KARST OF IRELAND

Landscape Hydrogeology Methods

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Suirbhéireacht Gheolaíochta
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Lower left: The sink of the Aille River near Westport, Co. Mayo (photograph by Aerial Eye for David Drew).

Lower right: Karstic spring in the inter-tidal zone at Kinvara, Co. Galway (photograph by Caoimhe Hickey).

Back cover, Top: The northern scarp of the Burren plateau with Galway Bay in the distance (photograph by David Drew). Lower left: The stream passage in Polldubh South cave, Co. Clare (photograph by Colin Bunce).

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FOREWORD

In the mid-1970s when I was a geology student in University College Galway and as part of a week-long course on groundwater, the geology class was brought to a turlough in east Galway and shown a swallow hole into which the effluent from the septic tank serving a local town was being discharged.

We were then brought to a spring approximately 4 km to the west where the effluent was shown by tracing to be discharging, albeit somewhat diluted. Even though it is now 44 years since that day, I can still picture clearly a local woman walking from a nearby house with a white enamel bucket to get water – this was at a time when there wasn't a treated public or private group water supply in the area. How much this situation and image has influenced my working life as a hydrogeologist and created an interest in karst, a concern for groundwater protection and, more recently, an involvement with catchment management I cannot tell with certainty, but it undoubtedly has been an influence. The person who was teaching the course was David Drew, the main author of this book (further details on David's career are given on the back cover). But David hasn't just been a key influence on me since then, his work and that of his former research students, has been instrumental in laying the basis for a proper understanding of limestone bedrock, particularly karstified limestone, which is fundamental to effective land-use planning and environmental decision-making in Ireland.

Whether you are a hydrogeologist, hydrologist, environmental scientist, catchment scientist, environmental or infrastructural engineer, planner, public health specialist, ecologist, environmental regulator or member of the public with an interest in and a concern for the natural environment, an understanding of the characteristics of the limestones – the predominant bedrock in Ireland – particularly those that have a significant degree of solutional features, is essential for the wise use, protection and management of the natural capital that these limestones in the Irish landscape provide. Can I justify this claim? **The overriding reason is that knowing and understanding the characteristics of our natural environment is the foundation of successful environmental management**. So, what are the specific reasons for having a proper understanding of limestones, particularly karstified limestones and karst groundwater? Look at the evidence:

- Limestones underlie 40% of the land surface of Ireland and 45% of the Republic of Ireland, with half of this area having a significant degree of karstification.
- Karstification dictates the landscape in many areas. In upland areas, such as the Burren, Bricklieve Mountains and Cuilcagh Mountains, karstification has provided distinctive and beautiful landscapes, that are the main basis for local tourism. In certain lowland karstified areas, such as mid Galway, mid Clare and parts of Mayo and Roscommon, an unusually 'dry' landscape with free draining soils, a low density of streams and many stone walls, springs, sinking streams and dolines (collapse features) is present.
- Approximately 30% of Ireland's drinking water comes from groundwater; most of which is sourced from our limestone aquifers.
- In many areas, karst groundwater is vulnerable to pollution, particularly by microbial pathogens, and therefore can pose a health hazard for those drinking untreated water.
- The presence of one of Ireland's unique and valuable ecosystems – turloughs – is due to karstification.

However, while there are good reasons for understanding the karst physical environment, it is perhaps the most difficult possible environment to understand, as I know after almost 40 years trying as a groundwater and catchment scientist. Why is this?

While limestones are the framework for a large proportion of the Irish landscape, it is the role of water that makes karstified areas distinctive and also difficult to characterise and to deal with. Over millions of years, it has produced landscapes of dominantly solutional origin, with bare rock sculpted by karren (small (mm-cm) solution channels), and with sinking streams, dry valleys and caves. Beneath the surface, water flow is concentrated into underground streams and conduits before issuing at large springs. In somewhat less karstified areas, water flow is in both conduits and rock fractures. The issue is that, unlike with surface water systems, we cannot 'see' what is happening underground and this makes conceptualisation difficult. This then poses a challenge to the hydrogeologist either looking for a water supply or developing protection measures, particularly as 'standard' hydrogeological investigations will usually be ineffective. It also poses a challenge to the regulator of developments in karst areas. Both must be able to conceptualise the underground effectively – the so called 'cook book' approach will not work.

As my then teenage daughter used to say to me when she was in a cheeky mood, 'so'…! Yes, karstified limestone areas are distinctive and complicated. However, in this book 'Karst of Ireland: Landscape Hydrogeology Methods' we now have a publication than can be the 'bible' for water scientists and engineers, particularly hydrogeologists, who will work in karst areas in the future in Ireland and abroad. Karst, karstic processes, landforms and hydrogeology are explained. Each karst region in the country is described – this information is essential reading for those undertaking development or environmental protection functions in these areas. And, importantly, the specific investigation methods needed for karst areas are described. This is a practical book for both specialists and non-specialists. All chapters contain excellent photos and illustrations to enable the 'mental image' of karstified areas that is needed for effective environmental management.

Without the karst applied research and practical work of David Drew for over 45 years in Ireland, this book would not be possible. The book is a fabulous legacy of one of Ireland's foremost hydrogeologists. However, we must make it an ongoing legacy by making sure that it influences relevant decision-making in a way that benefits Irish people now and in the future. I ask that you read, learn (every time I read it, I learn more), use and enjoy.

Donal Daly

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Chapter 1

INTRODUCTION

Limestone forms the bedrock of more than 40% of Ireland, including the most populated areas and the main agricultural areas. Limestone aquifers provide by far the greatest proportion of groundwater used. The hydrogeology of limestone (karstic) terrains is markedly different from that of other rock types, to the extent that the phrase 'conventional hydrogeology' is used to distinguish non-karstic hydrogeology from karst hydrogeology. This distinction is explicitly recognised in the aquifer classification system developed for use in Ireland.

Most karst in Ireland is lowland rather than upland in type, and the aquifers are commonly complex systems having intimate and varied interactions with surface water systems, such as rivers, wetlands and turloughs (the latter two are often protected eco-hydrological habitats). Karst terrains present particular challenges to geotechnical engineers, for example in road construction, as 75% of the total length of motorway in Ireland is underlain by limestone bedrock.

Despite the importance of karstic groundwater in Ireland, little or no training is available to trainee hydrogeologists or engineers at either undergraduate or graduate level. Textbooks on hydrogeology make only passing reference to the topic, and those texts on karst that are available are focused primarily on geological and geomorphological, rather than hydrogeological aspects.

Optimal management of groundwater in Ireland requires an informed understanding of the workings of the karst system and its relationship to associated surface waters and ecosystems, specific to Irish conditions. One aim of this book is to provide this basic information. A second aim is to summarise and integrate the ever-increasing amount of information on karst in Ireland that has been acquired in recent years. This includes (i) the outputs from university research projects (most recently the modelling of karst systems); (ii) the compilation of Groundwater Protection Schemes for counties, many of which contain significant karst aquifers; (iii) the initiation of hydrometric data collection from karstic springs; (iv) the production of Source Protection Reports for karst springs and numerous research projects related to the incidence of groundwater flooding and the eco-hydrology of karst; and (v) to karst water quality.

Unlike for most other aquifer types, karst hydrogeology cannot be fully understood apart from its geomorphological framework; therefore this handbook describes both the hydrogeology and the geomorphology of karsts.

Chapters 2–4 summarise the most relevant aspects of karst geomorphology and hydrogeology. They are intended to provide readers with the necessary minimum of background information on karst, as most hydrogeologists – or other people whose work involves engagement with karst – do not have this training. Little or no information is given on the more 'academic' aspects, such as the controls on the solution process in carbonates, but textbooks and journal papers which cover these topics are referenced. In these chapters examples are taken from all over the world with only a few from Ireland – this approach is to demonstrate the universality of karsts. However, nearly all the examples given relate to Irish-type limestone (that is, Carboniferous in age with very little matrix permeability) and to Irish-type conditions. Chapters 5–8 describe karst in Ireland, including descriptions of the karst landscapes, the hydrogeology of karst aquifers and more detailed accounts of specific karst areas.

Chapter 9 describes methods suitable for investigating karst hydrogeology with explicit reference to those approaches best suited to the Irish environment. Finally, case studies of recent karst hydrogeological investigations in Ireland are presented in Chapter 10. The bibliography includes sections listing the most useful/key readings on the subject of karst in general, as well as an extensive, if not comprehensive, thematic and regional listing of the literature on Irish karst. Appendix A is a short glossary of hydrogeological and karstic terms used in the text. Appendix B shows the geological timescale with particular reference to periods of time when karstification may have been significant in Ireland. Appendix C comprises 6 maps showing significant locations mentioned in the book.

Figure 1.1 Karst landscape on the south-eastern shore of Lough Mask, Co. Galway. (*Photograph by David Drew*)

Chapter 2

INTRODUCTION TO KARSTIC TERRAINS AND KARSTIC PROCESSES

2.1 Why Karsts are Distinctive

Around the world, karsts comprise some of the most distinctive landscapes, ranging from the tropical tower karsts of China and Vietnam to the barren mountain karsts of the Caucasus and the Pyrenees and to the almost featureless semi-desert karsts of Oman and the Nullarbor Plain in southern Australia. Karsts are distinctive because almost all runoff is underground in caves and smaller conduits and because karst surface landform assemblages are singular and similar worldwide.

The term 'karst' is the Germanic version of the Kras region of western Slovenia and northeastern Italy and means 'stony ground'. In Ireland 'Burren' has a similar meaning but has not become a generic term for such terrain. Indeed, there is no such term in the English language either, in contrast to the array of similar words in other languages:

Karra/Kar: pre-Indo-European

Carsus/Calx: Latin

Chalis: Greek

Il Carso: Italian

Krs: Serb-Croat

Kras: Slovene

Karst: Germanic

Causse: French

The great majority of karsts are developed on carbonate rocks, primarily limestone and dolomites, but karst landforms also develop on other soluble rocks, such as halite and gypsum.

Karsts are probably most abundant and best developed on rocks composed of calcium carbonate. However, the type of karst landforms and the nature of the aquifers also vary according to (i) the character of the particular limestone (Cretaceous, Jurassic, or Carboniferous ages, in northwestern Europe, for example – see Appendix B), (ii) the length of time for which karstification has been underway, (iii) the relative importance of limestone solution in comparison with other geomorphic processes operating and (iv) the climate of the particular area.

