groundwater fen peatlands), due to the build-up of peat deposition over millennia.

Eco-hydrology

Hydrological and biotic processes in peatlands are strongly coupled. Water tables are a function of topography, with very little recharge through peat. Raised bogs have a natural topographical gradient distribution, with low-gradient areas in the bog centre becoming progressively steeper towards their margins. This is reflected in vegetation composition, with peat-forming vegetation typically dominating the low-gradient slope areas. A vegetation classification scheme has been developed to map these distributions with respect to vegetation 'quality', with the wettest areas termed 'central' and the driest areas termed 'marginal'. Figure 13 illustrates the probability distribution of ecotope and topographic gradient; from this, it can be observed that the majority of central ecotope occurs on gradients less than 0.5%.

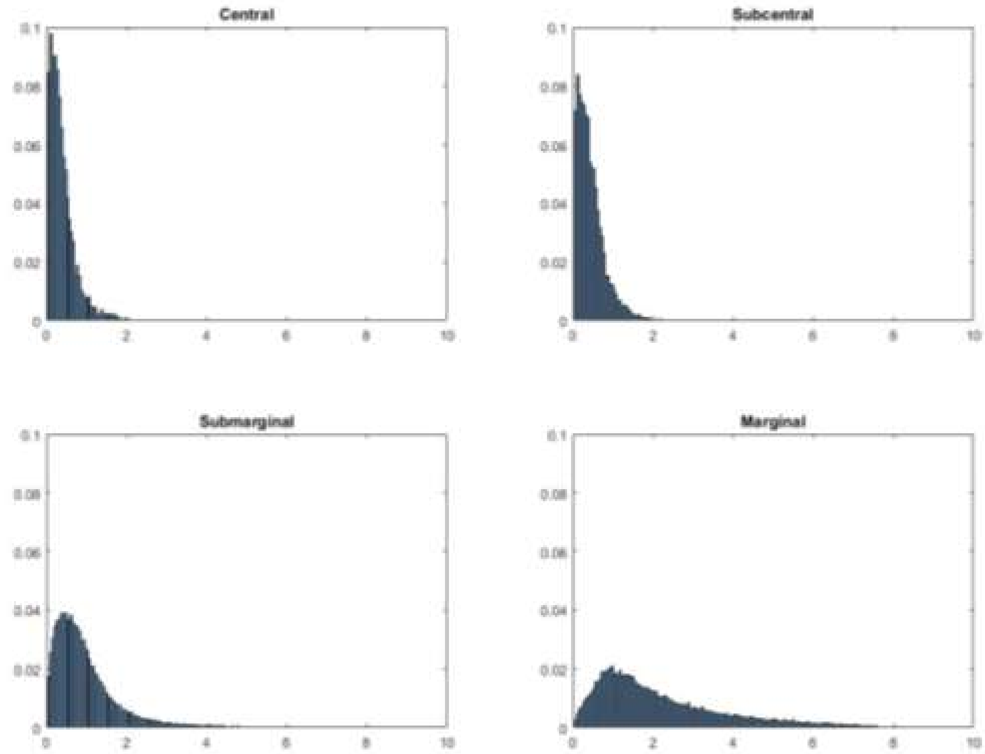


Figure 13. Gradient distribution of ecotopes.

Topographical conditions control ecotope water tables and there is a distinct difference in water table dynamic between, for example, the central and marginal ecotopes (Figure 14). Central areas are dominated by Sphagnum mosses, which can typically extract water from no more than approximately 10cm below the ground surface, due to their lack of root structure (they extract water through capillary action). This is a threshold for sustainability – however, it is not a fixed threshold, but rather this threshold must be adhered to for a large proportion of the year (> 70%). As means of comparison, marginal areas only have shallow water tables for a small proportion of the year, and this results in the absence of Sphagnum mosses.

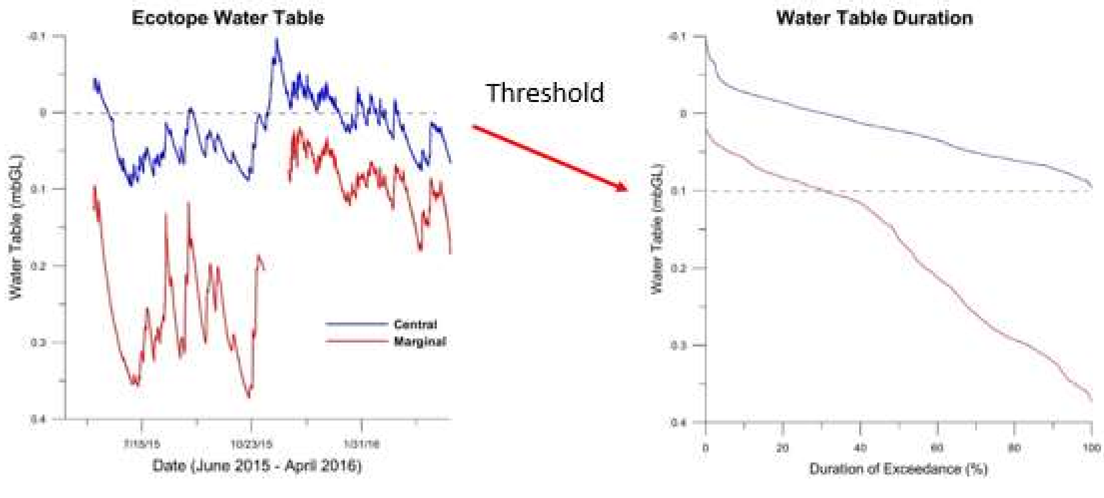


Figure 14. Ecotope time-series water table and duration

Groundwater dependency

However, bog hydrology is also controlled, somewhat, by regional groundwater heads and flows. Whilst a bog system itself is separated from the landscape catchment hydrology, in terms of surface inputs, the groundwater pressures play a supporting function in maintaining hydraulic gradients within the peat mass. The importance of this 'support function' has been demonstrated at Clara Bog, where marginal drainage of the regional groundwater table (drainage on the margins of the bog), has resulted in peat subsidence/settlement. This has resulted in catchment fragmentation and the loss of central, or 'active' ecotope (Figure 15). Recent topographical (LiDAR) and ecological surveying has indicated that this process is still occurring.

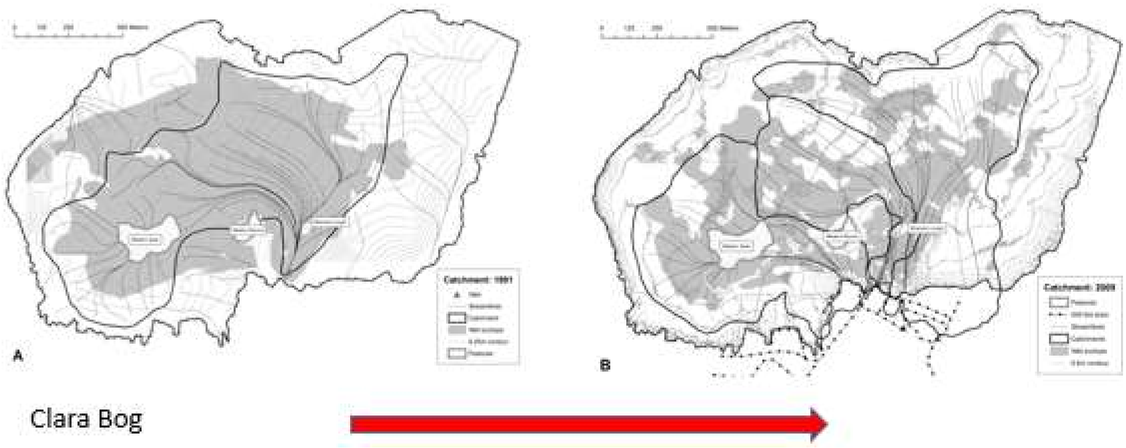


Figure 15. Catchment fragmentation at Clara Bog (1990-2010)

The impact of marginal drainage is to lower the hydraulic head at the base of peat, which results in an introduction of porosity to the peat mass (tension racks) and an increased hydraulic gradient and rate of downward infiltration (Figure 16 – phreatic water tables and hydraulic heads at base of peat in central and marginal areas). This is most pronounced in Clara where the peat rests on till subsoil, rather than lacustrine clay subsoil, which is more common.

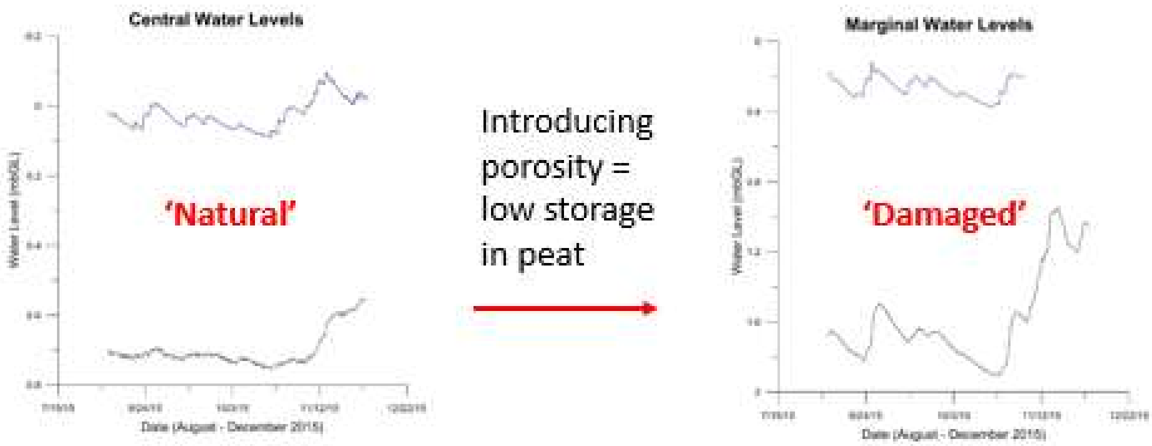


Figure 16. Effect of marginal drainage on water level dynamic.

Carbon balance

In a typical calendar year, a natural or intact bog sequesters carbon, meaning it is a carbon 'sink'. This is due to rates of vegetation decomposition exceeding primary production (measured via the net ecosystem exchange – difference between photosynthesis and respiration). However, whilst a bog sequesters carbon dioxide (CO_2), it naturally emits methane (CH_4) and waters flowing over peatland surfaces are typically concentrated in dissolved organic carbon (DOC). A typical carbon balance is shown in Figure 17.

Net Ecosystem Exchange

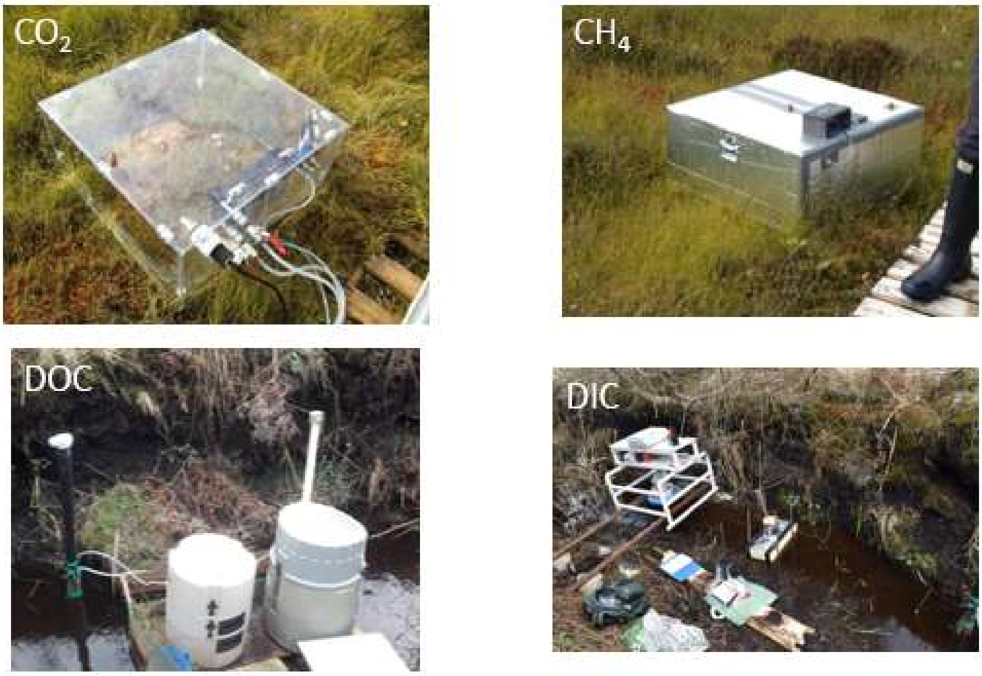
$$NECB = -(NEE + F_{CH_4} + F_{DOC} + F_{DIC} + F_{POC})$$

Lateral flux (DIC)

Vertical flux (CO_2 Evasion)

Figure 17. Effect of marginal drainage on water level dynamic.

Considering the morphological changes that have occurred on Clara Bog (and indeed, still occurring), a research project was initiated to measure the bogs carbon balance and better understand how eco-hydrology controls the relevant carbon fluxes. Static chambers were used to measure CO_2 and CH_4 at plot sites in representative ecotopes, whilst intensive measurements of DOC were taken from the bogs main drainage features (Plates 8a - d). In addition to this, measurements of CO_2 evading from drainage waters, were measured using floating chambers (the dissolved inorganic carbon flux).



Plates 8 a - d. Effect of marginal drainage on water level dynamic.

A preliminary carbon balance for Clara Bog is presented in Table 1. Whilst, overall, the bog sequesters CO_2 (measured over two years), it emits CH_4, and a significant amount of carbon is 'lost' via the fluvial pathways as DOC and DIC. Most of the DOC and DIC losses are attributed to marginal groundwater drainage. Without incorporating these elements to the carbon balance (which necessitated a detailed understanding of site hydrology), the bog could be mistaken as a carbon sequester, whereas in reality it is currently a carbon source.

Table 1. Preliminary Clara Bog carbon balance (positive number indicates emission loss)

.	**Flux**
	g m^{-2} yr^{-1}
NEE-C	-12
CH_4-C	4
DOC	25
DIC	3
Balance:	**20**

Management

The restoration, or management of Clara Bog, is very difficult. Groundwater levels need to be restored by filling in drains that are currently receiving groundwater recharge and altering bog hydrology. However, this is also complicated by there being a network of drains in a large area that was cut previously for turf. Restoring the conditions that allows central ecotope to develop are very difficult once peat has subsided and topography has changed; however, subsidence needs to be arrested to prevent further losses. Current estimations are that to carry out remediation works (AGL Consultant Engineers) is in the order of €4 million.

Why conserve?

The conservation of bogs has long been driven by ecologists for their value as ecosystems supporting a rich variety of biodiversity such as plant life and a breeding ground for migrating birds and insects. Their conservational value to other scientists and the wider public has been less appreciated. However, this has changed somewhat in recent years with the increased awareness of the provision of 'ecosystem services' from peatland environments. The most prominent of these services is the capacity of a peatland to be a carbon store, thereby playing a role in carbon mitigation strategies. This work demonstrates how a seemingly 'intact' bog can become and emitter when drained from the outside, which also has consequences for downstream water quality and a bogs capacity to attenuate runoff (flooding). Thus, restoration of peatland environments has a number of positive benefits to society, in addition to biodiversity/ conservation and recreational values.

Acknowledgements The research findings presented in this document are courtesy of an EPA research project entitled 'A framework for the restoration of degraded peatlands', and previous research work sponsored by the National Parks and Wildlife Service.