Figure 2.1 (A,B) Landscapes typical of the karst in western Slovenia. *(A, Photograph by Andrej Kranj; B, photograph by David Drew.)*

2.2 Defining 'Karst'

The following is a simple definition of what is meant by 'karst':

> *A terrain with distinctive hydrology and landforms due to the high solubility of the rock and the high degree of development of secondary permeability in the aquifer.*

A more sophisticated and hydrogeologically oriented definition is that of Klimchouk and Ford (2000):

> *An integrated mass transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organised to facilitate the circulation of fluids.*

Palaeokarst (sometimes called fossil karst) is karst that has lost its mass transport function and, therefore, does not gain or lose material. It may be rendered inert by burial (for example the ancient karstified surfaces infilled by clay deposits called 'wayboards' in Ireland) or by isolation from karstic processes.

Not all buried karst is palaeokarst however. For example, in the lowland karst of Ireland there is little surface expression of karst because of the blanket of Quaternary deposits overlying the limestone, but karst processes still operate to varying degrees; the presence of active karst hydrogeological systems does not necessarily mean that surface karst landforms are present.

Mantled karst or covered karst is one that is developing beneath a (generally) relatively thin cover of soils and/or subsoils through which the karst landforms are apparent to varying degrees. In bare or naked karst, bedrock or weathered rock is exposed at the surface.

Relict karst exists in the present-day environment but is displaced from the environment in which it formed – for example cave passages that have been abandoned by the streams that formed them.

2.3 The Evolution of Karsts

In comparison with most rock types, the evolution of landforms on limestone is relatively uncomplicated. Pure limestone is virtually a mono-mineralic rock so differential weathering of minerals does not occur. In addition, a single process – solution – dominates weathering and also transports the weathered rock as solution load in runoff. As a consequence, in a geomorphic system underlain by pure limestone, few insoluble residues are generated; therefore, there is little mass movement and deposition is mainly marine rather than on land. Hence a landscape of steep slopes and flats, of loose rocks rather than soil, characterises many karsts.

In humid areas, karst processes typically compete with fluvial processes for dominance. Karst processes may win *(holokarst)* or be confined to the higher ground – interfluves – with surface rivers in valleys acting as local base levels *(fluviokarst)* (Figures 2.2 and 2.3). Alternatively, karst processes may never dominate.

Karst develops best on very pure, well-fractured limestone, such as the Carboniferous limestone in Ireland. Although solution of the rock by acidified runoff is the dominant process operating,

Figure 2.2 Holokarst – no surface drainage, all runoff directed into the aquifer (Mallorca). *(Photograph by David Drew.)*

Figure 2.3 Fluviokarst – rivers occupy valleys which form the local base level while karst processes dominate on the interfluves (Matera, central Italy). *(Photograph by David Drew.)*

the degree of solutional erosion varies both across the surface and below the ground. These variations in intensity with the areal variability of the solution processes on different limestone lithologies and structures produce a variety of karstic landforms on large and small scales.

In more formal terms, variations in landforms are largely due to the existence of an open system of landform and aquifer development with two interacting sub-systems:

- hydrological: water providing the energy to dissolve and transport the rock
- hydrochemical: the processes that control the rate of dissolution of limestone

Over time, a 'plumbing' system evolves that allows water to sink underground, to circulate and to resurge, thereby creating a karstified aquifer and characteristic karst landforms above and below ground.

Thus, it is apparent that karst landforms and karst aquifers evolve over time and also that some areas karstify better than others.

The following features indicate how karstified a particular limestone region might be:

- a lack of surface runoff via streams
- a fragmentation/localisation/disorganisation of any surface drainage that may exist
- a solutional origin for landforms of all scales
- landform evolution controlled from beneath the surface (the drainage is in cave systems)

A gradation in the degree of the significance of the above factors corresponds to a gradation in degrees of karstification from non-karstic to holokarstic.

2.4 The Significance of Karsts

Ford and Williams (2007) estimated that carbonate rocks outcrop over approximately 20% of the land surface of the earth, though by no means are all of them karstified to a significant extent – perhaps between 35% and 60%.

A more recent attempt to map the worldwide and European extent of carbonate rock outcrop is shown in Figures 2.4 and 2.5, respectively (World Karst Aquifer Mapping Project, WOKAM, 2017). As remarked earlier, the fact that carbonate rocks outcrop does not necessarily mean that the terrain is karstified. However, carbonate rocks overlain by insoluble rocks may be karstified, sometimes to great depths.

The widespread occurrence of limestones and dolomites in Europe is apparent, with some 14% of its area directly underlain by carbonates (Chen et al., 2017). Apart from some of the countries of the Dinaric karst in southeast Europe and the small countries of Malta, Liechtenstein and Luxembourg, the Republic of Ireland, with almost 43% of its land area being directly underlain by limestone, probably has one of the highest proportions of potentially karstifiable rocks in Europe, if not the world.

Carbonate rock aquifers are an important source of water in Europe – not only the Carboniferous limestone aquifers which provide the overwhelming majority of Ireland's groundwater supplies, but also the Jurassic limestones and, in northwestern Europe, the Cretaceous chalk.

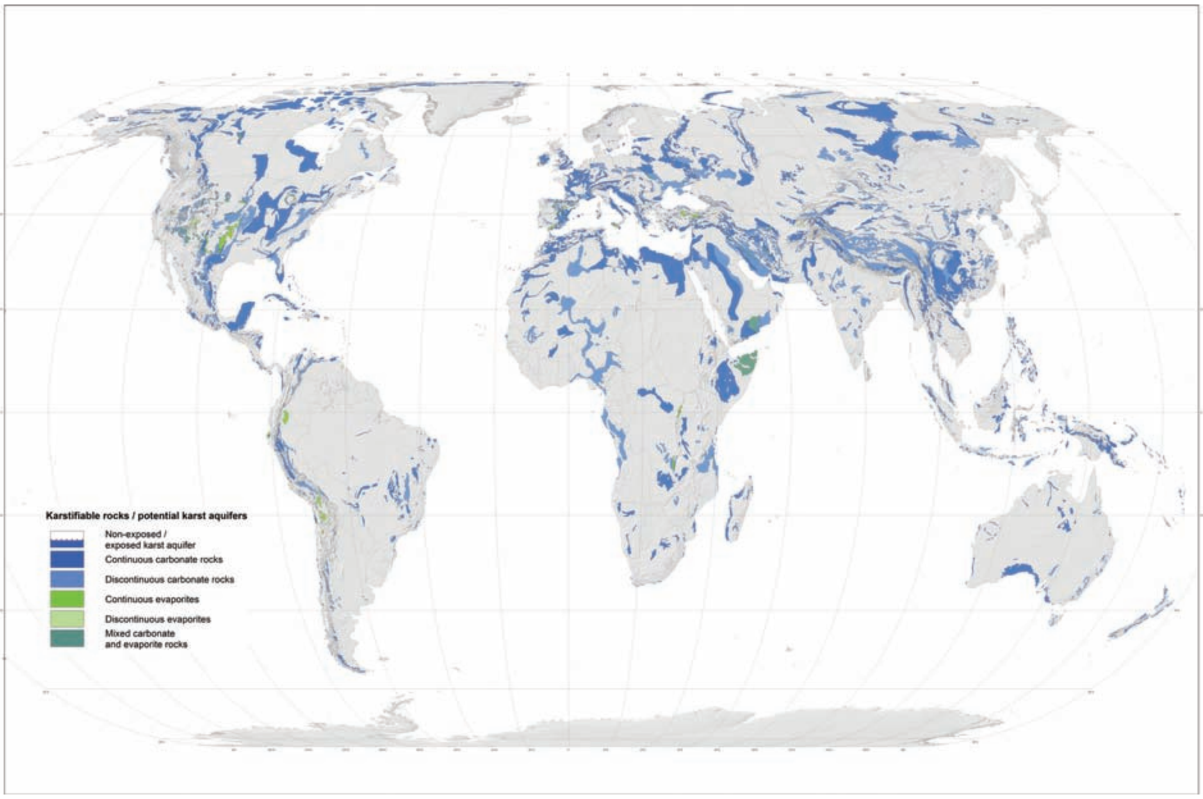


Figure 2.4 World distribution of carbonate rocks (Chen et al., 2017).

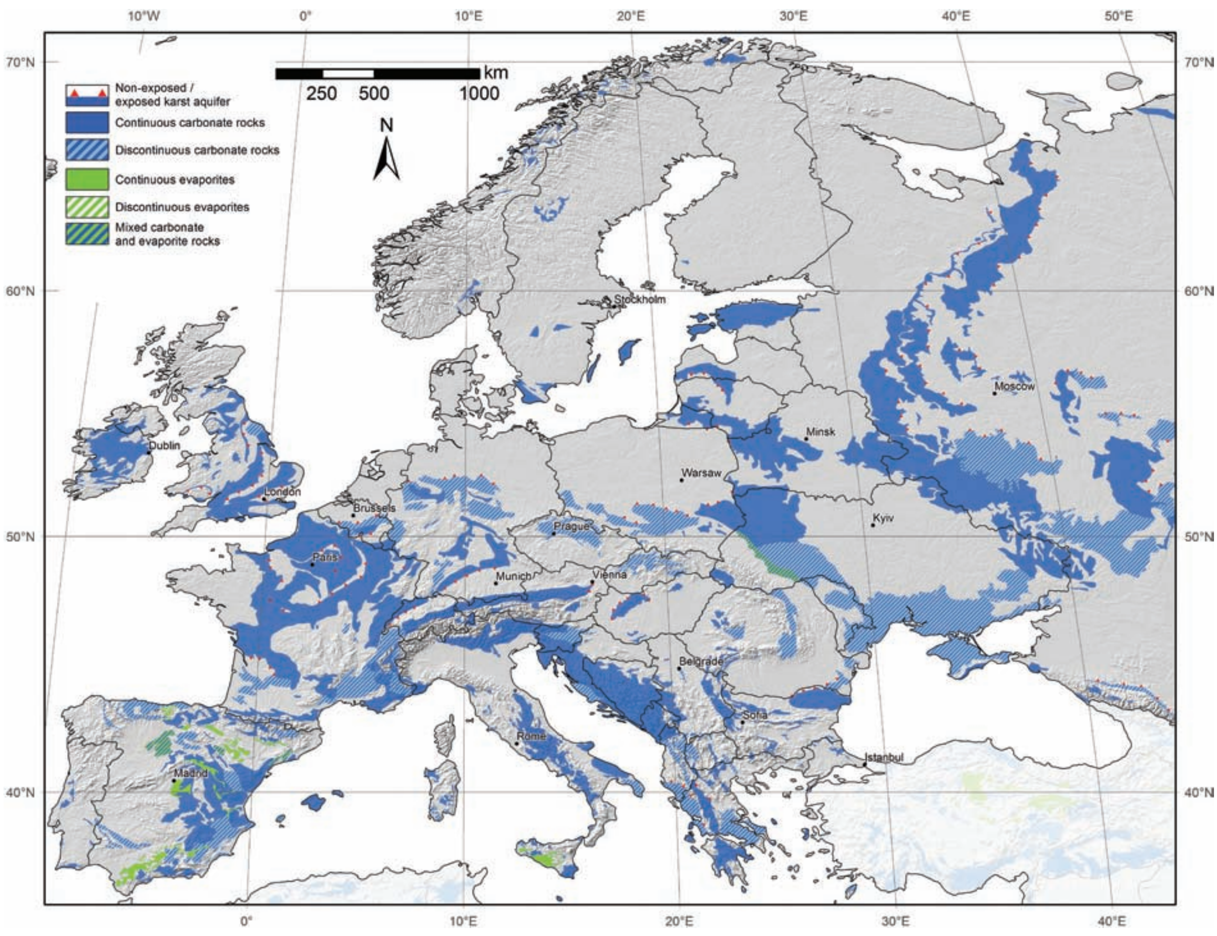


Figure 2.5 Carbonate rock outcrop in Europe (Chen et al., 2017).

Chapter 3

KARSTIC LANDFORMS

3.1 Introduction

This chapter describes the landforms – surface and subterranean – that are characteristic of karst areas. The factors that affect the development of these landforms are:

- the character and tectonic history of the limestone
- the controls on the intensity of, and spatial variations in, the dominant erosional process – solution
- the nature and degree of development of the system for draining excess rainfall, including the solutional load (the karstic plumbing system of channels, caves and conduits)

The limiting conditions for karstification are extreme aridity and extreme cold but even in these environments relict karst features related to past climates are often apparent. Most dissolution of the limestone bedrock usually takes place at or close to the surface of the land where acidified runoff first encounters the bedrock and therefore most landforms are developed in this zone. However, in some limestone areas, including some parts of Ireland, karstification may produce no distinctive surface landforms as the processes are concentrated underground. This occurrence of significant underground landforms (voids) is a peculiarity of karsts.

3.2 The Development of Karst Landscapes

As with all landscapes, karst landforms have a developmental sequence from the time when limestone is exposed for the first time to erosion, to the point at which either the limestone has been wholly eroded away or further erosion is not possible because a local base level has been reached. It is largely a theoretical concept and few karsts ever run through the full sequence before tectonic activity and/or climatic change interrupts the geomorphic evolutionary sequence.

An idealised sequence, first envisaged by the geomorphologist Grund in 1914, but still in accord with present day modelling results, is shown in Figure 3.1. The intact limestone surface is initially pitted by small dolines (enclosed depressions) which deepen, widen and coalesce until the dominant landforms become the residual small hills or towers rising from a planed surface at the base of the limestone or at the local base level for erosion. Figures 3.2–3.5 exemplify what such evolutionary stages might look like.

As described later, there are remnants of all these stages of karstification present in Ireland. However, in Ireland, as in most other karst areas, the development sequence is complicated by interaction with other geomorphic systems. Figures 3.6 and 3.7 illustrate some of the ways in which the karst development may be deflected or distorted when other processes operate as well as karstification.

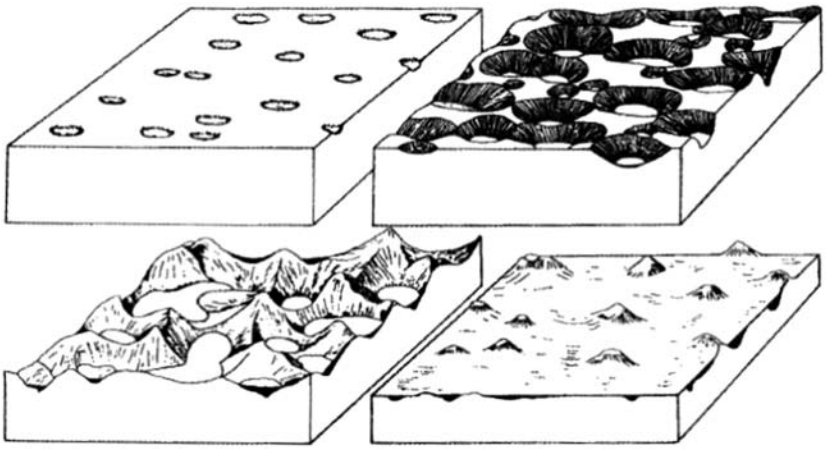


Figure 3.1 The evolution of a karst landscape according to Grund (1914).

Figure 3.2 Initiation of karst drainage as dolines develop beneath a cover of peat in northwest Yorkshire. *(Photograph by Tony Waltham.)*

Figure 3.3 Deepening, widening and coalescence of dolines (North Yorkshire). *(Photograph by Tony Waltham.)*

Figure 3.4 Solutional erosion of the limestone to the local base level – the elevated land between dolines becomes isolated hills (southern China). *(Photograph by Nico Goldscheider.)*

Figure 3.5 Lateral solution predominates, the base of the hills is undercut so that they become karst towers, the dominant landform is the plain on which surface drainage may become established. Karstification then ceases and a fluvial regime is established (southern China). *(Photograph by Nico Goldscheider.)*

Figure 3.6 Aeolian processes now predominate over karstic processes in this arid environment (Oman). *(Photograph by David Drew.)*

Figure 3.7 Glacial processes destroy and blanket karstic landforms (southwest Germany). *(Photograph by Nico Goldscheider.)*

3.3 Surface Landforms of Karst

3.3.1 Valleys

In humid climates, valleys or fragments of valleys are often found in karst areas. They exist despite, rather than because of, the limestone and develop when not all runoff can become sub-surface recharge. Such valleys may be devoid of streams and relate to different environmental conditions in the past, such as a higher water table, frozen ground, superimposition of the drainage pattern from a cover rock or wetter conditions in the past (Figures 3.8 and 3.9).

Surface streams on limestone are usually present because the solutionally enlarged channels along the stream course lack the capacity to engulf all of the discharge (Figure 3.10). This may be because the karst is juvenile or because the bedrock is blanketed to some degree by a subsoil (e.g. a carbonate till) that shields the limestone from aggressive water.

Figure 3.8 Dry valley developed in chalk (southwest England). *(Photograph by David Drew.)*

Figure 3.9 Dry valley (gorge) developed on Carboniferous limestone (northwest Yorkshire, England). *(Photograph by David Drew.)*

Figure 3.10 A stream traverses a limestone outcrop without sinking (northwest Yorkshire, England). *(Photograph by David Drew.)*

Figure 3.11 A stream sink terminates a valley on limestone (Turkey). The feature, with a cliff immediately downstream of the sink, is termed a blind valley. *(Photograph by David Drew.)*

Some streams originating on non-calcareous rocks may flow for some distance over the limestone before sinking at a swallow hole (Figure 3.11). Typically, there is a cliff immediately down-valley of the sink, corresponding to the continued down-cutting of the valley upstream of the sink. Eventually, the point at which the stream sinks migrates up-valley as far as the contact with the non-limestone strata.

3.3.2 Enclosed Depressions

Enclosed depressions, in which runoff is funnelled vertically down to become recharge, are generally regarded as the most common landforms of karsts. They range in diameter from a few metres to tens of kilometres and in depth from a few centimetres to hundreds of metres. They all represent local zones of concentrated solutional erosion of limestone. The smallest of these features are termed *dolines*, and these take several forms.

Collapse dolines

Collapse dolines may be vertical-sided cylindrical features – usually formed catastrophically by collapse of the overlying rock and subsoil into an underlying cavity (Figure 3.12). Over time, weathering of the steep walls degrades the slope angle and the doline becomes bowl-shaped and, finally, saucer-shaped. Collapse dolines are windows into the underground karst drainage system rather than primary recharge points to the aquifer.

Solution dolines

Solution dolines develop from the surface downward, where recharge and, hence, erosion become focused at particular localities, perhaps where a major vertical line of weakness allows large amounts of recharge water to enter the deeper aquifer. In contrast to collapse dolines, solution dolines commonly deepen as they evolve, becoming conical in form with progressively steepening slopes.

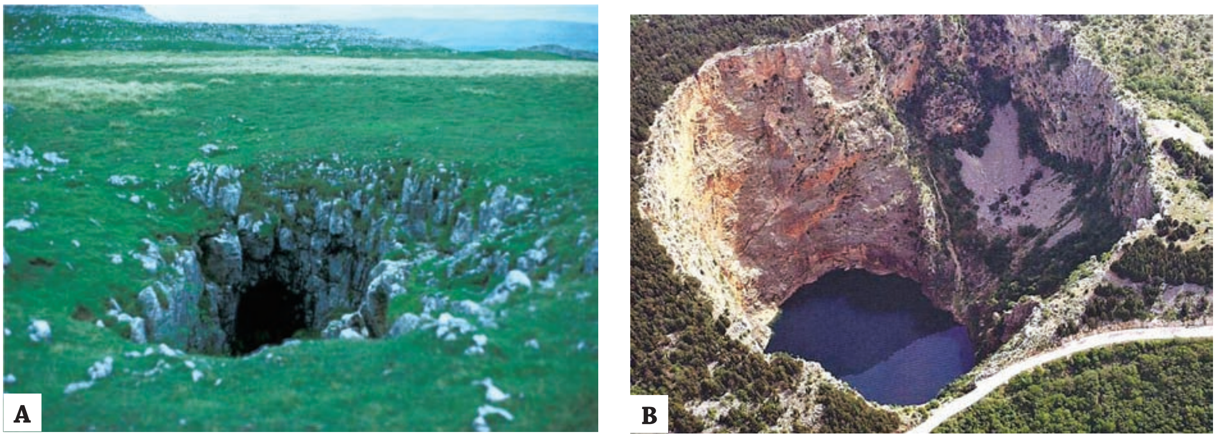


Figure 3.12 Collapse dolines: (A) northwest Yorkshire, England; (B) Croatia. *(Photographs by David Drew.)*

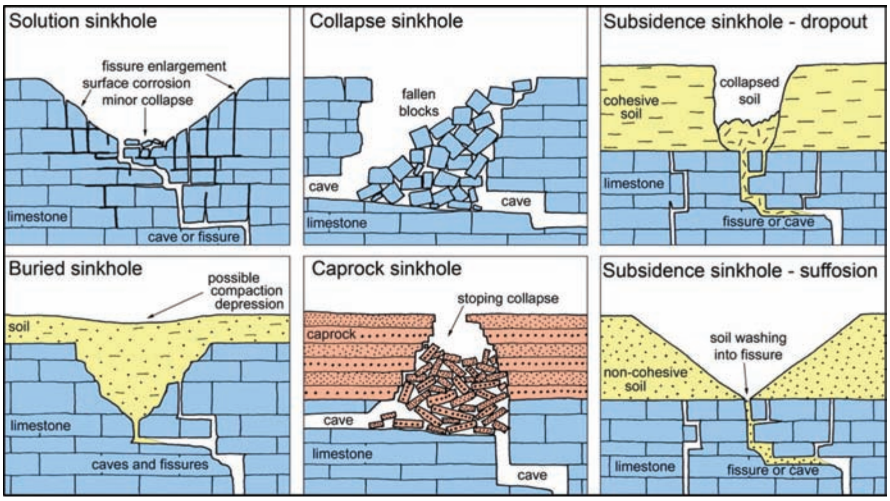


Figure 3.13 Types of dolines. *(From Waltham et al., 2005.)*

Figure 3.14 Incipient dolines: (A) suffosion (Jura, France); (B) cover collapse (or dropout) (Mendip Hills, England). *(Photographs by David Drew.)*

Figure 3.13 shows these doline types in cross-section and also other types, for example suffosion dolines (Figure 3.14A) and dropout dolines (Figure 3.14B). As can be seen, dolines may exist as bedrock features that function hydrologically but lack any significant surface expression. Solution, suffosion and dropout dolines are common in Ireland.