6. Restoring active raised bog in ireland's SAC Network 2016-2020; hydrology monitoring.

John Cody and William Crowley

Project Description

The goal of The Living Bog, LIFE Raised Bog Restoration Project is to restore the conservation status and ecological functions of Raised Bogs in 12 SAC's in Ireland. This will be achieved principally by reducing the rate of surface run-off from the bogs through blocking surface drains that were cut into the bogs to facilitate the harvesting of peat for fuel and horticultural purposes. At some sites water will be retained on site through the construction of barrier dams. The project will also seek to remove naturally regenerating shrubs and scrub from the sites.

The project objectives have been established by aggregating the assessed areas of actual and potential peat forming habitats areas on each of the 12 SAC's. This assessment was based on previous physical ecological assessments, and on the outputs of a "Peat Forming Habitat Predictive Model" (PFHPM) produced for the National Parks and Wildlife Service by RPS Group. (Mackin, Flynn, Barr, & Fernandez-Valverde, 2017). The PPFHM model is based on topography, using a DEM generated from LIDAR[i] aerial surveys carried out on behalf of the National Parks and Wildlife Service (NPWS) by Geological Survey of Ireland (GSI).

The model identifies areas where peat forming habitats are likely to develop if the current drainage network is successfully blocked. The outputs of the PFHPM are two GIS polygon data sets indicating where the model predicts there is the potential for peat forming habitats on the 12 sites.

1. The model predictions on cut-over sections is entitled Potential Peat Forming Habitats (PPFH)[ii],
2. The model prediction on high-bog sections is entitled Degraded Raised Bog (DRB).

Active Raised Bog (ARB)[iii] consists of central and subcentral ecotopes, active flushes and Bog Woodland habitat. DRB consists of three ecotopes (submarginal, marginal and face bank), as well as inactive flushes and dry woodland on the high bog.

The model does not reflect the influence of other factors thought to be important in sustaining peat formation on raised bogs such as peat depth, substrates, water losses or groundwater influences. For example it is generally accepted that PPFH is unlikely to occur in areas with less than 2 m peat depth remaining.

The objective of the project is to re-establish the hydrological conditions necessary to support active raised bog. Active raised bog requires that the phreatic levels on the bog are maintained within 10 cm of the surface.

The project will carry out conservation works on 12 sites with a combined area of approximately 1,577 hectares and a combined drainage network extent of approximately 182 kilometres. Approximately 60% of the area within the 12 SAC's is State owned while 40% is under multiple private owners. In addition to land ownership, a large number of individuals would hold Turbary Rights and Rights of Way within the sites. These rights are owned by multiple, and in many cases, unidentified private owners. A significant secondary objective of the project is to ensure that conservation and restoration of the bogs is accepted by the local communities. A key component in gaining this acceptance will be the minimisation and mitigation of adverse impacts on the rights of individuals within the SAC's and on adjoining lands.

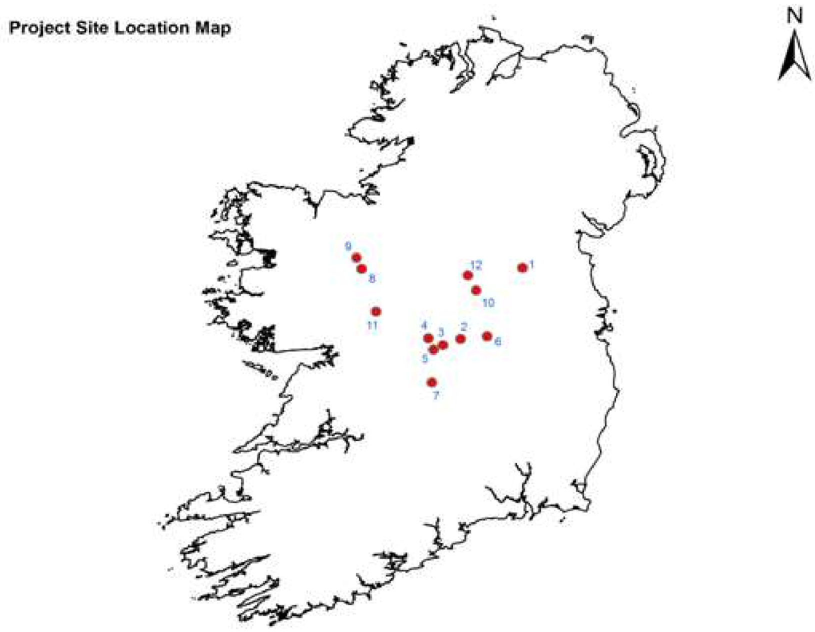


Figure 18: Raised bog restoration project site location map.

The Ecotope Concept

Ecotopes can be formally defined as areas which show certain homogeneity with respect to biotic and abiotic conditions (Kulcher 1967; Whittaker et al. 1973). The first large scale ecotope survey of Irish raised bogs was carried out in the mid-1990s based on work carried out by Kelly on Clara and Raheenmore bogs, which remain the most intensively studied Irish raised bogs, prompted by the need to select a representative sample of raised bogs for inclusion as NATURA 2000 sites[1]. The Ecotope concept has subsequently become the standard method of surveying, assessing and monitoring Irish raised bog habitats with subsequent surveys carried out in 1999-2000; 2004-05; 2011; and 2012-13.

Ecotopes represent the upper level of a three tier approach to vegetation mapping. Ecotopes are composed of a variety of community complexes, which are in turn composed of a variety of plant communities. Each ecotope is associated with a particular set of abiotic environmental factors such as acrotelm depth, mean amplitudes of phreatic level fluctuations, and hydrochemistry. Aside from flushes and soaks, Kelly and Schouten (2002) define five ecotopes; facebank, marginal, sub-marginal, sub-central and central, defined in detail in (Kelly & Schouten, Vegetation, 2002) and (Fernandez, et al., 2014). Kelly's original definition of ecotopes primarily relied on pH and electrical conductivity to represent hydro chemical gradients.

LIFE Project Site No.	SAC Name	SAC Code	County (nearest towns)	Total SAC Area (Ha)
1	Killyconny Bog	IE0000006	Cavan / Meath (Virginia, Kells)	191.22
2	Clara Bog	IE0000572	Offaly (Clara)	836.54
3	Ferbane Bog	IE0000575	Offaly (Shannonbridge)	153.08
4	Mongan Bog	IE0000580	Offaly (Athlone)	207.83
5	Moyclare Bog	IE0000581	Offaly (Ferbane)	129.86
6	Raheenmore Bog	IE0000582	Offaly (Daingean)	210.01
7	Sharavogue Bog	IE0000585	Offaly (Birr)	223.43
8	Carrowbehy / Caher Bog	IE0000597	Roscommon (Ballyhaunis)	343.83
9	Derrinea Bog	IE0000604	Roscommon (Ballyhaunis)	86.18
10	Garriskil Bog	IE0000679	Westmeath (Rathowen)	324.81
11	Carrownagappul Bog	IE0001242	Galway (Mount Bellew)	487.43
12	Ardagullion Bog	IE0002341	Longford (Edgeworthstown)	117.33
				3,311.55

Table 1: Raised bog restoration project site listing.

Acrotelm thickness was originally defined by (Ingram, 1978) as the surface layer of peat affected by fluctuations in the water table. Thus from a hydrological perspective the base of the acrotelm is defined by the amplitude of seasonal fluctuations in the phreatic levels below the peat surface. This strictly hydrological definition of the acrotelm, was not employed by Kelly in developing the ecotope concept, as she used measures of acrotelm thickness on Clara derived from sulphide concentrations (Lensen, 1991) and humification levels from core samples on Clara bog (Cruijsen, et al., 1993)

The development of the ecotope classification scheme adopted a more ecologically based definition of the acrotelm as the "living, actively growing upper layer of the bog surface, mainly composed of Sphagnum species". (Kelly, 1993).This shift from Ingram's original strictly hydrological definition of the acrotelm was noted as a general trend in an extensive review of published literature on peatland ecology and hydrology by (Morris, et al., 2011).

Hydrology monitoring

The 12 sites within the project represent ungauged catchments, with an average area of 280 hectares. In order to assess the impact of the concrete conservation works the project will establish networks on the site to monitor:

1. Precipitation inputs;
2. Discharge Hydrographs;
3. Nutrient and dissolved carbon fluxes;
4. Phreatic levels;
5. 3 dimensional flow fields.

The design of the hydrology monitoring components of the project has emphasised continuous monitoring of hydrological variables such as phreatic levels, geo-chemistry and surface run-off. The time series produced in such an approach will allow the identification and projection of trends in these key hydrological variables. This approach will allow the project team to quantify the response of groundwater and surface run-off to the concrete conservation works, and use stochastic analysis to forecast trends into the "After-LIFE" project phase. As the goal of the project is stated in terms of ecological outcomes, this approach offers a proxy indicator for the overall project goal.

Net Rainfall

There is a scarcity of the high temporal resolution precipitation data within the Irish meteorological observation network (Office of Public Works, 2016) required to monitor the response of phreatic levels to precipitation, the conservation works and to develop drainage management plans. Each of the project sites will be instrumented with an Adcon RG1[9] tipping bucket raingauge, logged at 15 minute intervals using a Solinst Rain Logger Edge[10]. The small areas of the SAC's make it reasonable to assume that precipitation will be evenly distributed across the sites.

This assumption is not reasonable for evaporation. Evapotranspiration rates are a function of surface cover, meteorological and vegetation types (Williamson & Campbel, 1999) and (Spieksman, et al., 1997). Methods of directly measuring Evapotranspiration fluxes, such as eddy covariance equipment are beyond the resources of the project. The use of lysimeters is technically challenging, and over the life time of the project would be similarly resource intensive. As the results from lysimeters are strictly valid only for the plant communities used in the lysimeter experiment, there would be a high degree of uncertainty inherent in extrapolating lysimeter data experiments results in the bogs due to high levels of inhomogeneity in surface cover, moisture content and microtopography.

As an alternative to empirically monitoring evapotranspiration rates, meteorological data from national monitoring networks will be used with standard models to approximate net rainfall estimates, where net rainfall is defined as

Given the difficulty in obtaining reliable estimates of land cover, and a lack of reliable crop coefficients for bog species, it is unlikely that employing more sophisticated techniques would provide more accurate estimates or significantly reduce uncertainties.

Surface run-off and hydrochemistry.

The project will monitor surface run-off by installing flumes, constructed in accordance BS 3680 (British Standards Institute, 1981) and equipped with Conductivity-Temperature-Depth sensors at discharge points from the drainage networks. The continuous hydrographs produced from the sensors will be used in conjunction with the rainfall hyetographs from the rain gauges identify catchment responses to rainfall inputs and to inform flood risk assessments of the concrete conservation works. On selected sites

[9] http://www.adcon.com/products/sensors-284/rg1-rain-gauge-200cm2-02mm-1498/
[10] https://www.solinst.com/products/dataloggers-and-telemetry/3002-rainlogger-edge/

Fluorescent Dissolved Organic Matter (FDOM) sensors will be substituted for CTD sensors to directly monitor the flux of dissolved organic matter from the sites.

Dissolved Organic Matter

Dissolved Organic Matter (DOM) is composed principally of humic compounds, with an array of simpler compounds such as organic forms of Carbon, Nitrogen and Sulfur and Phosphorous. DOM is a major pathway for the transfer of nutrients in aquatic ecosystems and can account for up to 50% of carbon inputs into streams (Bertilsson & Jones, 2003).

The bulk of autochonous aquatic DOM is derived from algal and macrophyte sources, either directly as biological exudates from photosynthesis, or indirectly as products of microbial degradation. DOM is a major substrate for aquatic microbes, and its concentration and composition influences both the composition and activity of aquatic microbial communities. DOM is photochemically active, absorbing UV radiation & attenuating Photosynthetically Active Radiation (PAR) all of which suggest that DOM is an important component chemical; cycling and trophic chains in riverine ecosystems, an area of increasing research activity.

Mineral soils remove DOM and streams receiving run-off from wetlands often have elevated concentrations levels of dissolved organic carbon relative to streams fed by catchments in mineral soils.

There are two mechanisms in operation in DOM production in peatlands:

1. As exudates from the sphagnum mosses and algae linked with primary production;
2. Aerobic decomposition resulting in aeration due to water table drawdown

Peatlands account for 20% of Ireland's land cover, and DOM inputs from degraded peatlands represent nationally significant sources of Dissolved Organic Carbon (DOC)[iv] and nutrients in rivers and ultimately groundwater.

Carbon is exported from degraded peatland catchments principally as surface discharge as dissolved inorganic carbon (DIC)[v], Dissolved Organic Carbon (DOC), and Particulate Organic Carbon [vi]. POC is defined as the fraction of TOC retained by filtration through a 0.45 μm filter membrane, while DOC is the fraction of TOC passing through such a filter.

Generally the raised bogs are acidic, ombotrophic, anoxic, low energy environments and the flow of carbon through the bog catchment is dominated by the flux of DOC, principally as DOM (Leach, Larsson, Wallin, & Laudon, 2016).

The conditions on the bogs suppress the natural processes that convert Dissolved Organic Nitrogen (DON)[vii] to Dissolved Inorganic Nitrogen (DIN)[viii] and the flux of DON is expected to be the dominant mechanism of nutrient export from the bogs. This hypothesis is supported by a study of 6 European raised bogs (Limpens & Bragaza, 2004) that found the concentration of DON was typically three times that of DIN in run-off from the bogs and that the contribution of DON towards the Total dissolved nitrogen export ranged between 60-80%.

Monitoring DOM

Equipment for in-situ continuous direct measurement of DOC and POC is not available. Ultra-violet spectrometry has a long history of use as a proxy for DOC in terrestrial waters, and is often used in favour of the more complicated and expensive techniques available for analysing DOC/POC. For example Nilsson et al (2008) have demonstrated a reliable, linear correlation between UV absorption at 254 nm and DOC concentration in bog environments, coupling spectroscopic analysis with high frequency sampling and analysis of DOC concentrations using established analytical and sampling techniques.

Experience in the oceanography field since the 1990's (Coble, 1996) has demonstrated a reliable correlation between concentrations of Chromopheric Dissolved Organic Matter (CDOM) and DOC concentrations using in-situ Fluorescent Excitation Optical sensors. CDOM is that proportion of DOM that absorbs light in the UV range, and is linked strongly with the presence of humic substances. Fluorescent Dissolved Organic Matter (FDOM) is the proportion of CDOM that fluoresces.

While a relatively new innovation in terrestrial waters the literature is already beginning to reflect the utility of continuous monitoring of DOM dynamics in natural hydrological processes, and deployment of these sensors in terrestrial environments and hydrological studies and monitoring networks appears to be increasingly common, if not yet routine. (Baker, Reynolds, & Hudson, 2007), have demonstrated their utility in urban catchments and several recent studies have demonstrated the use of these sensors in establishing links between micro and meso-scale catchment hydrological and ecological processes during storm events (Dalzell, Filley, & Harbor, 2005) and (Fellman, Hood, & Spencer, 2010).

Numerous studies have demonstrated the utility of CDOM sensors as a proxy for DOC in fresh water environments (Rochelle-Newall, Hulot, Janeau, & Merroune, 2013). CDOM has been demonstrated to provide a reliable, long-term proxy for high resolution DOC time series (Tunaley, Tetzlaff, Lessels, & Soulsby, 2016) in Scottish peat catchments. (Spencer, Butler, & Aiken, 2012) and (Spencer, et al., 2009). In situ DOM Sensors have also been shown to give reliable results in seepage lakes in sphagnum dominated catchments in the US (Watras, Morrisson, Crawford, McDonald, & Oliver, 2015). Indeed USGS has begun using optical FDOM sensors in real time water quality monitoring networks, and the deployment of these sensors is a current area of active applied research for USGS (Pellerin, et al., 2011).