Doline fields may develop, particularly in low-relief terrain, in which dolines occupy all the land surface and almost no level ground remains *(polygonal karst)* (Figure 3.15A,B). Each doline is a miniature catchment area.

In other karsts, structural controls may cause dolines to develop preferentially in areas of higher permeability – for example, in a linear arrangement, as in the example shown in Figure 3.16.

In karst areas with a soil and/or sub-soil cover, finer sediments may accumulate in the base of dolines by mass-movement and down-washing. This gradually renders the floor of the doline less and less permeable until eventually its hydrological function becomes reversed and it contains a pond or lake rather than being a point of high permeability and

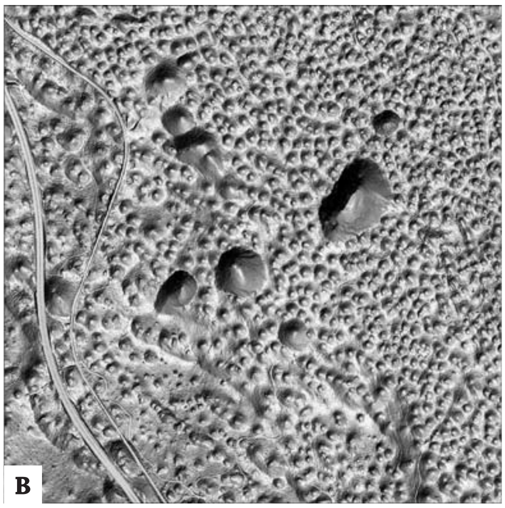


Figure 3.15 Polygonal karst in which dolines occupy almost all of the land surface. (A) Kentucky, USA. *(Photograph by Tony Waltham.)* (B) A Lidar DEM of a 2-km × 2-km area of doline karst in Slovenia with a road and railway on the left side of the image. *(Image by Andrej Mihevc.)*

Figure 3.16 Lines of dolines developed on a major fracture or fault line (Austrian Alps). *(Photograph by Nico Goldscheider.)*

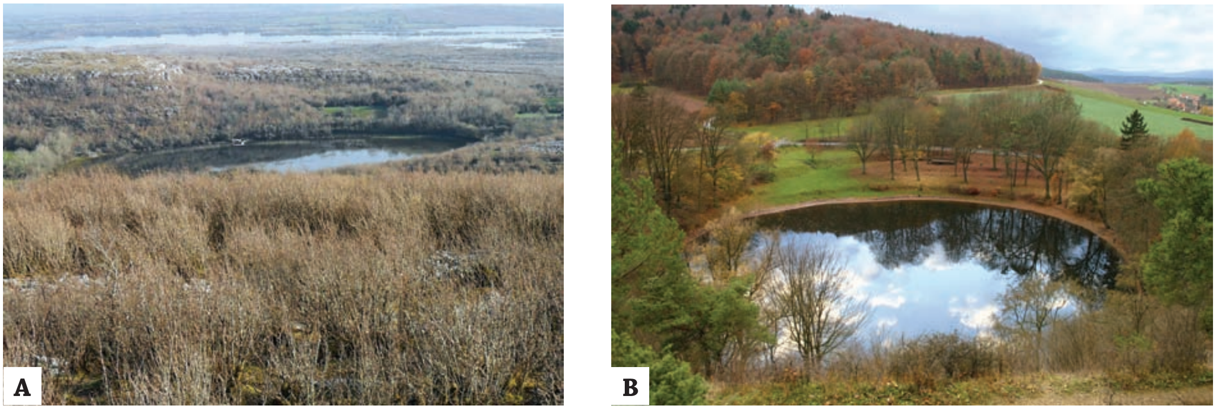


Figure 3.17 Non-functional dolines. (A) The Burren, Ireland. *(Photograph by David Drew.)* (B) Southwest Germany. *(Photograph by Nico Goldscheider.)*

concentrated recharge to groundwater (Figure 3.17A, B). When this happens, new dolines are likely to develop in areas where the subsoils are thinner and more permeable.

Very different processes, both natural and anthropogenic, can create similar landforms and this is very much the case with dolines. Enclosed depressions such as those shown in Figure 3.18A–D can result from radically different and wholly non-karstic causes, leading to uncertainty in identifying genuine karst landforms in some areas. In Ireland, depositional landforms due to glacial or fluvio-glacial processes are often difficult to differentiate from karstic forms (see Chapter 7).

Compound enclosed depressions, with hollows within hollows, are common and may develop by the coalescence of dolines or by the development of sub-basins within a larger feature (Figure 3.19). These were termed *uvalas* – a name that is now not commonly used. Larger enclosed depressions, with floor areas of hundreds of square kilometres in some cases, are found in some karst areas, particularly those of the Mediterranean and tropical areas where karstification is advanced. These landforms are termed *poljes*, the Serbo-Croat

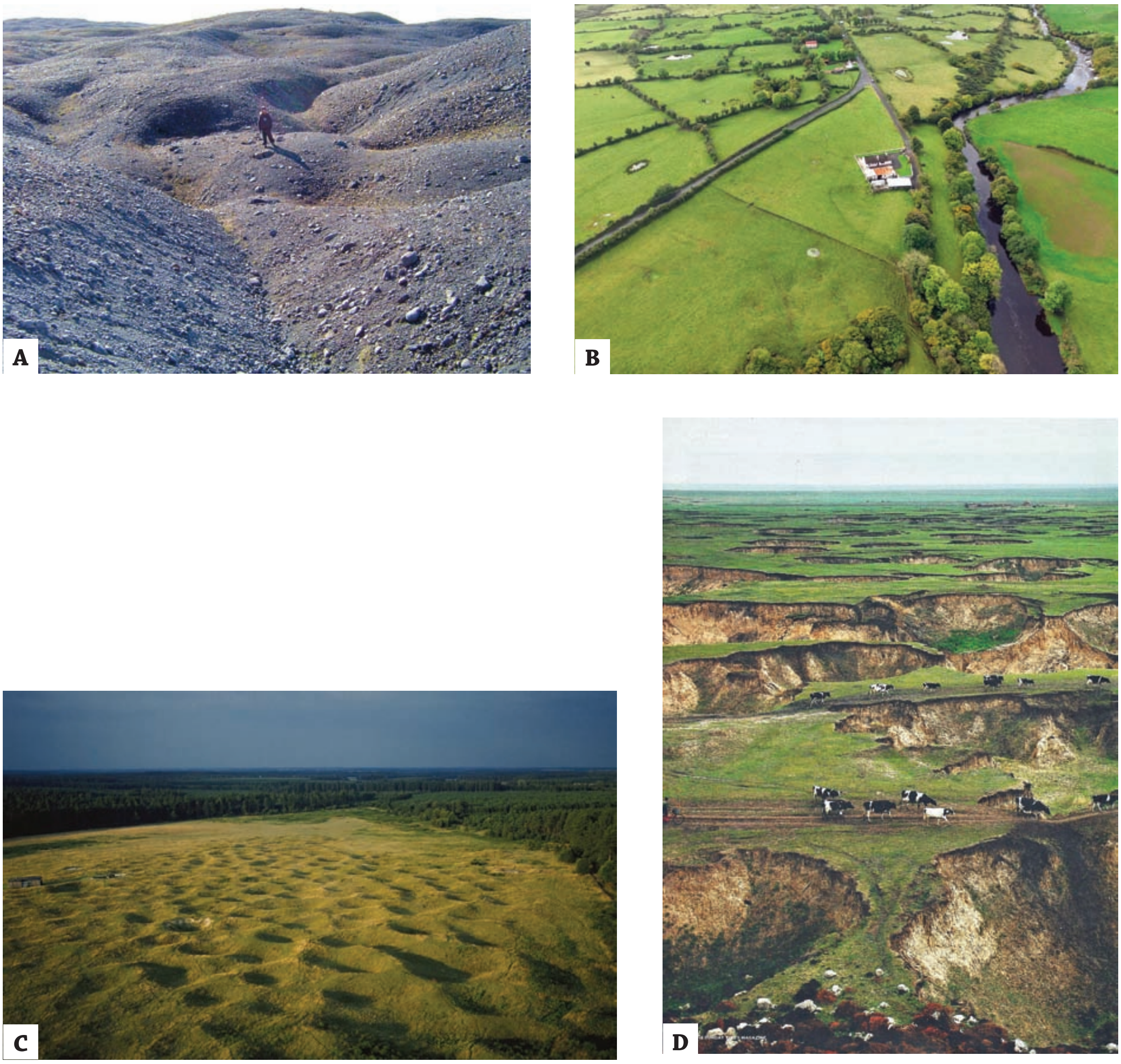


Figure 3.18 Pseudo-dolines. (A) Moraine (Iceland). (B) Dolines, kettleholes and dolines in kettleholes (County Mayo). *(Photograph by Aerpas.)* (C) Prehistoric mines (East Anglia). (D) Coalmine workings (Mongolia). *(Photograph by The Sunday Times.)*

Figure 3.19 Uvala/coalesced dolines (Slovenia). *(Photograph by Kenneth Gardner.)*

Figure 3.20 Popovo polje (Bosnia). *(Photograph by David Drew.)*

word for a field, emphasising the relatively flat-floored, sedimented base of the feature (Figure 3.20). They often have complex internal drainage systems. It may be that uvalas are a variety of polje. Both landforms are found in karsts in Ireland (Chapter 7).

3.4 Underground Landforms of Karst Regions (Caves)

3.4.1 Introduction

Caves are usually regarded as being underground channels accessible to humans that are of comfortable dimensions. However, in hydrogeological terms, every water-transmitting opening greater than 5–10 mm in diameter within the limestone aquifer has turbulent flow, and should be considered a conduit.

Nearly all caves are segments of present-day or past underground flow routes for water, from input points to discharge zones, though this may not be apparent in caves that are no longer hydrologically active.

Initially, caves are water-filled, but may then enlarge until only a part of the conduit is water-filled and eventually they will be abandoned by flowing water and become relict. Caves accessible to humans represent only a small fraction of the conduits that store and transmit water in the karst aquifer, yet, despite this, they uniquely allow direct access to the internal workings of a karst aquifer and therefore cave exploration, mapping, hydrometric and hydrochemical studies are an essential part of the hydrogeologist's investigations of karst groundwater systems.

Caves are like river valleys with a roof except:

- they are not gravity controlled in the saturated zone (so water and the cave conduits, may move and be oriented in any direction depending on hydraulic and geological controls)
- they are gorges rather than valleys (because the geomorphic processes that generate valley slopes are not operative underground)
- they can develop at successive levels in the aquifer over time (because groundwater flow is three-dimensional compared to surface streams)

3.4.2 Cave Development

The evolution of cave systems follows a developmental sequence as groundwater flow becomes progressively more focused on favoured pathways through the aquifer. The following stages in development are usually recognisable.

Inception

Initially, groundwater in a limestone region will behave in a similar fashion to groundwater in any other fracture-flow aquifer. However, unlike other groundwater systems, karst aquifers are dynamic and evolve in character through time. The prerequisite for karstification is the concentration of water at certain zones, vertically and horizontally, in the rock massif and, hence, the concentration of solutional erosion in these zones. Features (usually geological) that concentrate groundwater at a particular level below ground are often underlying layers of low permeability. Examples of such 'waterproof' layers, called *inception horizons,* are shown in Figure 3.21. The actual horizontal location of cave conduits above an inception horizon may be determined by the location of continuous lines of higher permeability, such as faults, veins or joints.

Crossing the threshold to turbulent flow

In the early stages of karstification, the flow of groundwater above an inception horizon will probably be laminar and therefore flow rates and solution rates will be low. This stage may persist for a long period of time (hundreds to thousands of years) until the flow path is sufficiently large to generate turbulent flow. Thereafter, the development rate of the micro-caves accelerates, larger/lower flow routes capture water from smaller routes and the drainage system becomes progressively more organised and more efficient in carrying away runoff from the surface of the land. Figures 3.22–3.25 show this progression.

Development of conduits

As noted previously, cave conduits will initially be completely water filled. Dissolution of the rock will take place equally on all surfaces and the conduit will evolve a circular or elliptical shape (Figure 3.26). Such water-filled conditions may be present simply because the conduit dimensions are too small to accommodate the flow or because the conduit is located beneath the water table – *phreatic* conditions. In the former instance the conduit may eventually become large enough to cope with the flux of water and no longer be completely water-filled. Once this happens, solutional erosion will cease in the upper part of

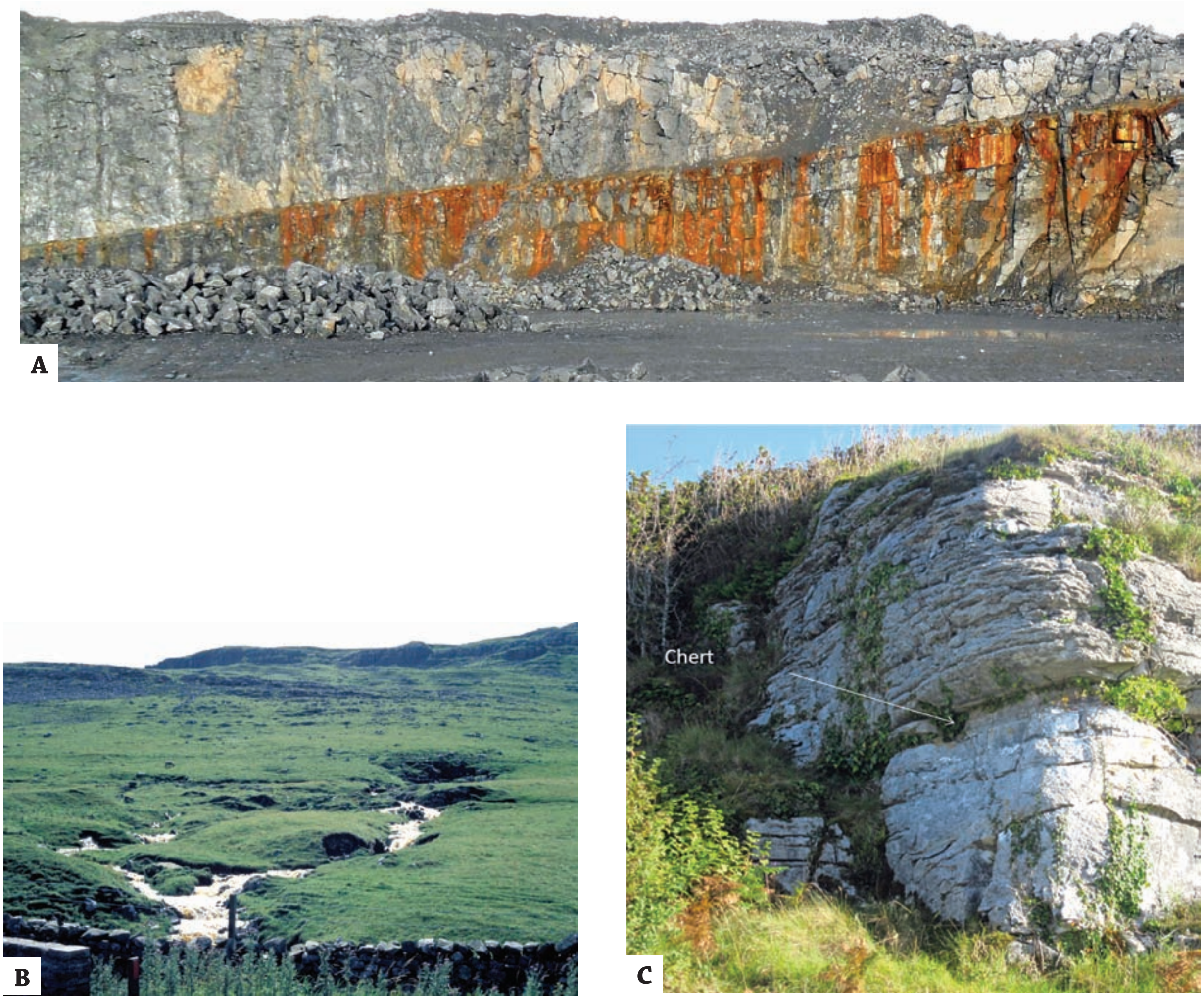


Figure 3.21 Examples of inception horizons. (A) A thin clay/shale band in the limestone allows little water to pass through. Lateral flow in a bedding plane along the strike of the strata results. Groundwater now seeps from the quarry face leaving iron-staining from the shale (County Clare). (B) The limestone is underlain by an impermeable rock and so groundwater flow and maximum karstification takes place in the lowest beds of limestone (Yorkshire Dales, UK). (C) A 10-cm-thick layer of chert impedes the vertical percolation of groundwater – hence there is less dissolution of the limestone below the chert (the Burren, County Clare). *(Photographs by David Drew.)*

Figure 3.22 Groundwater seeps out of a largely unopened bedding plane above a shale band – the flow regime is laminar. *(Photograph by David Drew.)*

Figure 3.23 Myriad small (2–3 cm deep) solution channels (anastomoses) developed in the underside of a bedding plane above a shale band – the onset of turbulent flow. *(Photograph by David Drew.)*

Figure 3.24 The development of a preferential (optimal) flow channel through the network of anastomoses developed above a permeability discontinuity (clay layer) along a bedding plane. Horizontal distance is approx. 1.5 m. *(Photograph by David Drew.)*

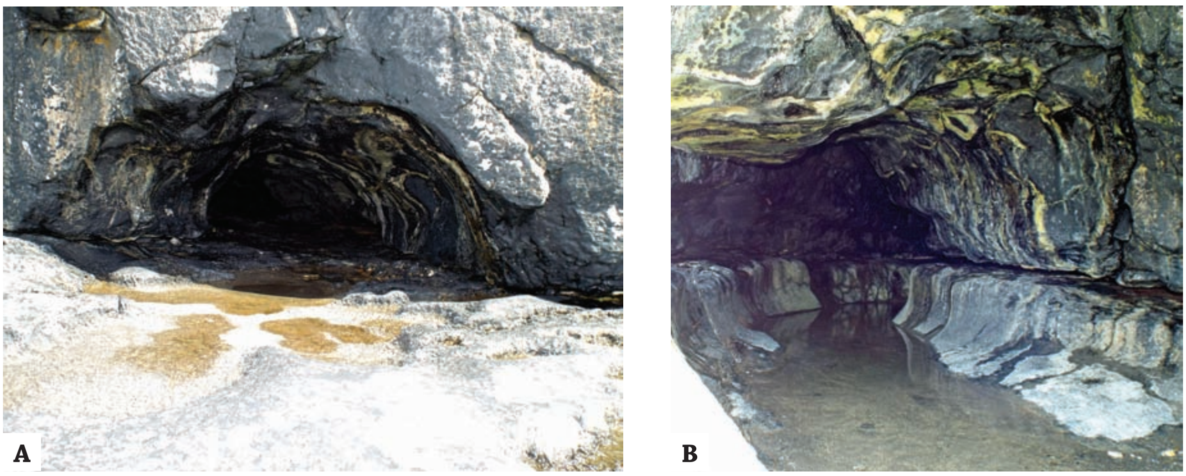


Figure 3.25 Close-up of the two main conduits shown in Figure 3.24. The conduit 'A' has become abandoned as the conduit on the right captured its water. The conduit 'B' has eroded through the inception horizon into the limestone bed beneath and is incising a vadose trench. *(Photographs by David Drew.)*

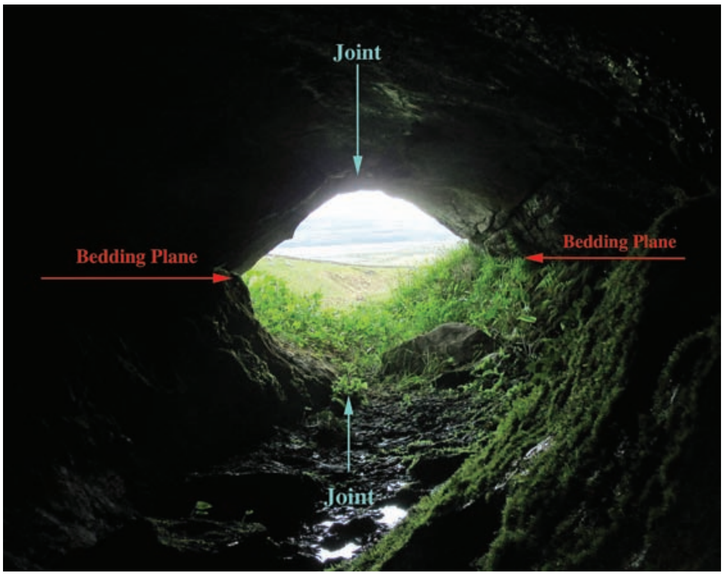


Figure 3.26 An abandoned phreatic conduit (1.5 m in diameter). The elliptical passage cross-section is the result of solutional erosion upward and downward in the previously water-filled conduit from a horizontal bedding plane inception horizon. *(Photograph by David Drew.)*

the conduits but continue in the water-filled lower part, hence developing a vertical trench (Figure 3.27). In the case of a phreatic conduit, the water table may drop below the level of the flooded cave, again allowing vertical incision into the rock to dominate. Groundwater flow of this variety is said to be in the *vadose zone* and operates under gravitational control, as does a surface river system. The vadose zone is the equivalent of the unsaturated zone but wholly flooded caves do not necessarily have to be located in the sub-water-table zone.