The project has installed a YSI EXO2[11] multi-paramater sonde equipped with pH, EC, Temperature, Turbidity and FDOM sensors on Clara bog in a pilot project to test the utility of these sensors. The sonde is installed in a flume operated by Trinity College Dublin. Researchers from TCD have established an autosampler at the location and are analysing DOC using traditional sampling and a laboratory based Total Organic Carbon Analyzer. Initial results have been highly promising, with a significant correlation between DOC and DOM concentration. Critically the FDOM sensor make it possible to monitor concentrations of DOM through the entire range of the discharge hydrograph, offering insights into the dynamics of the DOM flux with peak flows that have not been possible to date.

[11] https://www.ysi.com/EXO2

Sub-surface monitoring

In designing the sub-surface monitoring network it has been assumed that the distribution of ecotopes on a site reflects existing hydrological and hydrogeological gradients. Hydraulic properties in peat are related to the plant assemblages from which the peat formed and thus it is reasonable to assume that hydraulic conductivities and hence sub-surface flow patterns will vary across ecotopes (Baird, et al., 2008). Properties such as hydraulic conductivity and specific storage can change by orders of magnitude over a few linear meters (Holden & Burt, 2003), and (van Gerven, 1990). In many sedimentary formations horizontal hydraulic conductivities are larger than vertical hydraulic conductivities (Fetter, 2001), and this form of heterogeneity has been demonstrated on Irish raised bogs by (van der Schaff, et al., 2002) who estimated that vertical hydraulic conductivities were on average an order of magnitude less than horizontal hydraulic conductivities. Vertical and horizontal hydraulic conductivity, and specific storage in peat can vary by several orders of magnitude over a few meters linear meters (Holden & Burt, 2003) and (van Gerven, 1990). It is expected that hydraulic conductivities will be greatest towards the centre of the bogs, and will decrease with depth (Moore & Knowles, 1990)

Phreatic levels will be monitored using phreatic tubes: an open tube installed in a water bearing unit. The water level in a phreatic tube reflects the integrated vertical head profile in the aquifer along its depth, providing a direct measure of the phreatic level at the monitoring point. Fluctuations in phreatic levels in response to variations in rainfall and evaporation are expected to be relatively high frequency, with periods measured in hours (Allott, et al., 2009), requiring that phreatic tubes be automatically monitored using pressure sensors[12]. Barometric compensation will be accomplished on each site using automated barometric sensors[13].

Phreatic tubes will be located in each of the ecotopes, arranged to allow interpolation of phreatic levels over an area (Bennison & Moseley, 2003) providing continuous time series of phreatic levels. In contrast to a phreatic tube a piezometer is a closed tube installed in the water bearing unit open only at the depth of interest. The height to which the water rises in the tube provides a direct measurement of the pressure head of the groundwater at that depth.

Piezometer nests consisting of piezometers at 4m and 6m depths, within 1-2 m of each other will be used to estimate hydraulic gradients in the vertical plane and characterise 3-dimensional flow regimes within the catotelm. Fluctuations in the head field within the catotlem of the bogs are expected to be persistent over seasonal time periods (Shantz & Price, 2006), and piezometer nests will be monitored manually on monthly time scales.

The piezometer nests will also be used to establish the spatial variability of horizontal hydraulic conductivity in the horizontal and vertical planes using slug tests following the methodologies tested by (Surridge, Baird, & Heathwaite, 2005) in peatlands. While there is evidence that hydraulic conductivities in peats may vary in response to rewetting (Shantz & Price, 2006), this potential response will not be monitored during the project. At the time

[12] Solinst Level Logger edge sensors have been selected based on price points. https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/levelogger-junior-edge/

[13] Solinst Barrologger edge sensors have been selected based on price point and software compatibility. https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/operating-instructions/user-guide/1-introduction/1-1-2-barologger-edge.php

of writing there are no plans to determine storage coefficients. These decisions have been based primarily on resource constraints.

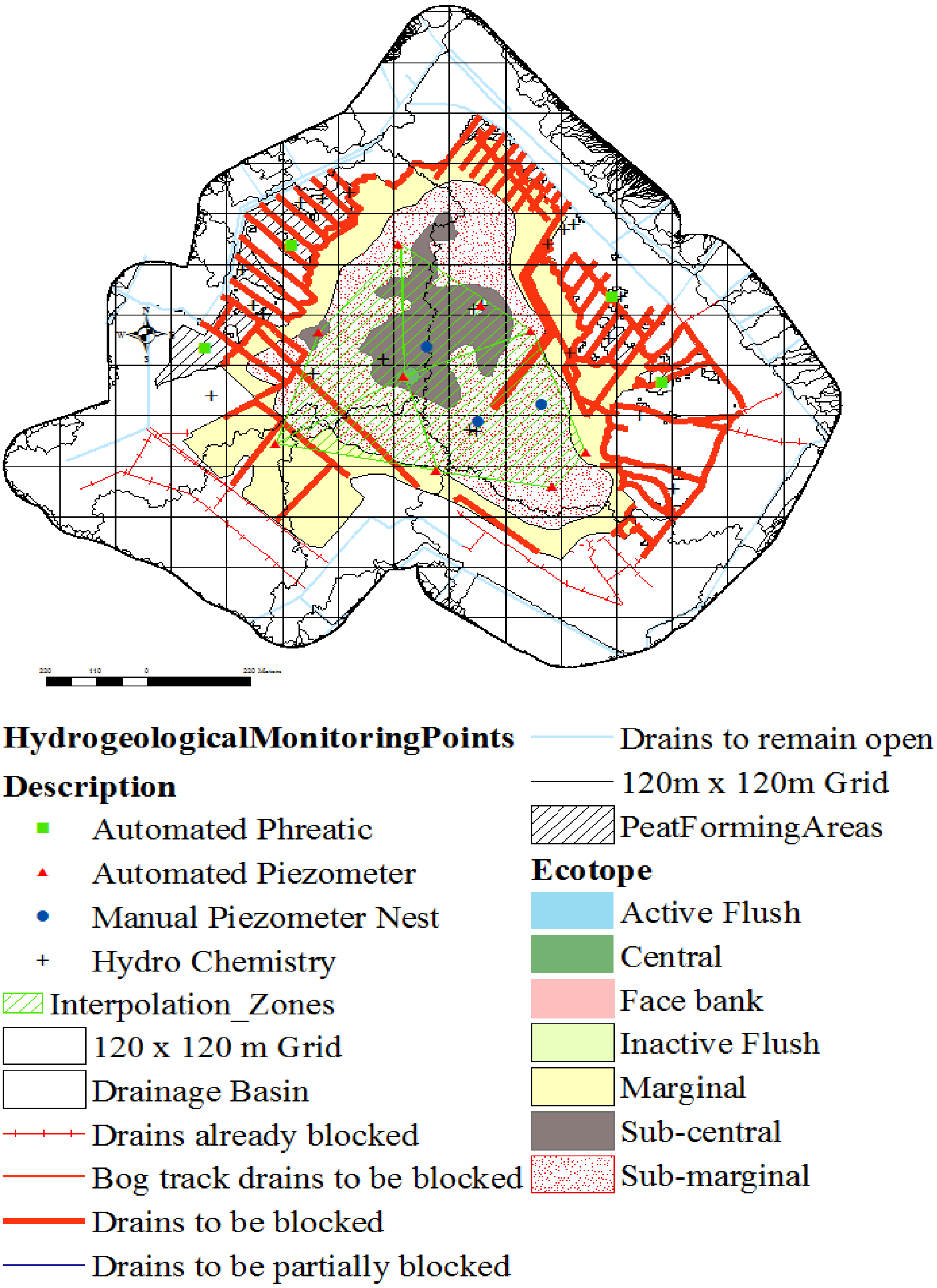


Figure 19. Ardagullion SAC Sub-surface monitoring network

Progress to date

The project technical team consists of a ½ time ecologist and a ½ time hydrologist, recruited in May 2016.

Hydrochemistry surveys (pH and EC, and Turbidity) have been completed Ardagullion, Carrownagappul and Ferbane. Soundings of peat depths were also completed during these surveys. Hydrochemistry survey points were selected in collaboration with the project ecologist and are coincident with ecological monitoring quadrats, providing coverage across all mapped ecotopes.

Progress on the installation of the hydrological monitoring networks has been constrained by the fact that incorporating hydrological variables represents a relatively new approach to routine monitoring on the SAC network.

This has necessitated the development of operationally feasible monitoring protocols for ground water, surface water and hydrochemistry. To date the rain gauge and the sub surface monitoring network have been installed on Ardagullion SAC. Current plans are to install two more FDOM Sensors, one on Ardagullion SAC and another on Ferbane and rain gauges will be operational an all sites by December. External contract assistance is expected to be available by December, and it is hope to have all of the ground water monitoring networks in place by January 2018.

Significant progress has been made on the cut-over surveys required to establish the ecological baselines for the project. This progress was facilitated by the fact that on high bog areas the project ecologist uses well established surveying methodologies that have been refined over 2 decades. As a consequence there is a pool of ecologists with experience in both bog ecology and ecotope surveying methods. Progress has also been made on developing a new ecological classification and surveying methodology for cut-over bog habitats that will incorporate abiotic elements such as hydro-chemistry and peat depths

7. On-site Wastewater Treatment
Laurence Gill

Overview

The domestic wastewater of approximately 30% of the population in Ireland (~ 490,000 dwellings) is treated on site by domestic wastewater treatment systems (DWWTS), of which 90% are septic tanks. Many of these households (~172 000 dwellings) also obtain their water supply from private sources, such as a well (CSO, 2017). The potential impacts of such on-site effluent are the pollution of either groundwater and / or surface water. If the effluent loading on the subsoil is too high, the permeability of the subsoil excessive or there is an insufficient depth of subsoil then the groundwater beneath a percolation area is at risk of pollution, in particular from microbiological pathogens and / or nutrients. Alternatively, if there is insufficient permeability in the subsoil to take the effluent load, surface ponding may occur with associated health risks, and there will be a risk of effluent discharge / runoff of pollutants (particularly nutrients) to surface water and also wells, especially where the latter have unprotected wellheads.

Site Assessment

The design of an appropriate DWWTS which will effectively attenuate microbiological and chemical contamination of groundwater and/or surface water needs to be based upon the particular site conditions where it is to be located, in particular the nature of the subsoil. In Ireland, legislation defines how such a risk assessment is carried out that takes into account the level of pollution in the *source*, the *pathway* that the pollutant travel once emitted into the environment and then the potential *target* of such pollution – the so-called **source-pathway-target** concept (Figure 20).

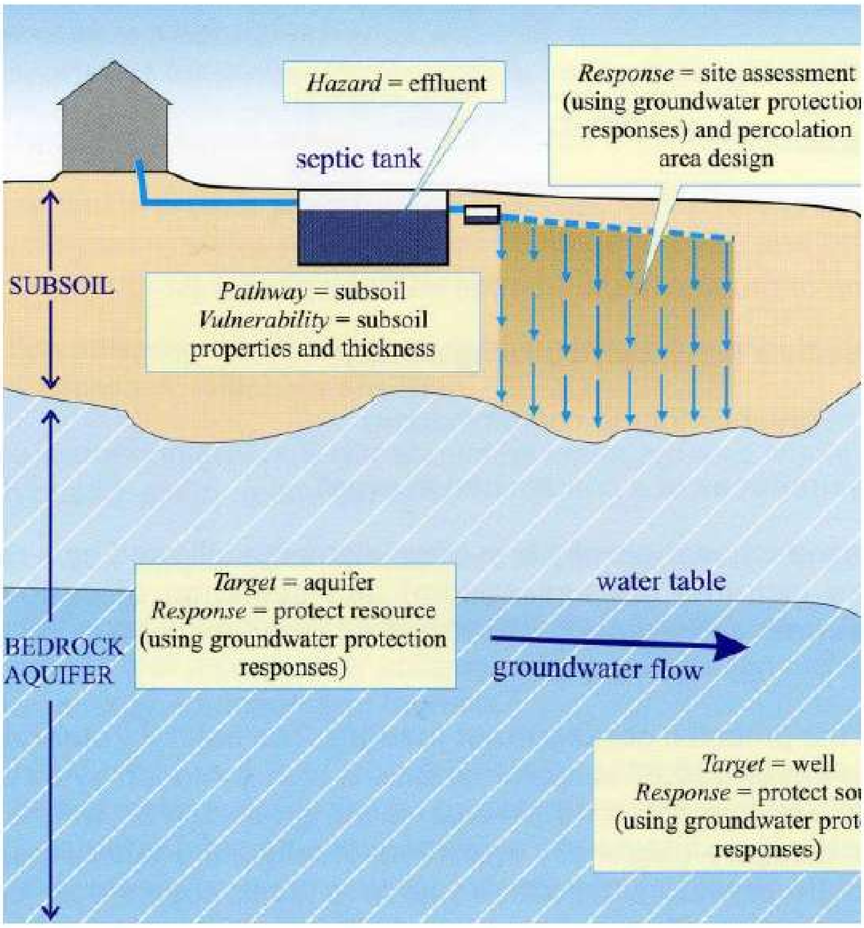


Figure 20. Source-pathway-target concept of risk as applied to on-site wastewater treatment (DoE / EPA / GSI, 1999).

In this case the source is the wastewater from the domestic dwelling, the pathway is the subsoil through which the effluent percolates and the target is either the groundwater or the local surface water (streams / rivers / lakes etc.). The risk assessment of any site must be carried out according to the EPA's *Code of Practice: Wastewater treatment and disposal systems serving single houses*. Initially a desk study is undertaken which takes into account the quality of the groundwater beneath the site as a potential water resource (i.e. its aquifer classification - Regionally Important, Locally Important, Poor) as well as whether it is located within a Source Protection Area. The nature of the overlying protection of the aquifer can also be defined by its Vulnerability (Extreme, High, Moderate or Low). Such information is available across the country, available from the GSI's

Groundwater Data Viewer portal. However, more site specific information is required to determine the exact nature of the subsoil as well as its unsaturated depth. This is accomplished by digging a trial hole on the site (Plate 9) to establish the depth of the unsaturated subsoil above the water table or bedrock, as well as the nature of the subsoil to be determined according to the BS5930 field test (GRAVEL, SAND, SILT, SILT/CLAY or CLAY). In parallel, percolation tests using clean water (Plate 10) also give an idea of how fast the water will percolate at the assumed depth of wastewater infiltration.

Plate 9. Trial hole to reveal subsoil classification and depth to water table / bedrock

Plate 10. Falling head *T-test* to determine percolation characteristics of subsoil.

All of the information from the Site Assessment then needs to be integrated to determine the optimal design of the on-site DWWTS. This is guided by a risk matrix that has been developed which takes into account the value and vulnerability of the underlying groundwater to pollution (the *target*) and the nature of the *pathway* through which pollutants must travel before reaching it – i.e. the depth and drainage characteristics of the overlying subsoil (Table 2).

This matrix determines the nature of pre-treatment needed for the effluent, how big an area of soil the effluent needs to be spread across and also what depth within the soil it should be discharged at. In general, gravelly / sandy subsoils allow water to percolate quickly, whereas silty / clayey of soils have a much more limited capacity to allow water to percolate. Also, the deeper the soil the better the treatment removal of any pollutants contained in any percolating water. So, the longer it takes the effluent to infiltrate the better (more treatment). However, if the soil is too slow for the amount of effluent being added to it then it will start to pond and flow overland, providing a risk to both public health and to the environment.

Response Matrix for On-site Treatment Systems

VULNERABILITY RATING	SOURCE PROTECTION AREA *		RESOURCE PROTECTION Aquifer Category					
			Regionally Important		Locally Important		Poor Aquifers	
	Inner (SI)	Outer (SO)	Rk	Rf/Rg	Lm/Lg	Ll	Pl	Pu
Extreme (E)	R3[2]	R3[1]	R2[2]	R2[2]	R2[1]	R2[1]	R2[1]	R2[1]
High (H)	R2[4]	R2[3]	R2[1]	R1	R1	R1	R1	R1
Moderate (M)	R2[4]	R2[3]	R1	R1	R1	R1	R1	R1
Low (L)	R2[4]	R1	R1	R1	R1	R1	R1	R1

Table 2. Risk matrix used to determine DWWTS design (DoE / EPA / GSI, 1999).