Abandonment and decay of the cave network

As surface rivers continually change course and develop optimal routes to the base level, new underground routes through the aquifer are also developed through time, partly in response to changes in external controls such as base level and partly to evolve the most 'efficient' route through the aquifer from recharge to discharge points. Once a cave ceases to be water-filled it begins to decay – from (i) collapse of roof and walls (Figure 3.28), (ii) by infilling with internally derived deposits (calcite formations, Figure 3.29) and (iii) from infilling by externally derived sediments carried or injected into the cave (Figure 3.30).

3.4.3 Cave Networks

Speleologist-drawn maps, plans and sections of cave systems, now abandoned by the water that formed them, may give valuable information about the controls on groundwater flow in a limestone aquifer, the main directions of flow and the nature of the palaeo-hydrology of the aquifer. Examples of differing types of cave networks are shown in Figure 3.31. It should be borne in mind that the surveys only show those passageways that have, to date, been discovered by speleologists and they may or may not be representative of all of the aquifer flow system.

Figure 3.27 A vadose trench with a cave stream and a tributary stream perched above a chert layer entering at roof level. The scalloped cave walls testify to the turbulent flow regime. *(Photograph by Terry Dunne.)*

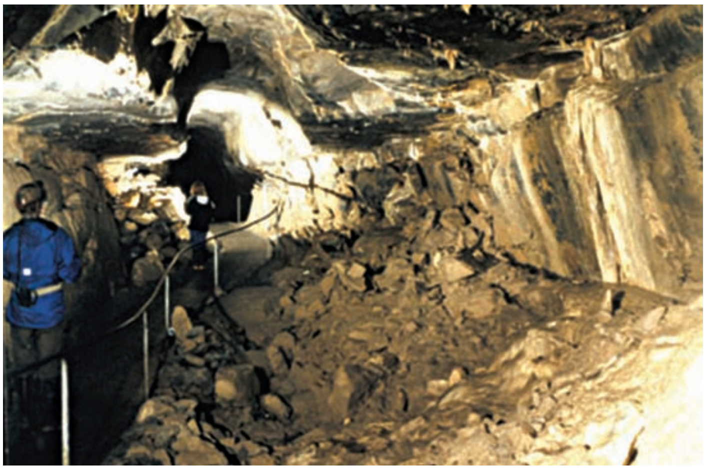


Figure 3.28 Rockfalls from roof and walls infill a former cave stream passage (Aillwee Cave, County Clare). *(Photograph by David Drew.)*

Figure 3.29 A relict cave passage being infilled by calcite deposits (Mitchelstown Cave, County Tipperary). *(Photograph by David Drew.)*

Figure 3.30 A cave passage abandoned by its stream and now partly infilled with externally derived sediments (Vigo Cave, County Clare). *(Photograph by Terry Dunne.)*

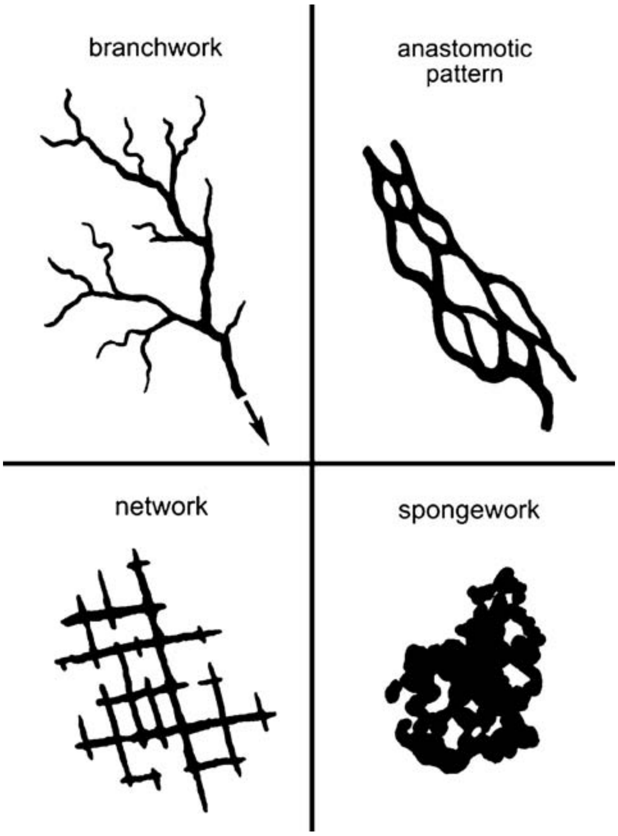


Figure 3.31 Cave/conduit networks related to geological and hydrogeological conditions. In inclined strata dendritic drainage networks may develop. Where joint networks are well developed and groundwater flow is slow and unfocused the conduits may form a 2-D or 3-D grid or maze. *(Figure courtesy of Arthur Palmer.)*

Chapter 4

OVERVIEW OF KARST HYDROGEOLOGY

4.1 The Karstic Groundwater System

A karst aquifer is one that has been modified from earlier granular or fractured bedrock conditions by the development of interconnected solutional channels.

As with other lithified rocks with secondary permeability, the basic control on the occurrence and behaviour of groundwater in limestone is the geological framework (including lithology, fracture density, bedding, faulting and folding) within which the water is stored and transmitted. Uniquely, however, as water moves through a carbonate aquifer it modifies the structure of the aquifer by differentially dissolving the rock and thus enlarging certain flow-paths for groundwater. These solutionally driven modifications increase exponentially through time and vary markedly in space. Within a short passage of geological time (thousands or tens of thousands of years) the character of a carbonate aquifer may be utterly transformed by selective solutional erosion.

As the aquifer evolves through time:

- flow systems increasingly resemble those of surface fluvial systems but with a cover of rock
- storage decreases and transmission becomes more efficient
- groundwater flows become more concentrated, localised and integrated
- anisotropy and heterogeneity increase

The term *channels* is used by Worthington and Ford (2009) to describe all solutionally enlarged openings ranging from fissures and conduits to accessible caves and to differentiate these openings from unmodified voids such as fractures or bedding partings. *Conduit*s are channels which have turbulent flow and therefore a diameter exceeding 5–10 mm. A *cave* is a conduit accessible by humans. The relative proportions and locations of channels will vary greatly within and between karst areas but their existence is a fundamental characteristic of a karstified aquifer. The distinctive aspects of the karstic groundwater system are illustrated schematically in Figure 4.1.

Various definitions of what constitutes a karst groundwater system have been offered. For example:

- an aquifer dominated by solution conduits in which a turbulent flow regime occurs (Atkinson and Smart, 1981)
- an aquifer with a permeability structure dominated by interconnected conduits dissolved from the host rock, which are organised to facilitate the circulation of water in a down-gradient direction wherein the permeability structure evolved as a consequence of dissolution (Huntoon, 1995)
- an aquifer with self-organised, high-permeability channel networks formed by positive feedback between dissolution and flows (Worthington and Ford, 2009)

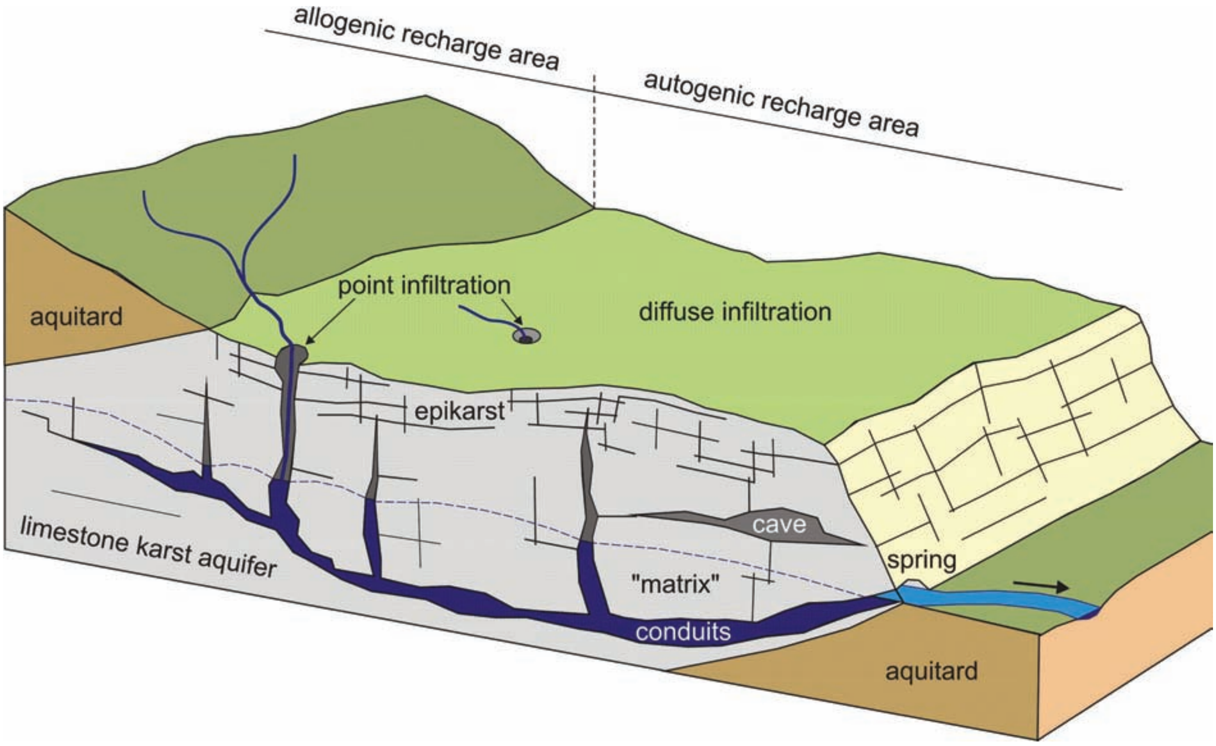


Figure 4.1 Schematic diagram illustrating the main components of the karstic hydro-geomorphological system. *(From Goldscheider and Drew, 2007.)*