Domestic Wastewater Treatment Systems

The site assessment will have determined the range of treatment options available for the specific site conditions. The first stage is to specify the nature of pre-treatment that the effluent requires prior to being discharged into the soil percolation area. This could be a septic tank (Plate 11) as a form of primary treatment if the soil has adequate unsaturated depth and reasonable percolation characteristics. Alternatively, the effluent may need to be treated to a higher level (secondary or tertiary treated) using a packaged treatment system (Plate 12) before discharge to soil. Such effluent can also be treated by systems constructed on site, for example constructed wetlands / reed beds (Plate 13) or sand filters (Plate 14).

The percolation trenches must then be designed to the correct depth and combined lengths to allow the effluent to infiltrate into the soil at appropriate hydraulic and organic loading rates as determined by the upstream unit treatment processes. The number of trenches and length will dictate the hydraulic loading rate based upon the number of people living in the house (and thus the expected wastewater production). In general, a lower hydraulic loading rate should be used for lower permeability soils to ensure the effluent does not back-up. This is further complicated by the nature of the effluent. Septic tank effluent contains a high organic load (compared to secondary treated effluent), providing a significant food source for microorganisms in the soil which form a dense *biomat* at the infiltrative surface in the trench. This acts to slow the percolation of effluent into the soil.

Plate 11. *Septic tank installation.*

Plate 12. *Typical packaged DWWTSs.*

Plate 13. Subsurface flow reed bed.

Plate 14. Sand filter under construction.

The impact of the biomat, as well as the need to maintain unsaturated conditions in the underlying subsoil for effective treatment, is taken into account by loading the soil at a fraction of its saturated hydraulic conductivity – a design loading rate known commonly as the *long term acceptance rate* (LTAR). Finally, it is critical to ensure that the effluent is distributed across the requisite number of trenches whether flowing by gravity or pumped to a distribution manifold.

Plates 15 a and b. Construction of percolation trenches for effluent infiltration.

In summary, the legislative procedure used to design on-site wastewater treatment systems in Ireland links the understanding of how water related diseases (and other contaminants) are spread using the *source-pathway-target* concept to a robust assessment of the natural conditions which can be used to ensure a sustainable approach to effective treatment of domestic wastewater on-site in order to protect both public health as well as the natural environment….in theory.

In practice, the situation is often less satisfactory on the ground!

8. The Molloy Environmental Systems 3-D Infiltration Area Demonstration Facility.

John Brennan

Molloy Environmental Systems in Tullamore have installed a facility that allows prospective homeowners or site assessors view percolation areas and polishing filter, which discharge partially-treated wastewater to ground and ultimately groundwater, in three dimensions.

The facility compliments the visual display of a range of septic tanks and secondary treatment plants, and allows any person interested to view ‘what they will have under their back garden’ ‘live’ on-site.

Some of the various systems follow graphically.

Plate 16. Overview of the Molloy Environmental Systems demonstration facility.

Plate 17. Three dimensional view of a sand filter.

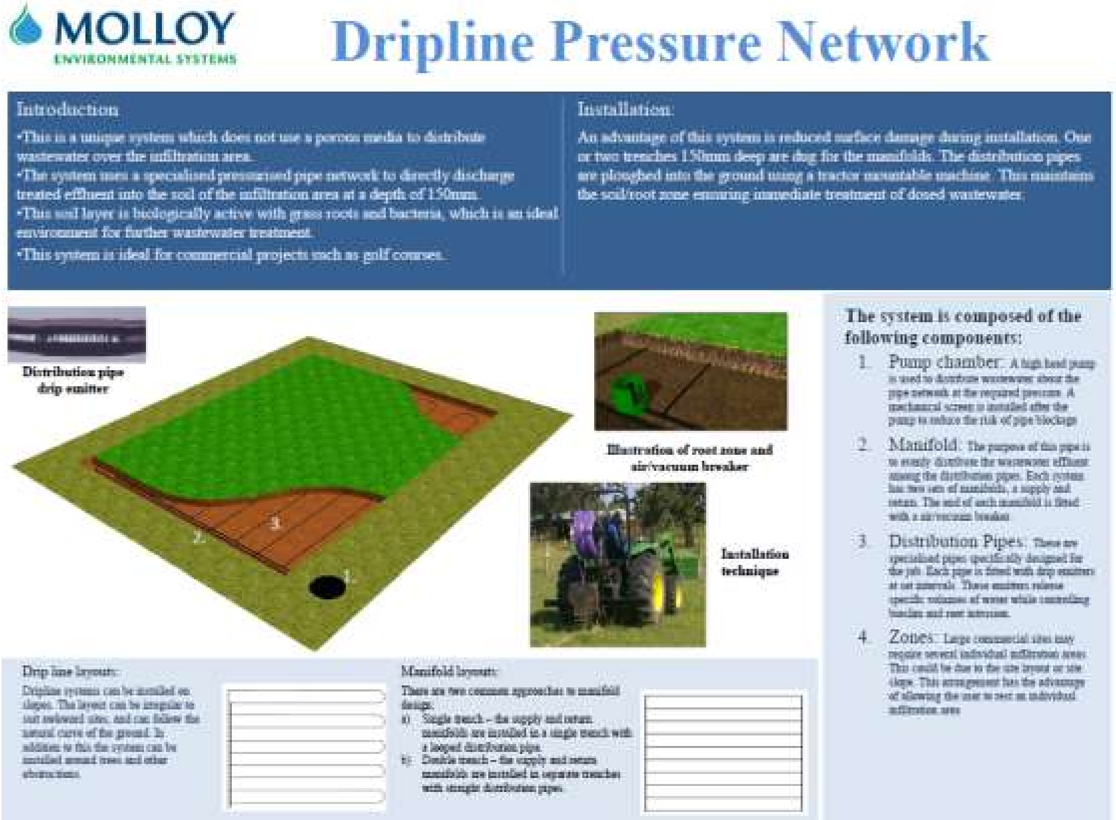


Figure 21: Schematic and details of drip distribution.

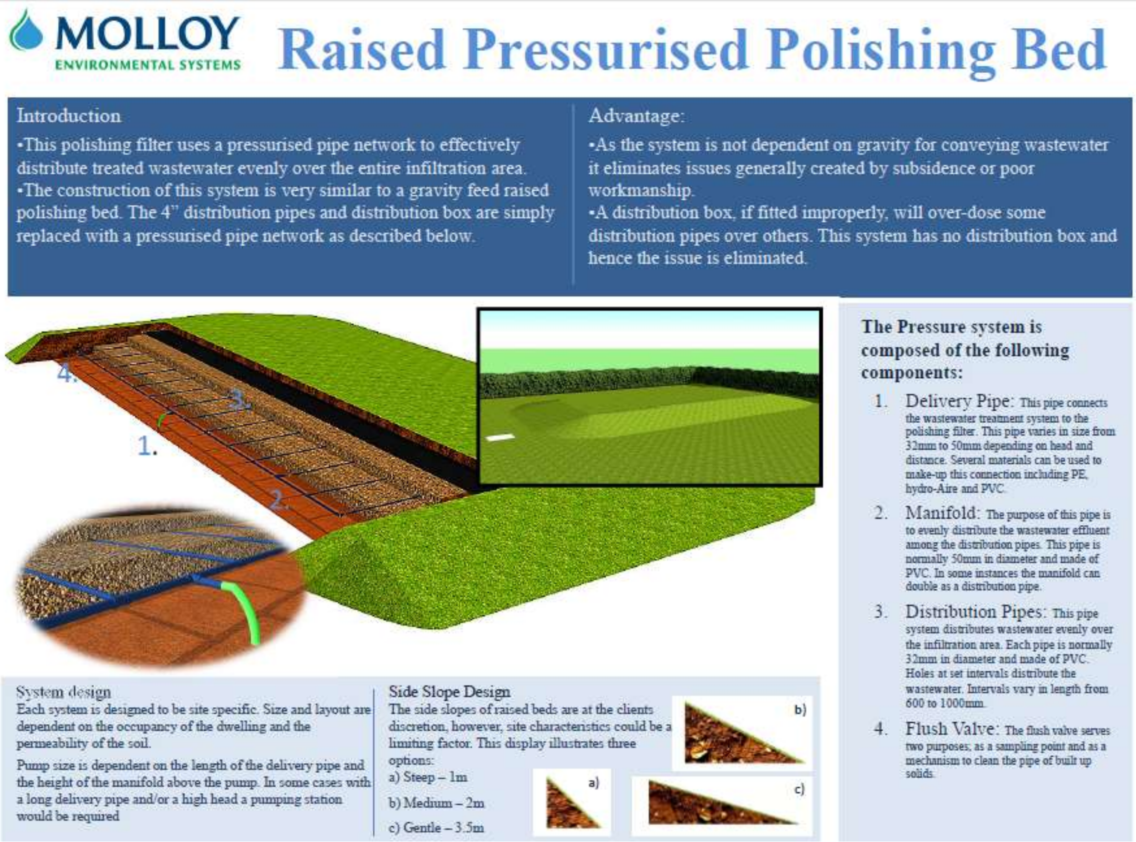


Figure 22: Data sheet on raised pressurised polishing filter bed.

Figure 23: How a sand filter is constructed.

9. Cullahill Group Water Scheme; an introduction.
Robert Meehan

The pumphouse and springs for Cullahill Group Water Scheme are located between 2 km and 3 km east-northeast Cullahill Village, which is on the N9 between Durrow, County Laois and Johnstown, County Kilkenny. The spring source is one of the the largest of eight springs in Toberboe, Graigueavoice and Newtown Townlands, all which are within 915m of each other. Their locations are shown in Figure 24.

The second largest of these eight springs forms the spring source, which has supplied Cullahill Village and its' surrounding rural area since the late 1930s. At the spring, groundwater emerges from sands and gravels along four individual subsurface conduits to collect in a circular, 0.3m thick solid concrete chamber dug into the subsoil (approximately 4m in diameter by 2.0m deep), with a solid concrete roof just above ground level. The sump and drainage channel are fenced off relatively poorly, and the overflow channel is overgrown with weeds and scrub, as recorded on a number of site visits and by the caretaker. The water is then pumped to the pumphouse which is 950m to the north-northwest.

The water is chlorinated and fluoridated at the pumphouse before flowing into a 40 m^3 capacity tank in the fenced-off area outside, before being pumped to a reservoir at Graigueavoice with a storage capacity of approximately 300 m^3 (80,000 gallons), which equates to just over 2 days storage. The chlorination tank and chemicals are stored in the pumphouse and a tap is present for raw water samples.

The entire pumphouse site area of *c*. 0.25 acres is fenced off with good quality fencing, and is partially surrounded further by a narrow belt of young forestry.

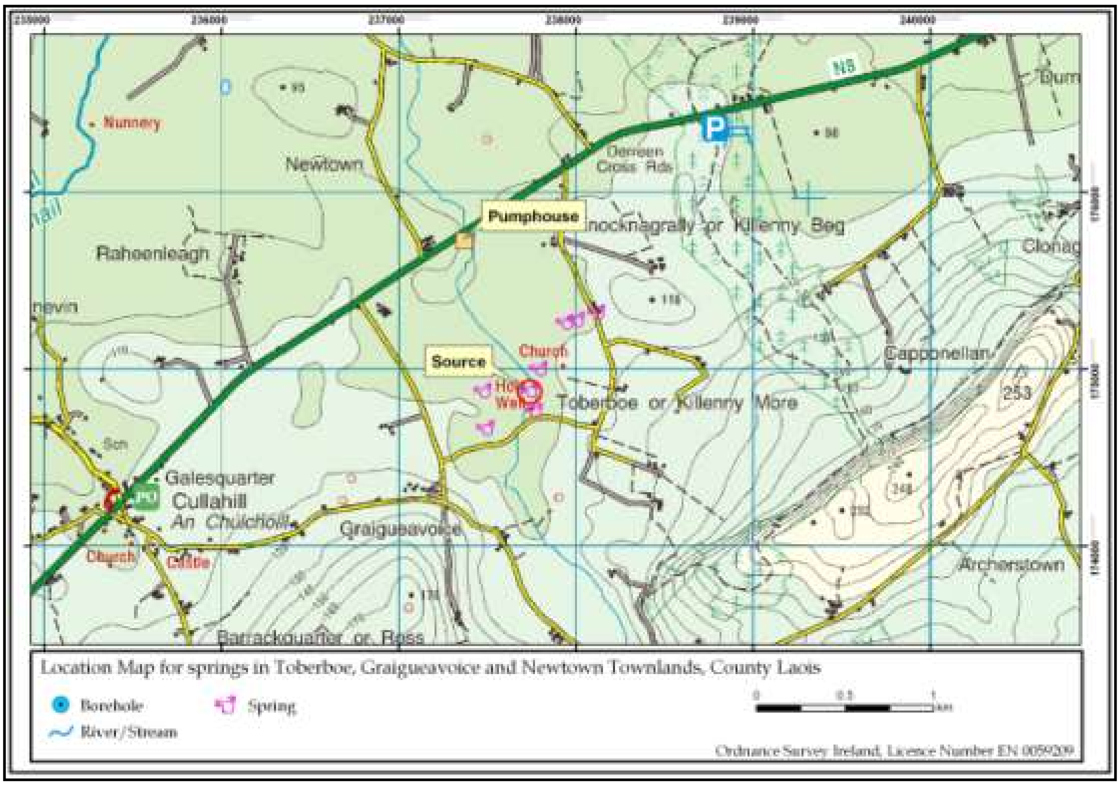


Figure 24. Location Map showing the region around Toberboe Spring(s).

Topography and Land Use

The springs are located within a wide valley gouged into the northwesternmost flank of the Castlecomer Plateau. The springs emerge at elevations between 96m and 100m OD at the boundary between higher, hummocky land to the southeast and an extensive flat-lying alluvial flat at the northwest (Figure 24). Though being generally hummocky, the land to the southeast and southwest rises gently from the valley floor, before an abrupt change in gradient at the steep backslope of the high plateau. The average topographic gradients are 1:90 to the north of the springs, 1:30 for the first kilometre to the south, and 1:7 on the high plateau backslope.

The natural and artificial drainage density in the immediate vicinity of the source area is high owing to their situation at the edge of the alluvial flat area. To the east, south and west, however, there are no surface drainage features on the hummocky terrain, but drainage ditches become common on the high plateau area. Rushes occur sporadically on these higher ridge slopes also, but are completely absent from the hummocky areas.

One stream flows through the springs' area from the south, rising at the eastern edge of Cullahill Mountain and flowing off to the northeast, before turning at Ballykealy 2 km south of the springs, where it flows northwards past them before joining the River Goul at Ballyboodin. Toberboe Spring and St. John's Well are adjacent to and flow directly into this along short channels a number of metres long, with the Farmyard, Copse and Wetland Springs conducted into it *via* a long network of surface drains, and the Pipe, Church and Newtown Springs fed into it *via* subsurface pipes.

Two small wetland waterbodies which fluctuate markedly with respect to their water levels and area between winter and summer are situated at the southwestern edge of the springs, at NGR 237460 174645 and NGR 237400 174455. The Wetland Spring rises in the northernmost of these, and it is noted that the southern wetland flows into the northern one *via* overland flow following extreme rainfall events (as seen there on 03/12/2009), with it in turn flowing *via* drains into the aforementioned stream.

Parts of the extensive alluvial flat to the north of the springs, in particular the area 500m from them adjacent to the pumphouse and the N9 road, was flooded at the start of December 2009, owing to the recent heavy rains. In contrast, the hummocky areas around the springs seem to constitute extensive areas of well drained soils upon first inspection,

Land use in the area is primarily agricultural, with the majority of the lands set to pasture for dairying (c. 80%) or used for tillage (c. 15%). Small areas of scrub, broadleaf forestry and bedrock outcrops (hosting a few small, disused quarries) also occur (5%). A number of farmyards occur in the area, with the nearest to the source spring *c.* 450 m to the east. Many of these farmyards host slatted units, milking parlours and silage pits. Grazing of areas hosting small pockets of scrub, and with bedrock at the surface, was noted to the southeast.

No major industries occur in the area. Single houses discharge to ground *via* septic tank systems and mechanical aeration systems along the base and flanks of the valley. Disused sand and gravel pits also occur to the southeast of the spring source.

Bedrock geology

According to the 1:100,000 bedrock sheets of the region (Archer *et al.*, 1996, see Figure 25), this area is underlain principally by limestones of the Ballyadams Formation, which are also described as the Dinantian Pure Bedded Limestones for the purposes of the generalised rock unit map prepared for the WFD in characterising and describing groundwater bodies in Ireland by the GSI. These rocks are crinoidal wackestones and packstone limestones, and are the classic 'Burren' type limestone,

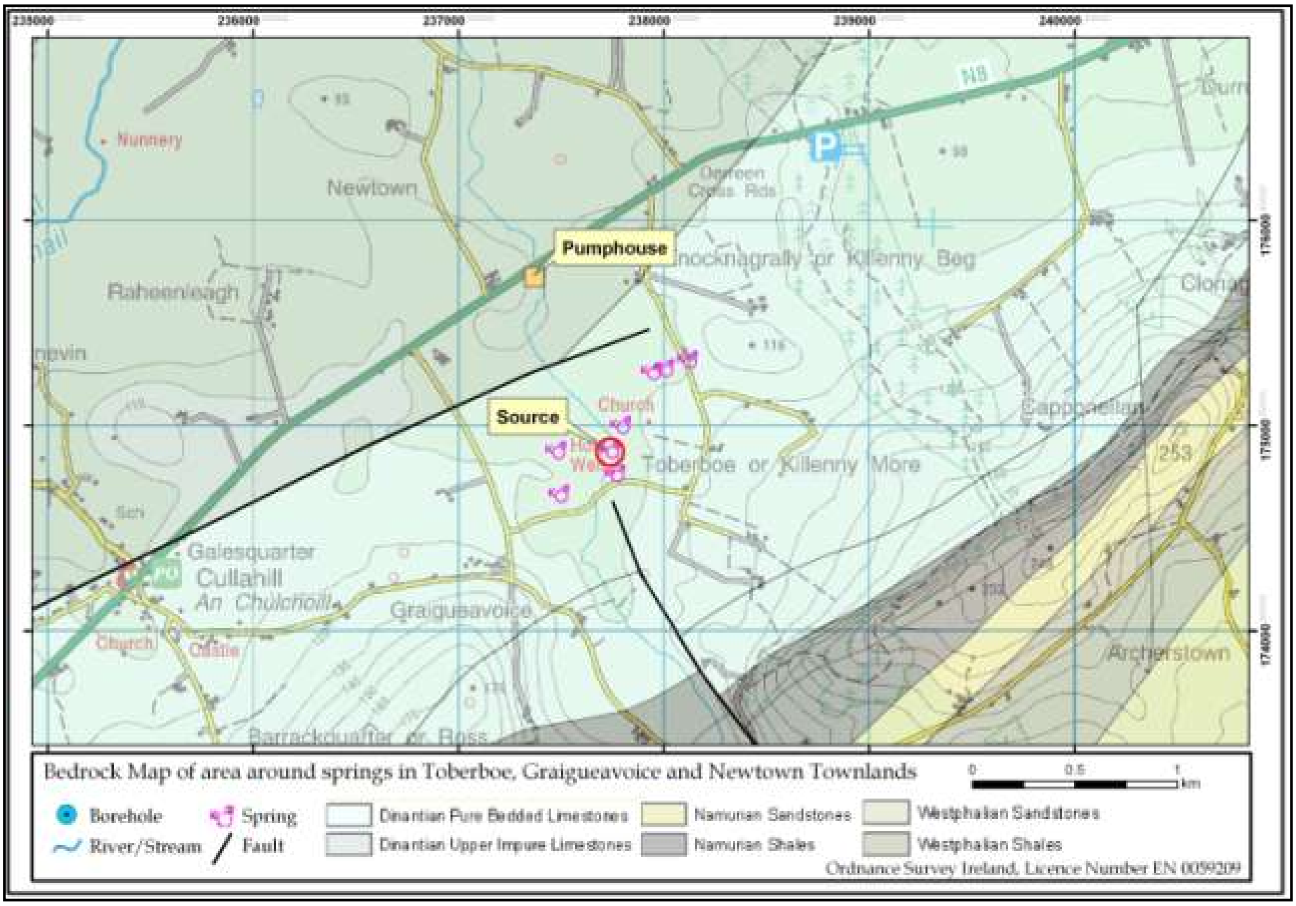


Figure 25. Bedrock geology of the area around Toberboe Spring(s).

The Dinantian Pure Bedded limestones of the Ballyadams Formation are composed of clean-bedded limestone which is generally homogenized, comminuted shelly debris, cemented by fine spar. Some oolithic and even micritic beds may occur near the base, just above the highest shales which define the top of the underlying Durrow Formation. The formation is over 200 m thick.

The Ballyadams Formation rocks outcrop rarely in the area around the springs but forms a strip between 1.5 km and 2 km wide under the subsoils, and extends along a northeast-southwest orientation by at least 4 km in each direction along the base of the high ridge. A thin strip of cherty, muddy, calcarenitic limestone of the Cloghrenan Formation then occurs at the base of the scarp to the southeast, overlying the Ballyadams Formation. This has thinner beds and more chert than the Ballyadams Formation, but is still classed as Dinantian Pure Bedded limestone.

An extensive area of Dinantian Upper Impure limestones extends off to the northwest from approximately 500 m to the northwest of the spring source. These rocks are the shaly fossiliferous and oolithic limestones of the Durrow Formation, and are partially separated from the pure limestone by a marked west-southwest to east-northeast oriented fault. Faulting has also occurred south of the springs along a north-south orientation, both within the limestones and extending into the 'Namurian' upland region further south again (Figure 2). This is only 150m - 200m from the largest of the springs, including the source itself.

A number of surface exposures of limestone were mapped during field studies conducted in December 2009. A small, disused quarries which has no current rock outcrop occurs 750 m west of the spring source. On the ridge backslope to the southeast, small outcrops occur on the farm 800m from the source, at NGR 238464 174110 and NGR 238511 174498 respectively. The bedrock units comprised thinly bedded bluish-grey, clean limestones, generally dipping less than 5^0 to the south. Adjacent to this, the landowner states (03/12/2009) that the large field at NGR 238610 174450 is known as 'The Quarry Field', having hosted old quarries and currently having bedrock within 0.3m of the surface across it's extent.

To the south and southeast of the springs by 1.25 km, and forming generally the highest ground on the steep scarp, the limestones are succeeded unconformably by Upper Carboniferous (Namurian) age shales of the Killeshin Siltstone Formation, as well as thick, flaggy sandstones of the Bregaun Flagstone Formation further west.

Subsoils Geology and Groundwater Vulnerability

The subsoils around the source comprise a mixture of coarse- and fine-grained materials. Sands and gravels and limestone tills are the dominant subsoils in the area, with more restricted areas of bedrock outcrop, lacustrine clay, alluvium and tills derived from Namurian shales and sandstones also occurring (Figure 26). In general, subsoils are relatively shallow on the high scarp south and southeast of the source, but are considerably deeper in the valley and around of the source on the more lowlying and hummocky terrain.

The area around and east of the spring source comprising the hummocky terrain is mapped on the Teagasc subsoil map as being underlain by deep glaciofluvial sands and gravels derived from limestones. These were deposited by a wide meltwater river flowing off a retreating ice margin along the valley side during deglaciation, when the ice sheets of the last Ice Age melted. From examination of gravel pit faces at NGR 237995 174565 and NGR 238160 174375, 300 m to 600m southeast of the spring source, the sands and gravels are generally deep at >5 m, with depths of over 10 m possible given the topography of the area.

A northwest to southeast-oriented esker ridge, also comprised of sands and gravels, occurs 500m to the south of the source. This extends along the lower slopes of the high ridge at Graiguavoice.

Till or 'Boulder clay' is an unsorted mixture of coarse and fine materials laid down by glacier ice during the last Ice Age. Till is the dominant subsoil type on the hummocky to gently undulating terrain west of the spring source. The till here is dominated by limestone. This gently undulating to hummocky, lowlying area of till derived from limestone extends to the southeast around Cullahill Village, as well as to the north towards the River Goul. It also occurs on the lower flanks of the ridge to the south at

Graigueavoice, and extends from the sands and gravels at the northeast towards Durrow (Figure 26).

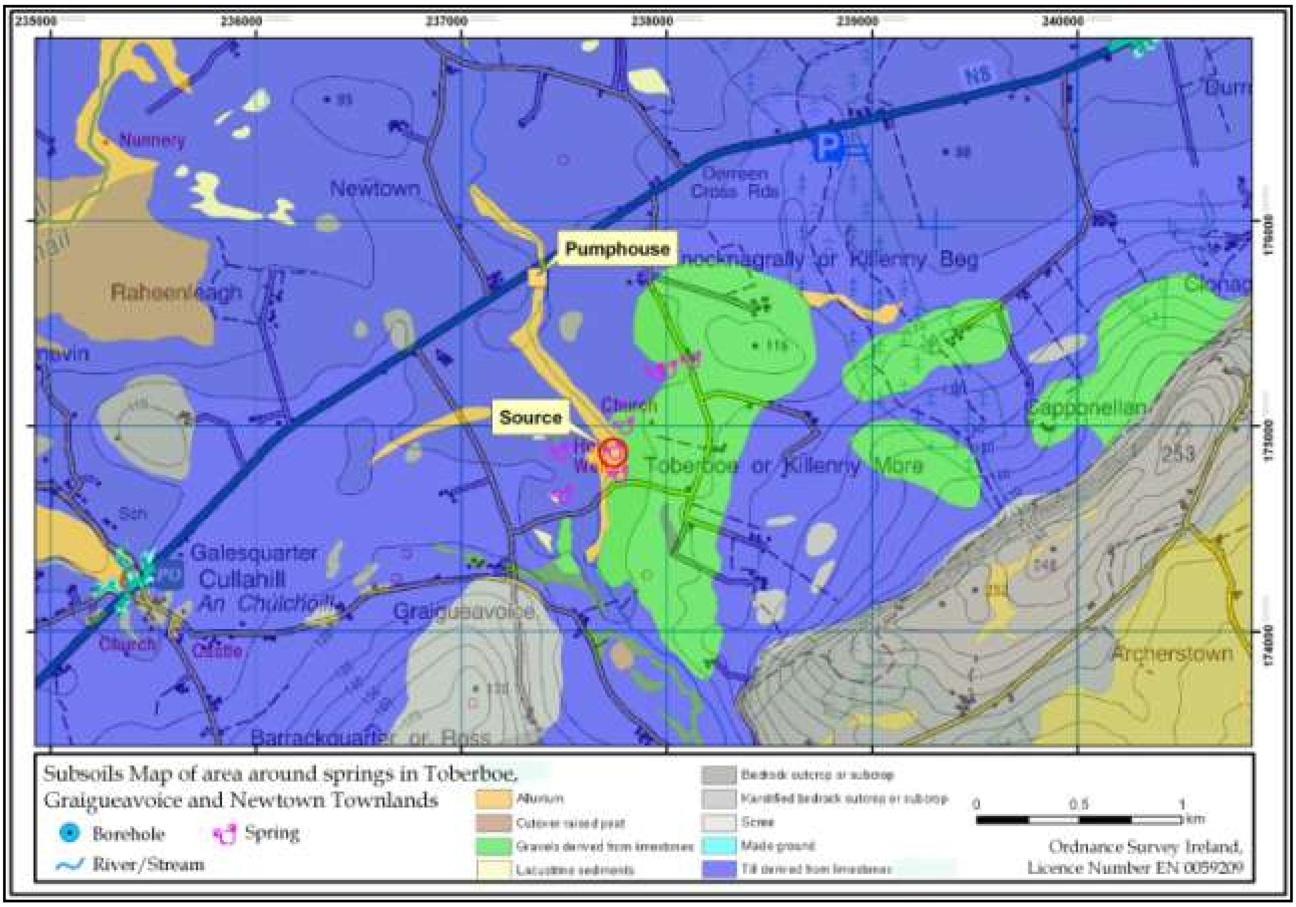


Figure 26. Subsoil Map for the area around Toberboe Spring(s). The valley is dominated by the sands and gravels (green) and till derived from limestone (blue), with a narrow strip of alluvium along the stream (orange) and much bedrock outcrop and subcrop on the flanking ridge crests (grey).

Immediately adjacent to the stream flowing south to north past the source, a long, narrow, flat, low-lying strip of postglacial alluvial deposits occur. These have accumulated from repeated flooding of the stream in this lowlying area since the last Ice Age. The alluvium material seems to be dominated by SAND but also hosts interbedded GRAVELS, and seems to overlie glaciofluvial sands and gravels, as seen in the stream sections to the north of the source.

Small areas of lacustrine CLAY flank the wetlands southwest of the spring source, at NGR 237460 174645 and NGR 237400 174455. These materials have accumulated in the hollows since deglaciation by repeated flooding there, similar to the alluvium along the stream.

To the southeast of the boreholes by 1 km, bedrock protrudes through the deep glacial and postglacial subsoils. The area north of this also forms an extensive area of bedrock subcrop (within 1 m of the surface). Bedrock outcrop and subcrop is also common on the summits of the upland ridges to the south and southeast.

In and around Cullahill Village, much of the subsoils have been covered by 'Made' ground; built land and concreted/tarmacadamed areas. This 'Made' material is underlain by shallow bedrock and till, similar to the areas immediately adjacent to it.

The soils on the sand and gravel areas are dominated by 'dry' soil types: typically well drained deep mineral soils of brown earths and grey brown podzolics, and well drained shallow brown earth soils (Conry, 1974, 1987; Gardiner and Radford, 1980). The tills derived from limestone in the region are also characterized by generally well drained grey brown podzolic soils, whereas the Namurian ridges to the south and southeast are often characterized by poorly drained gleys. Within the areas of bedrock outcrop/subcrop and alluvium, the soils are widely variable in their depths and drainage status.

Within the study area of the source, the only subsoil exposures discovered were in gravel pits within the sand and gravel areas.