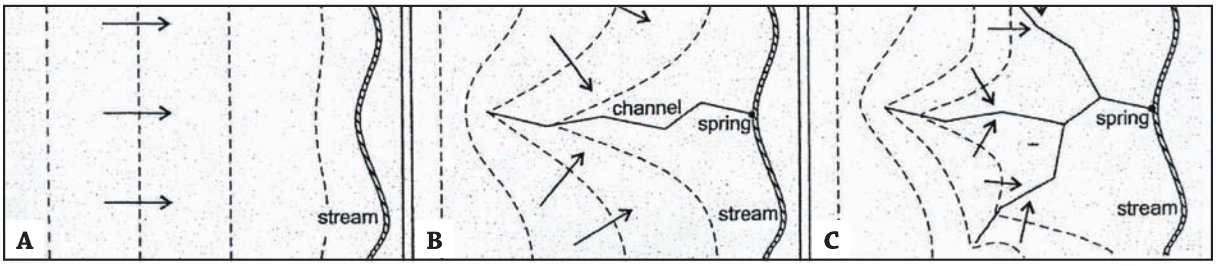


Figure 4.2 Hypothetical evolution of a karstic drainage system from an initial fracture flow (Darcian?) aquifer, showing contours of hydraulic head. *(From Worthington and Ford, 2009.)*

Figure 4.2 shows the evolution of 'self-organised permeability', as described by Worthington and Ford (2009), from the initial Darcian groundwater flow system (Figure 4.2A), down the steepest hydraulic gradient. Figure 4.2B shows modification as a conduit develops, extending from input to output. Figure 4.2C shows later tributary channels evolving collecting water from more distant parts of the aquifer until an underground fluvial system is in place.

In addition to the geometry of the plumbing system, discharge through a conduit network is controlled by the hydraulic gradient, which is limited by the base level of the outflow (e.g. a spring or other emergence).

In subsequent sections of this chapter, recharge, throughflow and discharge from karst aquifers are considered separately. These distinctions are difficult to maintain, however, as the three are inextricably connected genetically for each particular area. For example, the mode of discharge is a function of the type of groundwater flow system whilst the flow system is largely determined by the recharge mechanisms.

4.2 Recharge to Karst Aquifers

If the limestone has no matrix permeability, then some degree of concentration of potential recharge at the rockhead will take place as the rainwater can only infiltrate where a secondary opening, such as a joint, exists; however, this is true for all fracture flow aquifers. In some carbonate rocks, where solution has not selectively enlarged some fractures (thus creating vertical zones of high permeability), all fractures generally have similar but smaller dimensions. This may be because the limestone is inherently not very soluble due to impurities, such as chert or clay, or because it has been protected from solutional erosion until recently. Under these conditions recharge is diffuse. Figure 4.3 shows a quarry section of weakly karstified limestone in which little concentration of recharge is apparent.

At the opposite end of the recharge spectrum is point recharge on a large scale where streams, generated on the limestone or flowing on to the limestone from adjacent non-soluble rocks, sink underground at a point or as line-recharge. Such point recharge flows can be thousands of litres per second (Figure 4.4).

An intermediate type of recharge, semi-concentrated, may be important if an epikarst is present. The epikarst is a heavily weathered layer of rock extending less than 10 m below the base of the soil/subsoil. The near-surface zone of a rock is commonly characterised by stress-release (unloading) fissures predominantly sub-parallel to the land surface and this is the case with many rock types – for example in granite, as shown in Figure 4.5.

Figure 4.3 Impure limestone, County Meath. Fracture flow rather than karst channel flow is predominant *(Photograph John Paul Moore)*

Figure 4.4 Sinking stream (Gort, County Galway). *(Photograph by David Drew.)*

Figure 4.5 The unloading zone in granite bedrock (Yosemite, California). *(Photograph by David Drew.)*

However, in limestone these initial fissures are likely to be significantly enlarged by solutional erosion as recharge water is at its most aggressive near the soil–bedrock interface. It is considered that more than 80% of erosion of limestone takes place in the uppermost 10 m of the bedrock. Porosity in the epikarst in Irish limestones may reach 20% compared to 2%–5% in the main body of the aquifer, with greater than 80% of total aquifer storage being located in the epikarst. Similarly, permeability may be an order of magnitude greater. Throughput time for epikarst water can range from a few hours to several months. Figures 4.6–4.8 show examples of epikarst.

Figure 4.6 Epikarst in western Ireland (close-up). *(Photograph by David Drew.)*

Figure 4.7 Epikarst (County Clare) showing the highly karstified uppermost four or five beds of limestone separated by an enlarged bedding plane from the much less karstified limestone beds beneath. Vertical routes for recharge below the epikarst are infrequent. *(Photograph by David Drew.)*

Figure 4.8 Tilted epikarst encouraging groundwater flow downslope, parallel to the ground surface (western Burren, County Clare). *(Photograph by David Drew.)*

Figure 4.9 Localised recharge to a karst aquifer (New Zealand). In this instance surface landforms (dolines) mark some of these point recharge locations. *(Photograph by Lloyd Homer, GNS Science Ltd.)*

Thus, in addition to storing water, the epikarst may serve to encourage lateral flow, focusing recharge on discrete points 1–10 m beneath the top of the rock, which offer a preferred vertical pathway deeper into the unsaturated zone. These are the distal tributaries of the channel system of the karst aquifer.

Such recharge foci may evolve into the characteristic karstic landform of the doline (Figure 4.9) or may remain without surface expression if mantled by a sufficient thickness of subsoil. If vertical drainage of recharge water from the epikarst is restricted then lateral f ow of water may be dominant (Figure 4.10), especially under conditions of heavy rainfall and the water may re-emerge from an epikarst spring, bypassing the saturated zone of the aquifer completely (Figure 4.11). Figure 4.12 summarises the characteristics of near-surface recharge routes in karstified limestone as described above.

Figure 4.10 Tufa deposits associated with water discharging from discrete zones at the base of the epikarst. The tufa is shown by the white calcareous deposits that start just below the top of the measuring staf . *(Photograph by Caoimhe Hickey.)*

Figure 4.11 Ephemeral spring discharging from the base of the epikarst (County Clare). *(Photograph by David Drew.)*

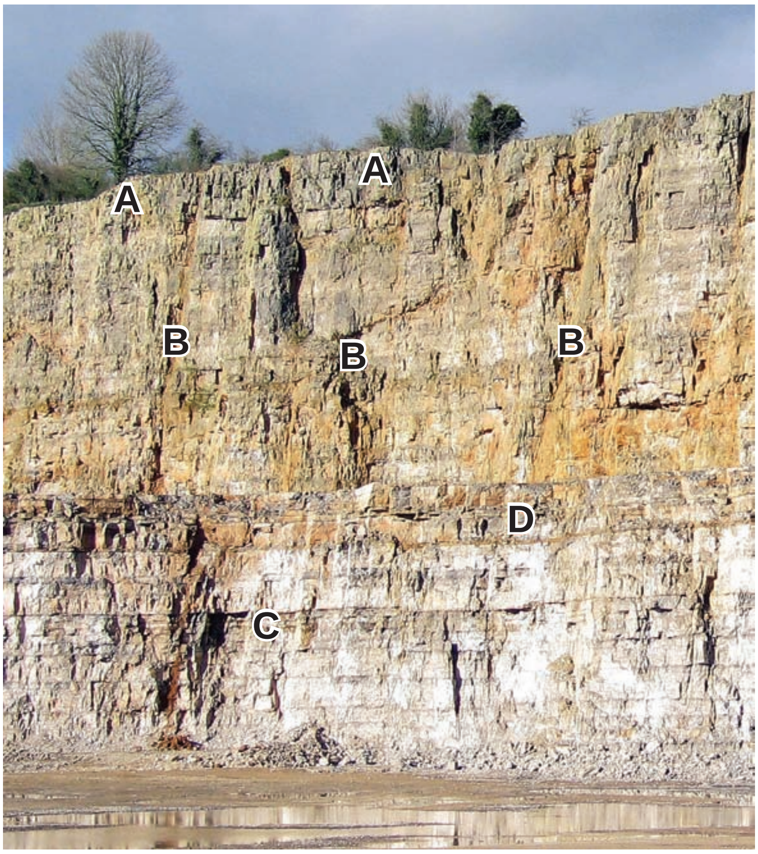


Figure 4.12 Limestone quarry section showing epikarst (A), vertical shafts (B), conduit (C) and semi-impermeable shale bands (D). *(Photographs by David Drew.)*

4.3 Karst Groundwater Flow Systems

A true karst groundwater flow system cannot exist until dissolution of the limestone has created a through route from the recharge zone to an outlet point (Figure 4.2). This conduit then becomes a hydraulic control upon which flow converges and, thus, tributary conduit systems are formed and the network evolves progressively headwards. In immature karst systems, this channel network will consist of a network of poorly integrated, small-diameter channels, whereas in a developed karst drainage system a hierarchy of channels, often ordered in a dendritic network, will convey recharge swiftly and efficiently to discharge points. Both end-members of this range are present in Ireland.

Conduits typically occupy less than 0.1% of the volume of a Carboniferous limestone aquifer in Ireland, but transmit more than 99% of the flow (Figure 4.13). Residence times in conduits are short (typically hours to days), because turbulent flow rates are extremely rapid (mean velocity is estimated to be ca. 80 m/h globally and 90 m/h in Ireland) and approximate more closely to lowland river velocities (ca. 500 m/h) than to flow in porous media (which is usually Darcian and a few centimetres per day).