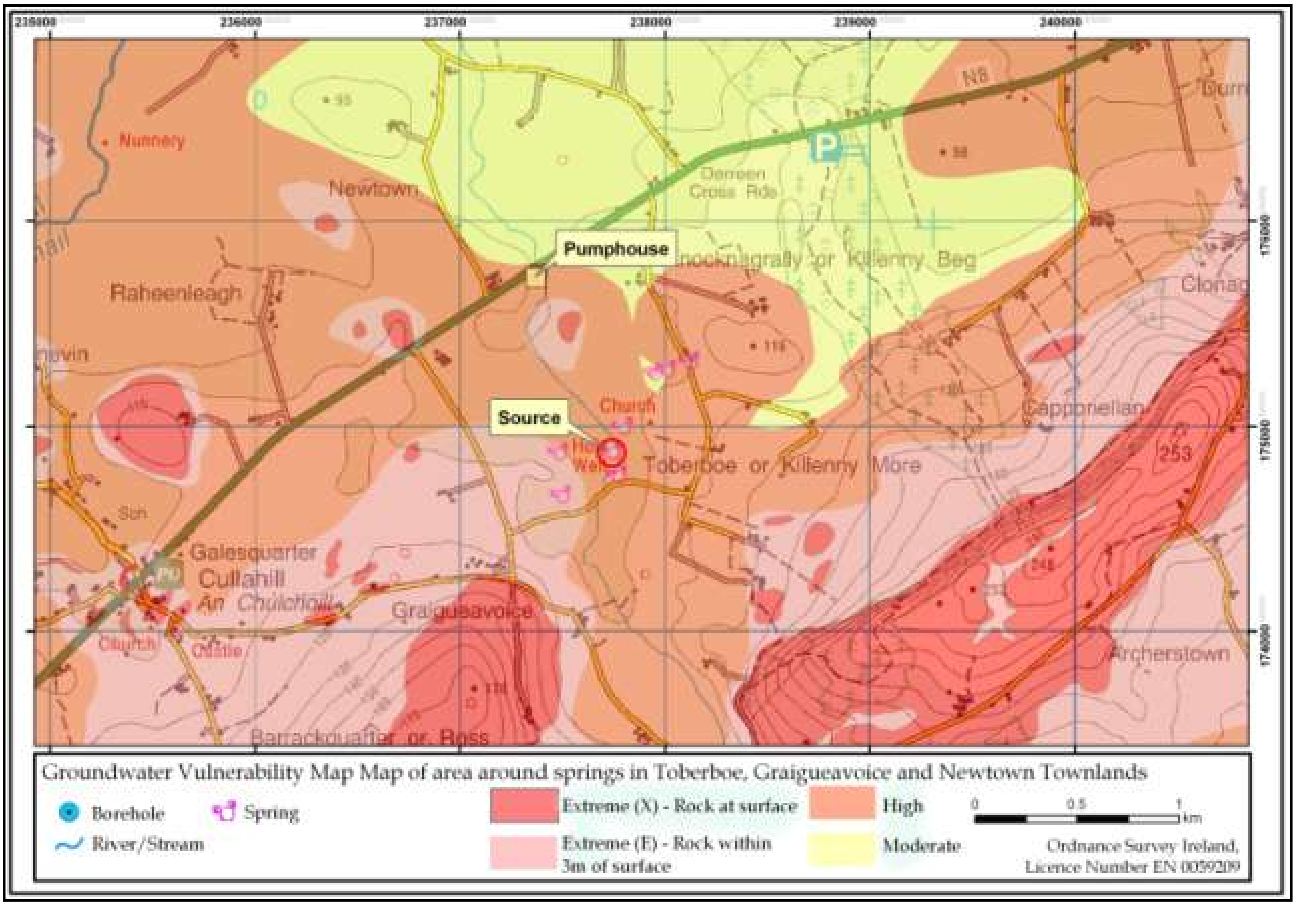


Figure 27. Groundwater Vulnerability Map for the area around Toberboe Spring(s).

Groundwater levels, flow directions, and gradients.

All eight springs emerge either in or at the edge of flat, lowlying areas: none emerge from bedrock and all pass through (interpreted) relatively deep subsoil. In the majority of the flat area around the springs a high density of artificial drainage is required in order to utilise the land, which is mainly grazed. There is also a relatively high natural drainage density in this lowlying area around Toberboe Spring(s). The land to the north of the springs is flat, covered in rushes and saturated, and was flooded following extreme rainfall on

03/12/2009. As stream sections through this zone expose sands and gravels and gravelly alluvium, it therefore seems that this area is a discharge zone.

The emergence of the springs, the high natural and artificial drainage densities and the rushes/flooded areas therefore generally indicate a shallow water table in the area around the springs (*i.e*. close to the surface).

The fact that seven out of the eight springs goes dry in summer, and given that the source diminishes to a very low flow during these times also, suggests that the springs are an overflow mechanism for the regional groundwater flow system. From this, in order to attain reliable groundwater flow data and in the absence of specific, reliable depth to bedrock or borehole data in the immediate vicinity of the springs, the measurement of groundwater levels in wells around the source was required. This was completed using GPS Total Station on 12/01/2010.

The results of the groundwater level monitoring are shown in Figure 28. Four out of the five wells dipped and positioned were within the Ballyadams Formation bedrock; the most southerly was in bedrock of the Cloghrenan Formation. No wells were pumping at the time; only two were still in use.

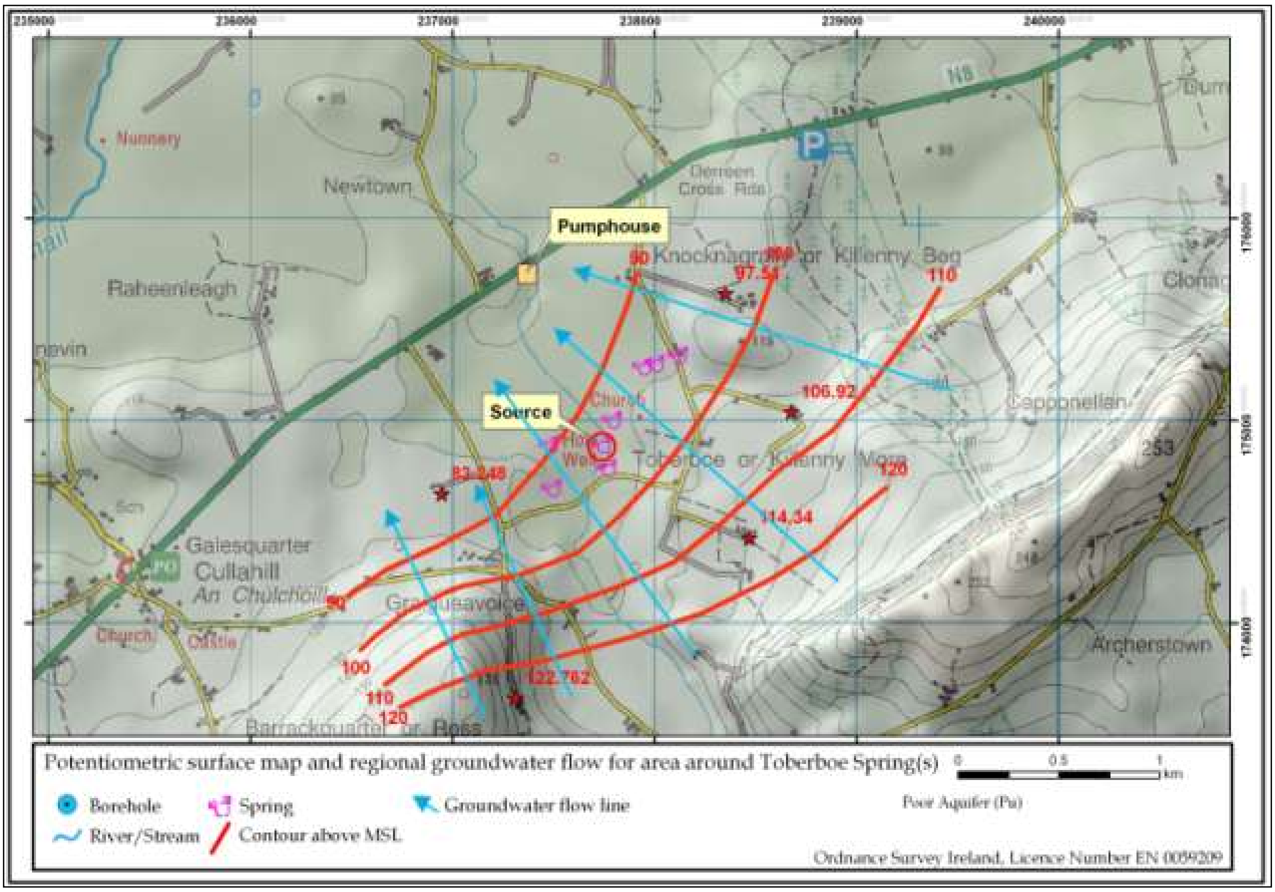


Figure 28 Potentiometric surface map of the area around Toberboe Spring(s). Groundwater elevations at individual wells are shown in metres OD. The general flow gradient along flow towards the northwest is clearly seen.

On the lower flanks of the ridge to the east, where depth to bedrock is relatively shallow, the water table is c. 4m from the surface. The water table deepens moving westwards into the sands and gravels, at 8.57m bgl in the northern portion of this area (and also emerging as an overflow around the springs). To the south of the springs, in the Cloghrenan Formation bedrock, the water table is at 10.02m bgl and to their west in the till the water table is at 17.32m bgl.

The sequence of water levels to a common datum and the resultant contour map, when allied with topographical data, shows that the regional-scale groundwater table demonstrates a regular groundwater gradient of approximately 0.022 from southeast to northwest. Groundwater is therefore expected to flow from southeast to northwest across the area. This flow direction therefore broadly focuses toward the River Goul discharge area, mirroring to a large degree the valleys' macro- topography.

The stream flowing off the high ridge to the south catches the surface water flow from the Namurian-bedrock upland, reflected in the conductivity measurement of 402 µS/cm at Ballykealy (NGR 238341 173208) on 03/12/2009. The relatively low conductivities along the stream (maximum of 574 µS/cm in the vicinity of the springs) suggest that this stream is largely fed by surface water along it's length, and therefore seems to be largely removed from the groundwater regime, excepting around the springs.

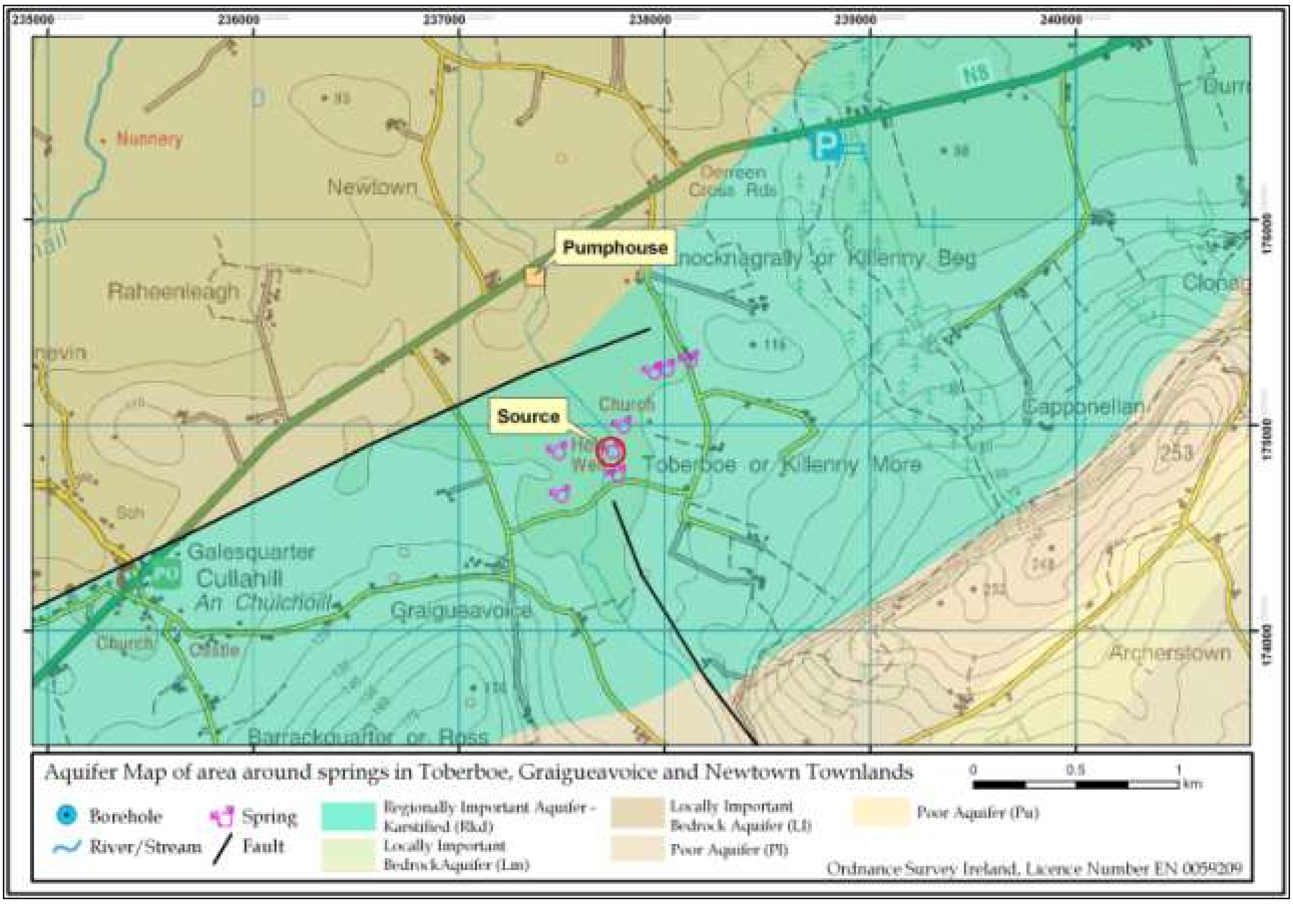


Figure 29 Aquifer Map of the area around Toberboe Spring(s). The site overlies a Regionally Important Karstified Aquifer characterized by diffuse flow.

Delineating a Source Protection Area

The Outer Protection Area (SO) is bounded by the complete catchment area to the source, or the zone of contribution (ZOC). This is defined as the area required to sustain abstraction from the springs considering long-term recharge. Given that the abstraction from Toberboe Spring itself is less than half the considered ‘mean’ discharge from the spring, it is felt that the delineated ZOC also covers a potential increase in abstraction from the spring source by more than 50%.

The ZOC is controlled primarily by (a) the total discharge, (b) the groundwater flow direction and gradient, (c) the subsoil and rock permeability and (d) the recharge in the area. The shape and boundaries of the ZOC were determined using hydrogeological mapping, water balance estimations, and conceptual understanding of groundwater flow. The ZOC is shown in Figure 30 and its’ boundaries are described below along with associated uncertainties and limitations.

The southeastern boundary is based on the topographic divide along the topographical high on the ‘Namurian’ ridge in Ballykealy and Aharney Townlands, that is assumed to coincide with the groundwater divide.

The northeastern and southwestern boundaries are based on the assertion that the springs are ‘overflows’ to the regional groundwater flow as they go dry in summer, and the assumption that groundwater cannot flow to the source from the majority of the area to the east and south them, as the contours drawn from water level and topography data mean that flow from this area is directed alongside the springs. This means that recharge to the Griagueavoice ridge will flow to the northwest, west of all the springs.

For the **northwestern boundary** it is assumed that the water down-gradient of the springs will not flow back to contribute to their discharge. Therefore the boundary delineates the groundwater flow down-gradient of the springs, which will be outside the ZOC. It is based on the direction of flow suggested by the water level and contouring data, and the general trend of surface water drainage patterns. A buffer of 30m downgradient of the springs is incorporated into this boundary.

Based on a an estimated ‘mean’ discharge of 23.6 l/s (2,029 m^3/day) and the estimated recharge of 362 mm/year, a zone of contribution of 2.04 km^2 in area is calculated. This is shown in Figure 30 and is delineated as the ZOC.

If we take into account the topography of the area south and southeast of the source, and using the topographic catchment as a ‘potential’ ZOC, the area covers 4.18 km^2. Taking into account the area within this which is directly ‘up-gradient’ using the regional groundwater flow data, means an area of only 2.25 km^2 is delineated. This has then been further refined by taking off the sharp corners of the area on the Namurian bedrock topographic high at the southwest and southeastern extremes of the area.

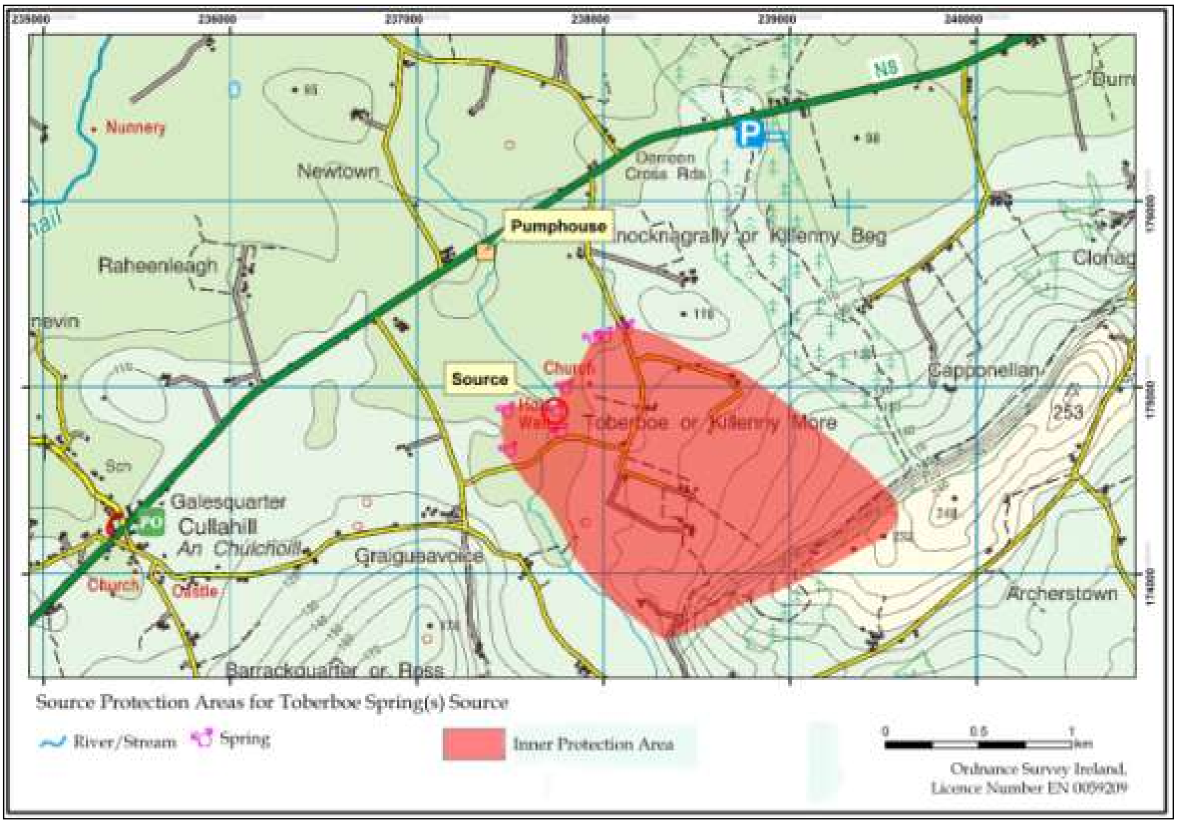


Figure 30 Delineated Source Protection Areas for the Toberboe Spring(s) Source. This assumes no sinking stream.

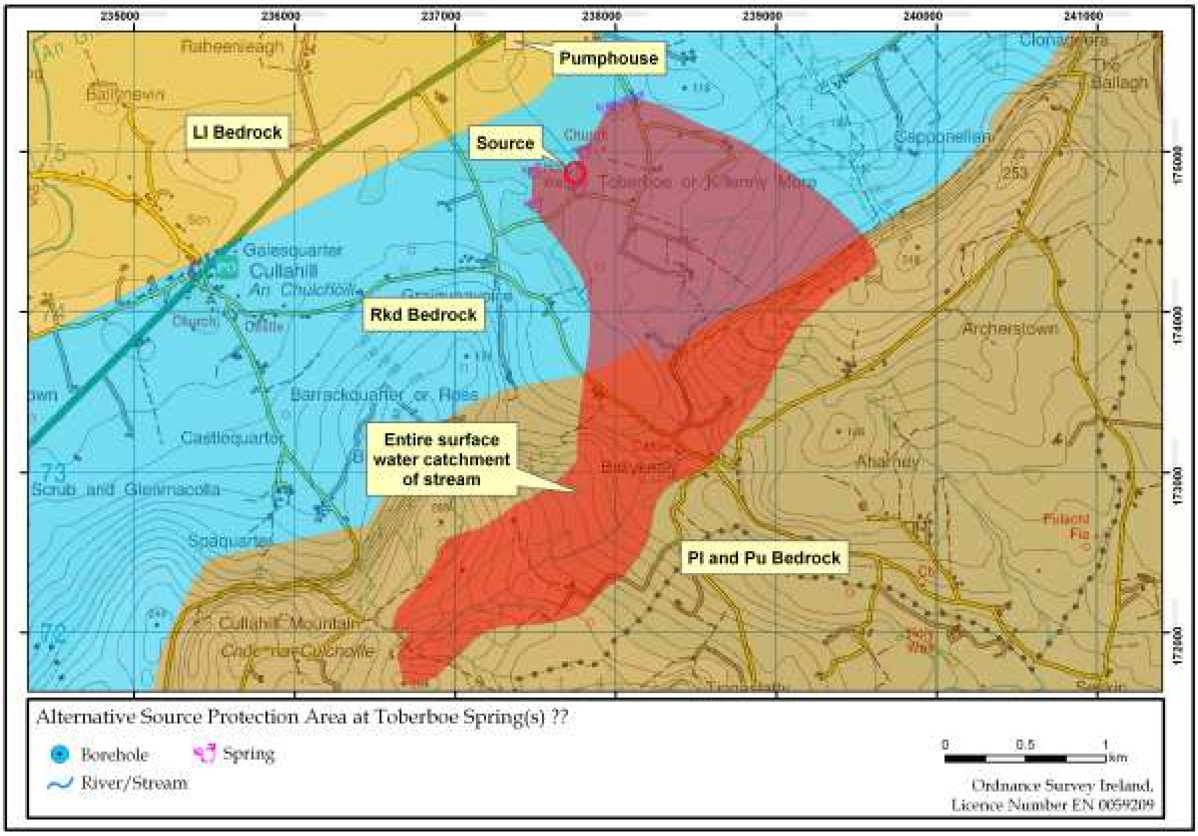


Figure 31 Alternative Source Protection Area for the Toberboe Spring(s) Source ? This ZOC assumes that the stream sinks.

10. Investigation into the Sources and Pathways of Nitrate Contamination in a Group Water Scheme in Cullahill, Co. Laois

Roisin Dowd Smith, Catherine Coxon and Taly Hunter Williams

Background and methods

The Toberboe spring supplies water to the Cullahill Group Water Scheme (GWS). This GWS supplies 250 m^3 of water per day to 100 connections in the village of Cullahill and surrounding rural area, 80 of which are house only. The water at this spring comes from a karst limestone bedrock aquifer. Since the beginning of 2014, there has been an issue of elevated nitrate levels in the drinking water, coming from the Toberboe spring. Nitrate levels have stayed consistently above the Groundwater threshold (S.I. 9/2010) value of 37.5 mg/L NO_3, which is set out under the Groundwater Regulations (S.I. 9/2010). Since the beginning of 2016 levels have remained above the European Drinking Water Limit (EC/12/2014) of 50 mg/L, set out under the European drinking water regulations (S.I. 122/2014), with a peak of 72.2 mg/L recorded on the 29/01/2016.

The aim of the project was to identify the main sources and pathways by which excess nitrate is entering the aquifer and subsequently contaminating the group water scheme's supply. This project was carried out as an MSc course project (Dowd Smith, 2016) from May 2016-September 2016. It was carried out in conjunction with Trinity College, the National Federation of Group Water Schemes (NFGWS) and Geological Survey Ireland (GSI), following on the report by Meehan *et al.* (2010) on the zone of contribution for this supply. Some of the findings are summarised in a recent Irish Groundwater Newsletter article (Dowd Smith and Flock, 2017).

The project involved field-mapping, existing data compilation and water sampling, as well as interviewing the local landowners. Water samples were collected from both groundwater and surface water sources across the Zone of Contribution (ZOC), and chemical analyses and statistical analyses were performed. A wide range of cations and anions was examined and additional analyses of contaminant source markers were carried out by other researchers from TCD and NUIG, including tests for sweeteners, sterols and stanols, and fluorescent whitening compounds, and Microbial Source Tracking (MST).

Main Findings - Identification of Karst Features

Before this study, the nearest recorded karst features to this ZOC (apart from Toberboe and neighbouring springs) were three swallow holes at Seskin, 4.5 km southeast of Toberboe and approx. 2.4 km beyond the Toberboe ZOC boundary (Meehan *et al*,. 2010).

During field surveys in this study, a swallow hole was identified by the landowner in a field 1.7 km east-southeast of Toberboe spring, at the eastern extremity of the ZOC. This is fed by the overflow from an open dug well located at the base of the scarp, close to the boundary between the Namurian shales and the Dinantian Pure Bedded Limestone. The water flows along a drainage ditch and is piped to a swallow hole in the field; the swallow hole is no longer visible at the ground surface due to infilling following culverting of the water.

Figure 32. Aerial photograph of the ZOC.

There is also a possibility that the stream flowing towards the ZOC at the other end of the scarp, south of Toberboe, may lose water to the karst aquifer. This stream rises on Cullahill mountain and flows off the Upper Carboniferous rocks onto the Pure Bedded Limestone towards the springs and on north of the ZOC to the river Goul. During July and August 2016 following prolonged dry weather the stream had dried up and no water was flowing off the Upper Carboniferous uplands onto the limestone. However, earlier in the summer, in June 2016, there was measurable flow in the stream at Ballykealy, upslope of the Pure Bedded Limestone, yet no flow immediately upstream of the springs. Therefore, water must have been lost in the interim stretch, but it is not known at present whether this involved infiltration into gravels or to the karst limestone. The possibility that this stream may contribute flow to the karst limestone within the ZOC merits further investigation.

There is also a swallow hole 350 m to the northwest of the westernmost springs within the ZOC, which captures flow from the springs. The springs were not observed to be flowing when visited in July 2016.

Main Findings - Nitrogen Inputs

The land-use in Cullahill is primarily agricultural with a majority being used for dairying (80%) and tillage (15%) and small areas of forestry (5%) (Meehan *et al.*, 2010). At present, there are no major industries occurring in the area. Figure 32 shows an aerial view of the entire catchment.

There are three farms in the catchment. These are all dairy farms and they would each be relatively large, with over 100 cattle in each farm. From carrying out farm surveys with each of the three farmers the total nitrogen input to the ZOC from each farm per year was calculated. Table 3 gives a breakdown of the different forms of nitrogen inputs along with the total nitrogen input, from agriculture for the ZOC.

Table 3: Nitrogen input figures for the three farms in the ZOC

Farms	Inorganic Fertiliser Grazing (kg N/ha/yr)	Inorganic Fertiliser Silage (kg N/ha/yr)	Livestock Densities (kg N/ha/yr)	Farm Total (kg N/ha/yr)
A	108	102.6	111	321.6
B	100	97.2	101.54	298.74
C	97.2	91.8	128.35	317.35
				937.69/3
Average per farm				312.56 x 200ha
Catchment Total (kg N/yr)				**62,513**

Not all the agricultural nitrogen input to the ZOC will be utilised by plant growth: although the majority will be retained in the soil layers and taken up by grass growth and grazing, studies elsewhere suggest that in freely draining soils 10-20% of agricultural N inputs may be leached. This would mean loss of nitrate to groundwater of approx. 6,250-12,500 kg N/yr (corresponding to 31-61 kg N/ha/yr).

There are 17 houses in the ZOC, each of which has a septic tank. The annual figure for total N discharge per person as calculated by Gill and Mockler (2016), is 4.15 kg N/person/yr. From the most recent census, in 2011, it found there to be an average of 2.18 people per Irish household. By multiplying 4.15 kg N per household by 2.18 people per household by 17 households, the annual amount of N discharge to the ZOC from septic tanks is calculated as 153.8 kg/N/yr. Note that this assumes that all N discharged from the septic tank reaches groundwater and the figure is therefore an over-estimate: for systems with properly constructed percolation areas a significant amount of N may be retained in the soil zone and taken up by plant growth.

These initial estimates suggest that agricultural N inputs to the ZOC are about 40 to 80 times greater than the maximum potential input to the ZOC from the septic tank systems. While the figures should be treated with caution and further investigations of agricultural N inputs are desirable, agriculture has a potentially far greater nitrogen input compared with septic tanks.

Inorganic hydrochemistry and nitrate concentrations

Chemical analyses of samples from Toberboe spring and other locations within and adjacent to the ZOC (additional springs, private wells and streams) were carried out at 14 locations in June and 16 locations in July 2016. The results from July are summarised in Table 4.

Table 4: Mean, min and max values for all the tested chemical parameters for July. Red indicates parameters for which there were private wells that exceeded the Drinking Water Limit (EC/12/2014) and yellow indicates parameters for which there are sites that exceed that Groundwater threshold (S.I. 9/2010)

Chemical Parameter	Units	Toberboe spring	All sites Mean	ZOC Min	Max
Alkalinity*	(mg/L $CaCO_3$)	340	291	98	384
Chloride	(mg/L Cl)	21.2	23.5	12.2	46.7
Sulphate	(mg/L SO_4^-)	14.0	14.4	9.1	23.6
MRP*	(mg/L P)	0.005	0.02	0.004	0.09
Nitrate	(mg/L NO_3^-)	54.5	38.7	2.8	62.9
Ammonia	(mg/L NH_4^+)	<0.005	0.02	<0.005	0.13
Nitrite	(mg/L NO_2^-)	<0.005	0.03	<0.005	0.2
Calcium*	(mg/L Ca)	128	108.5	38.9	146.2
Iron	(mg/L Fe)	0.014	0.03	0.01	0.15
Potassium*	(mg/L K)	5.5	5.0	1.1	12.9
Magnesium*	(mg/L Mg)	13.4	11.6	3.9	18.8
Manganese	(mg/L Mn)	<0.001	0.003	<0.001	0.021
Sodium	(mg/L Na)	8.0	10.2	6.3	17.9
pH	n/a	7.10	7.36	7.03	8.16
Conductivity	(µS/cm)	795	692	286	944
Turbidity	NTU	0.36	0.9	0.007	4
DOC	(mg/L)	1.13	1.37	0.38	3.02
Colour	PtCO	3	13.06	2	42

*Chemical parameters, for which there are no Drinking Water Limits (EC/12/2014)

The water quality in the area is classified as hard to very hard, with a calcium-bicarbonate chemical signature. Nitrate is the only parameter to breach the drinking water limit. In June 2016, three private wells had nitrate above the groundwater threshold (S.I. 9/2010) of 37.5mg/L, and in July 2016 seven private wells had nitrate concentrations greater than this threshold and three of these wells were above the Drinking Water Limit (EC/12/2014). There are elevated levels of ammonia, potassium and sodium at some sites, suggesting the presence of localised organic contamination at some locations.

Figure 33 shows a frequency histogram of the distribution of nitrate concentrations at all sampling sites, surface and groundwater, in July 2016. It can be seen that there is a wide range of nitrate values, but with a substantial proportion close to or above the drinking water limit.

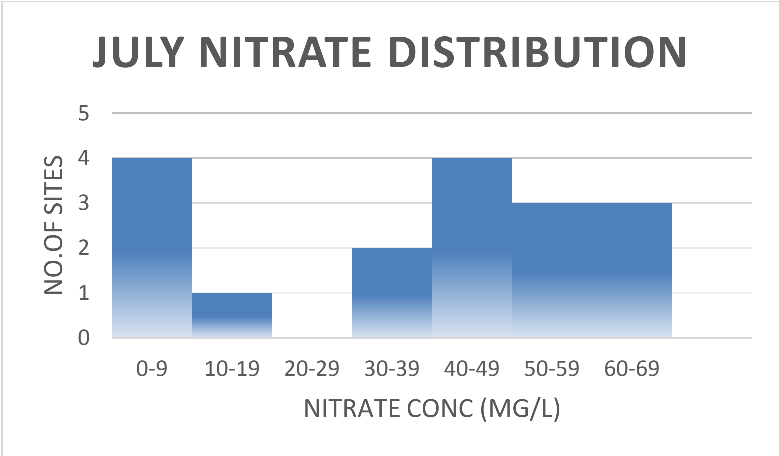


Figure 33: Frequency histogram representing the distribution of nitrate concentrations in July 2016

Analysis of nitrate in wells across the ZOC did not show the expected relationship of increasing nitrate with increasing groundwater vulnerability. The highest concentrations were found in areas of high vulnerability, whereas the lowest nitrate concentrations were found in areas of X extreme vulnerability at the southern edge of the ZOC, as can be seen from Figure 2.3. It is thought that this spatial distribution reflects variations in land use, with more intensive agriculture in the high vulnerability areas. Therefore, in this ZOC, where the soils are generally freely draining, source factors are more important than pathway factors in controlling groundwater nitrate concentrations.

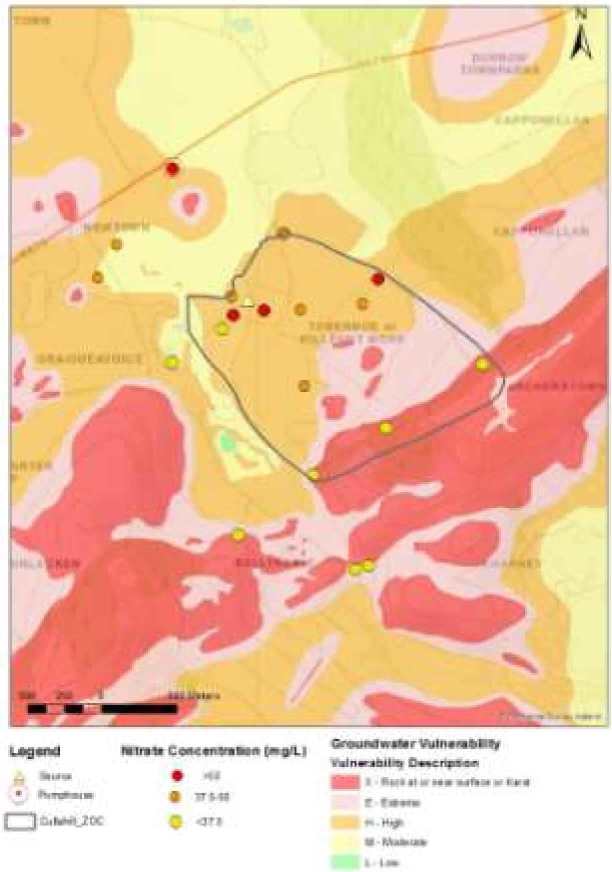


Figure 34. Groundwater vulnerability map showing nitrate concentration ranges for the sampling sites.

An alternative approach to that given in Table 2.1 for estimating N inputs to the ZOC is to use nitrate concentration at the springs and estimated mean spring flow. This gave an approximate load of N discharging from the spring of 7,702 kg N/yr. The basis of this simple calculation is as follows:

- Mean nitrate concentration at Toberboe = 55 mg/L NO_3
- Estimated natural background concentration = 8.7 mg/L NO_3 (Tedd *et al*., 2017)
- Additional nitrate above natural background = 46 mg/L NO_3 = 10.4 mg/L N or 10.4 g/m^3 N.
- Estimated mean spring flow = 2,029 m/day (Meehan *et al*., 2010) = 740,585 m^3/yr
- Estimated load of N discharged from the spring per year is 10.4 g N/m^3 x 740,585 m^3/yr = 7,702,084 g N /yr or 7,702 kg N/yr.

This estimate is of the same order of magnitude as the estimated agricultural N leaching losses presented in section 2.1. The load corresponds to leaching losses of approximately 38.5 kg N per hectare per year (12% of estimated N inputs).

Figure 35 shows the relationship between rainfall and nitrate from January 2015 to September 2017. As can be seen from the graph, nitrate concentrations consistently stayed above the 50mg/L drinking water limit (S.I. 122/2014) for most of 2016, and only started to drop below this level at the beginning of 2017.

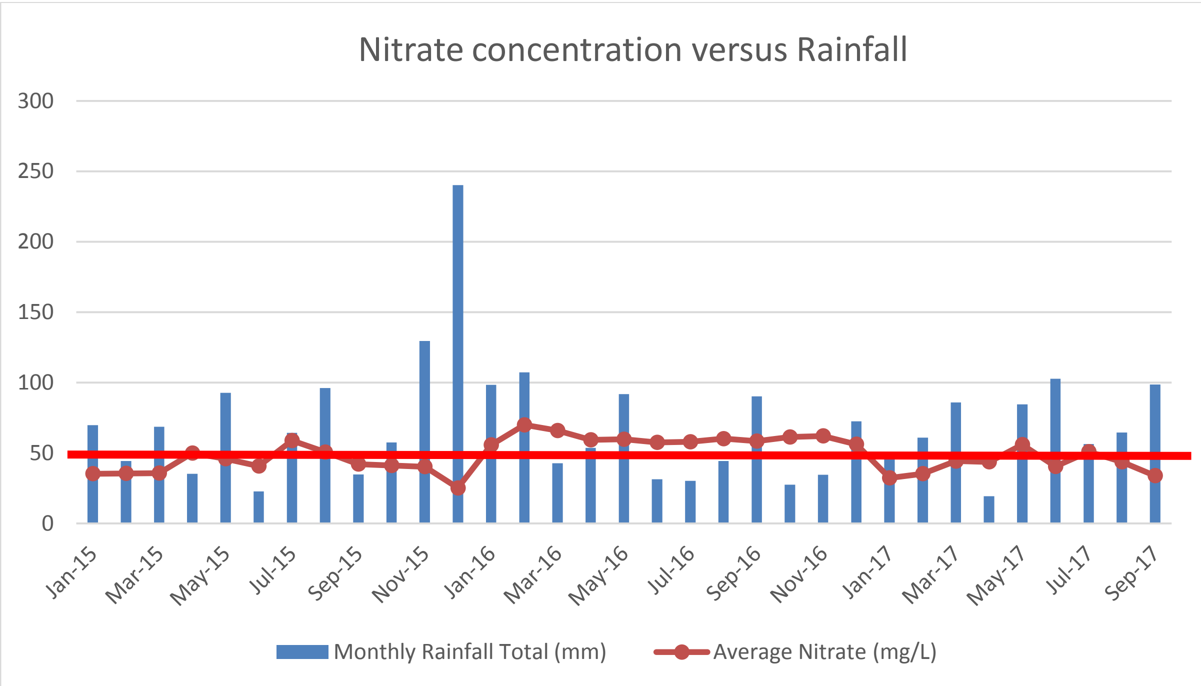


Figure 35. Nitrate concentrations versus rainfall for Jan 2015 to Sep 2017. Red line indicates the 50mg/L drinking water limit. With thanks to Laois CoCo laboratories for providing the nitrate concentration data.

Microbial Results

Table 5 provides the counts of *E. coli*, total coliform bacteria and *Clostridium perfringens* that are present in the raw water at Toberboe spring and private wells around the ZOC.

For the Toberboe spring (raw water pre-treatment), there was 1 count of *E. coli* present in June, and the *E. coli* count of 47.2 per 100ml in July is very high and gives a strong indication that faecal matter is present. No *Clostridium perfringens* were detected.

Table 5: Microbial identification results. Values in red are above the acceptable limits

Month	Sample Site	*E. coli* (MPN/100ml)	Total coliform bacteria (MPN/100ml)	*Clostridium perfringens* (cfu/100ml)
May (13/05/16)	**Toberboe Spring**	<1	**4.1**	<1
June (01/06/16)	**Toberboe Spring**	<1	**9.1**	<1
June (29/06/16)	**Toberboe Spring**	**1**	**26**	<1
	A4	<1	<1	<1
	A16	<1	<1	<1
	A18	<1	**1**	<1
July (11/07/16)	A2	<1	**382.2**	<1
	Toberboe Spring	**47.2**	**103.6**	<1
	A4	<1	<1	<1
	A15	<1	<1	<1
	A16	<1	**13.5**	<1
	A17	<1	**2**	<1
	A18	<1	**23.5**	<1
	A19	4.1	**145.5**	<1

Contaminant indicator parameters

Microbial Source Tracking

Microbial source tracking using DNA assays was carried out on samples from Toberboe and other selected sites in the ZOC by Dr. Maria Barrett, NUIG. The purpose of this work was to distinguish DNA from bacteria with human hosts from DNA from bacteria with bovine (*i.e.* cattle) hosts.

All the sample sites, including Toberboe spring (A3), have higher human bacterial DNA counts compared with bovine bacterial DNA. A8, an open well, has the highest count of human bacterial DNA present and the highest count of bovine bacterial DNA. Cattle are occasionally present in the field where this open well is located.

Table 6: DNA microbial source tracking results from 29th June 2016

			BacHum Detected		BacBov Detected	
Sites	*E. coli*	Coliform Bacteria	Concentration (copies/L)	Standard Deviation	Concentration (copies/L)	Standard Deviation
A3	1	26	2.39E+03	0.00E+00	1.95E+02	0.00E+00
A8	158	2419	3.16E+04	0.00E+00	2.61E+02	2.35E+01
A16	<1	23	2.39E+03	0.00E+00	1.95E+02	0.00E+00
A18	<1	37	4.23E+03	1.93E+01	1.95E+02	0.00E+00

Sterols and Stanols

Analyses of sterols and stanols, which are potential markers of human and animal waste contamination, were carried out on samples from Toberboe by Dr. Donata Dubber, Department of Civil, Structural and Environmental Engineering, TCD.

It can be seen from Table 7 that four phytosterols were present in the water samples collected in May and/or July. Stigmasterol and Sitosterol were present in significant quantities above the LOD. Campesterol was present in levels only slightly above the LOD in both May and July.

The water samples in both May and July did not test positive for many animal sterols, which is a positive sign in terms of water quality. Cholesterol and cholestantol were detected in the May sample; however, the July sample had no detections of any animal sterols.

Table 7: Sterol results, with cholestane as the internal standard, performed on the Toberboe spring on the 13th May and 11th July 2016

Sterols	May	July	LOD (μg/L)	LOQ (μg/L)
Animal Sterols				
Coprostanol	NF	NF	6	10
Epi-coprostanol	NF	NF	1.5	2.5
Cholesterol	XX	NF	19.83	33.05
Cholestanol	X	NF	5.4	9
Phytosterols				
24-ethyl-coprostanol	NF	NF	4.8	8
24-ethyl-epi-coprostanol	NF	NF	5.4	9
Campesterol	X	X	6.6	11
Stigmasterol	XX	XX	7.2	12
Sitosterol	XX	XX	12	20
Stigmastanol	X	NF	5.4	9

NF means the sterol was not found. All X relate to sterols found that were very close to the detection limit. All XX refer to sterols that were found above the LOD.

Analyses for fluorescent whitening compounds, which are markers of septic tank effluent (arising from detergents), were also carried out on samples from Toberboe on three occasions by Dr. Donata Dubber, but no such compounds were detected (photodecay experiments indicated that fluorescence in the samples was attributable to natural organic matter).

Synthetic organic compounds, including artificial sweeteners

Analyses for synthetic organic compounds, which are potential septic tank effluent markers, were carried out using HPLC/MS on samples from Toberboe spring from May and June 2016 by Dr. David O'Connell, TCD Department of Civil, Structural and Environmental Engineering, at the Teagasc Ashtown Food Research Centre. Eight compounds were investigated (five artificial sweeteners, caffeine and two pharmaceuticals). Concentrations of each compound were below the detection limit of 25 ng/L except for the sweetener Acesulfame, which was detected on both occasions at very low concentrations close to the detection limit (approx. 26-29 ng/L).

Conclusion

Carbonate aquifers, which underlie this ZOC, are particularly vulnerable to an array of different human impacts due to the presence of karst features such as swallow holes and sinking streams.

The chemical analyses show that groundwater contamination exists in the ZOC to varying degrees. The detection of *E. coli* at the Toberboe spring indicates that either human or animal waste is entering the spring. The presence of certain septic tank markers, sterols and sweeteners, as well as the detection of human bacterial DNA in the Toberboe spring, confirm that there are traces of septic tank discharge in the ZOC. Although there is a larger amount of human bacterial DNA present in the Toberboe spring, there is bovine bacterial DNA present too.

The groundwater vulnerability is extreme–high in most areas of the catchment. This results in there being a rapid transit time down to the aquifer from the soil zone, as well as a high leaching potential to surface waters via the underground pathway.

The calculations of nitrogen input to the ZOC from agriculture and septic tanks indicate that agriculture has much greater nitrogen inputs than septic tanks, tentatively estimated as over 40 times greater. Part of the reason why agriculture is having such a large impact on the ZOC is due to the highly vulnerable nature of the catchment.

Recommendations

Farms in areas that have shallow, freely-draining soils often have ideal conditions for good grass growth, which is essential for effective dairy farming (Huebsch *et al.*, 2013). Farms in catchments such as those in Cullahill, where farming activities outweigh dwellings, have the greatest capacity to effect positive groundwater quality changes by implementing changes in farm management. This could be achieved through assistance for improved nutrient management plans.

It is important to ensure the regular maintenance of possible point sources of pollution such as farmyards, slurry stores and silage effluent. During site investigations, there were no observed issues with any of these sources, but as they have the potential to release large amounts of contaminants into the environment, it is important they are operated and maintained correctly.

It is also advised to ensure that steps are taken not to spread fertiliser or slurry onto land surfaces that are close to a spring or near any karst features such as swallow holes or sinking streams, or near to a borehole used for drinking water. The Good Agricultural Practice and Regulation of Waters Regulations (S.I. 31/2014), which implement the EU Nitrates Directive in Ireland, sets out landspreading exclusion zones. Setback distances for drinking water sources can vary from 25-200 m, depending on the number of people served by the supply and the daily abstraction rate of the supply. The Good Agricultural Practice Regulations also state that the spreading of organic fertiliser or soiled water is also not allowed to be applied to land within: 15 m of karstified limestone features; 5 m of a non-sinking stream or drain; or 20 m of a lake.

Approximately half of the homes in the ZOC are pre-1980's, meaning that the percolation areas associated with the septic tanks are prone to having issues, resulting in the likely discharge of pollutants. From the MST results, there are traces of bacterial DNA from human hosts in the source water, and so septic tanks are having some degree of input of nitrogen into the source water. Regular septic tank check-ups are therefore advised, with attention being paid to older homes. However, the data on nitrogen inputs within the ZOC suggest that evaluation of agricultural practices within the ZOC should be the main focus of efforts to reduce nitrate in the water supply.

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http://www.epa.ie/pubs/reports/research/water/EPA%20RR%20183%20Essentra_web.pdf

[i] LIDAR :Light Imaging, Detection and Ranging
[ii] PPFH Potential Peat Forming Habitat
[iii] ARB: Active Raised Bog
[iv] DOC Dissolved Organic Carbon
[v] DIC Dissolved Inorganic Carbon
[vi] POC Particulate Organic Carbon
[vii] DON Dissolved Organic Nitrogen
[viii] Dissolved Inorganic Nitrogen DIN

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