Figure 4.14 shows an example of a groundwater catchment, that of the Killeany spring in County Clare, which is dominated by conduit flow. Numerous streams arising from peripheral non-soluble rocks sink underground at the contact with limestone. Speleologists have mapped tens of kilometres of cave passage in this catchment and it is apparent that the karst drainage system is almost a replica of the surface drainage network but with a

Figure 4.13 A now abandoned karst conduit which would have been capable of transmitting very large f ows of water at high velocities (Castleguard Cave, Canada). *(Photograph by Derek Ford.)*

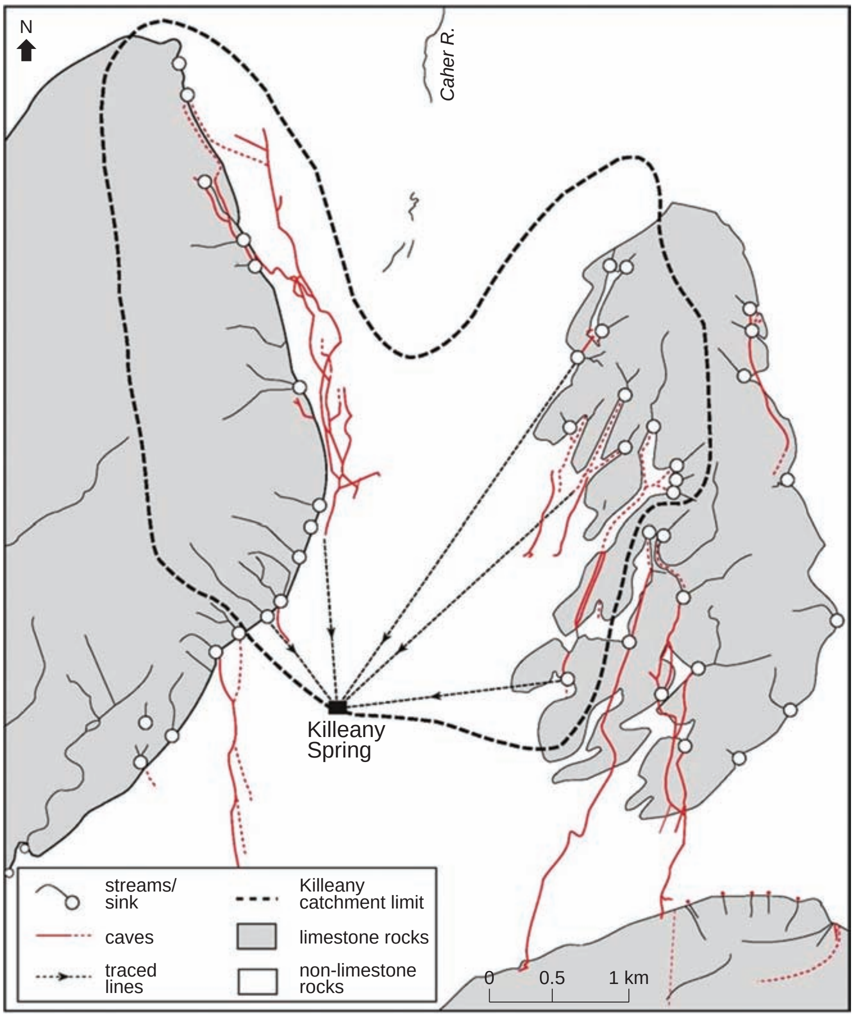


Figure 4.14 The catchment of the Killeany spring (western Burren, County Clare). *(Adapted from Tratman, 1969.)*

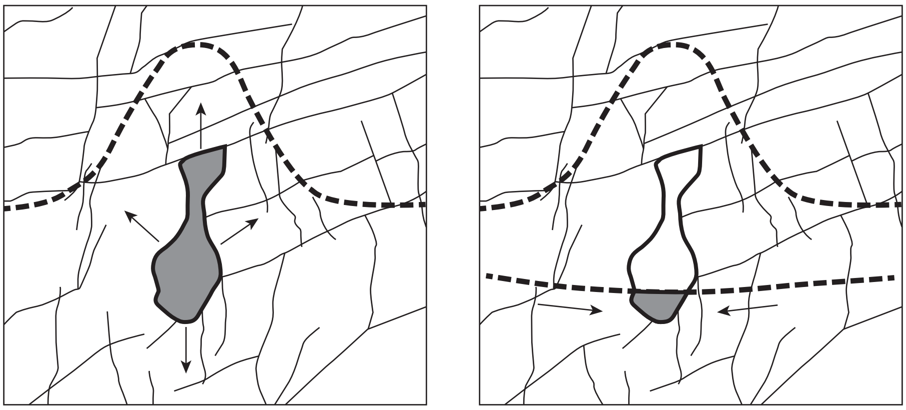


Figure 4.15 Changes in hydraulic head between conduit and fissure systems in a karst aquifer. *(From Kresic, 2013.)*

roof of limestone. Not shown on the survey of conduits is the extensive system of tributary channels, too small for human entry that feed into the larger conduits.

Fracture permeability outside of the main conduit network is usually low in Carboniferous limestones, as is storage, except in the epikarst. Data for residence times are limited as few injection tracings have been carried out via the fracture system. However, information from environmental tracers suggests that residence times of months to years are possible.

In highly karstified aquifers, f ow rates are often highly dependent on stage conditions with velocities varying by at least an order of magnitude over short time periods (Chapter 8). Catchment areas for springs can also expand and contract according to potentiometric conditions.

There is usually a water table of sorts in karstic aquifers but it may be a semi-discontinuous surface as evidenced by the considerable variations in standing water levels recorded in adjacent boreholes in many karst areas. The significance of the water table is also less than in conventional groundwater hydrology as so much of the groundwater is in localised conduits rather than being evenly distributed through the aquifer. For example, cave streams may be perched above the regional water table. There is some evidence to suggest that the zone of maximum permeability in karst aquifers may be in the water table zone, where dissolution of the rock is theoretically greater than deeper in the aquifer.

Exchange of groundwater between the conduit and fissure/matrix voids may take place in response to dif erences in hydraulic head. The exchange can operate in either direction, taking water into longer-term storage or releasing it from fissure/matrix storage into the highly transmissive conduits (Figure 4.15). Such exchanges of water can temporarily alter f ow routes within the aquifer. Irish examples are given in Chapter 7.

4.4 Discharge From Karst Aquifers

Highly karstified aquifers develop f ow systems that are usually conservative, hierarchical and convergent, ref ecting the evolution of progressively more ef cient networks of drainage channels to dispose of runof /recharge. This is analogous to the development of f uvial networks on the land surface where all drainage in a catchment is collected into a single channel, the trunk stream. Hence, groundwater discharge from karst aquifers is common via springs or groups of springs. Various classifications of springs have been proposed based on the geological, topographic or hydrological characteristics or simply by flow magnitude.

Karst springs often show a range of flows of several orders of magnitude, particularly those with a high proportion of point recharge and conduit flow. However, some springs appear to be capped in terms of maximum discharge values and these are termed *underflow springs* (Figure 4.16). Other springs exhibit a wide range of flows, sometimes drying altogether. These may be *overflow springs* (Figure 4.17), which function to discharge water flows beyond

Figure 4.16 Underflow spring (County Galway). *(Photograph by David Drew.)*

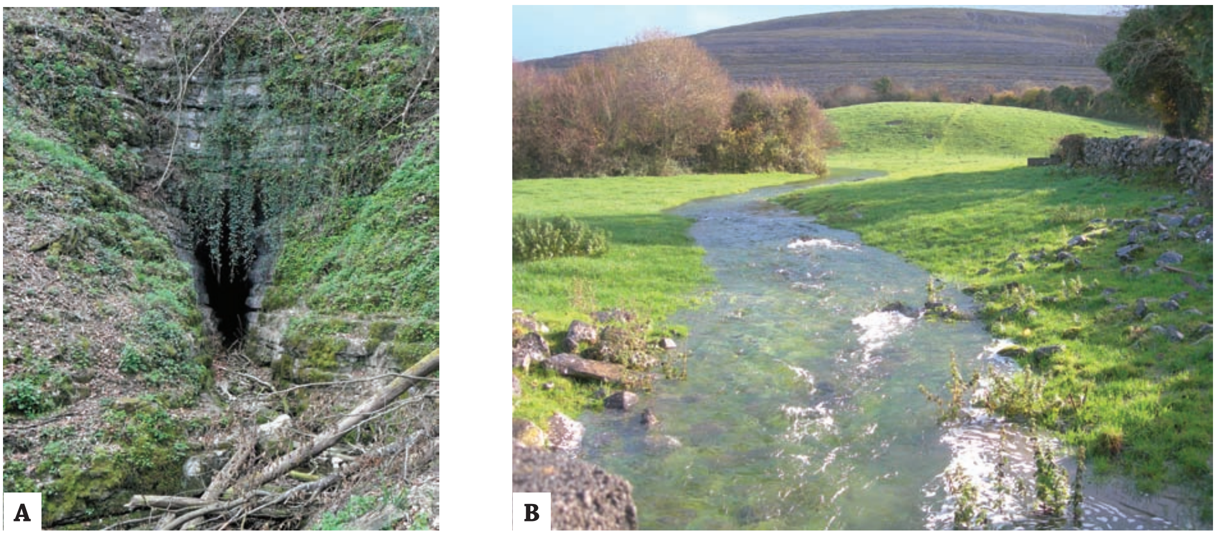


Figure 4.17 Overflow springs. (A) Southern Germany. (B) County Clare. *(Photographs by David Drew.)*

the capacity of the main (underf ow) spring. A fuller classification of springs of relevance in Ireland might be as follows:

free-draining or dammed springs:
- underf ow
- overf ow
- distributary

or by origin of the spring:
- emergence
- resurgence (from swallow holes)
- exsurgence (from dif use recharge)

4.5 Classifying Karst Aquifers

A variety of ways of conceptualising and, hence, classifying karst aquifers have been proposed. Criteria have included strict hydrogeological factors, such as f ow regime, characterisation of the recharge, f ow and discharge mechanism, and also indirect, surrogate indicators of the nature of the aquifer, such as the chemical and physical profile of the spring waters. Figure 4.18 shows the classification suggested by Atkinson (1985). This classification is based on the relative importance of dif use, fissure/fracture and conduit f ow in an aquifer with increasing karstification corresponding to the conduit/turbulent f ow segment of the triangle.

A more elaborate scheme of classification is that of Smart and Friederich (1987) (Figure 4.19). The aquifer is characterised on a triaxial diagram based upon the recharge type (point-dispersed), the type of storage and the f ow type (conduit-dif use). Highly karstic systems are positioned to the front left of the cube with dif use fracture f ow systems at the rear right.

Figures 4.20–4.22 show sample hydrographs from three springs which drain aquifers in Carboniferous limestone in Ireland which may, to some extent, relate to the three types of

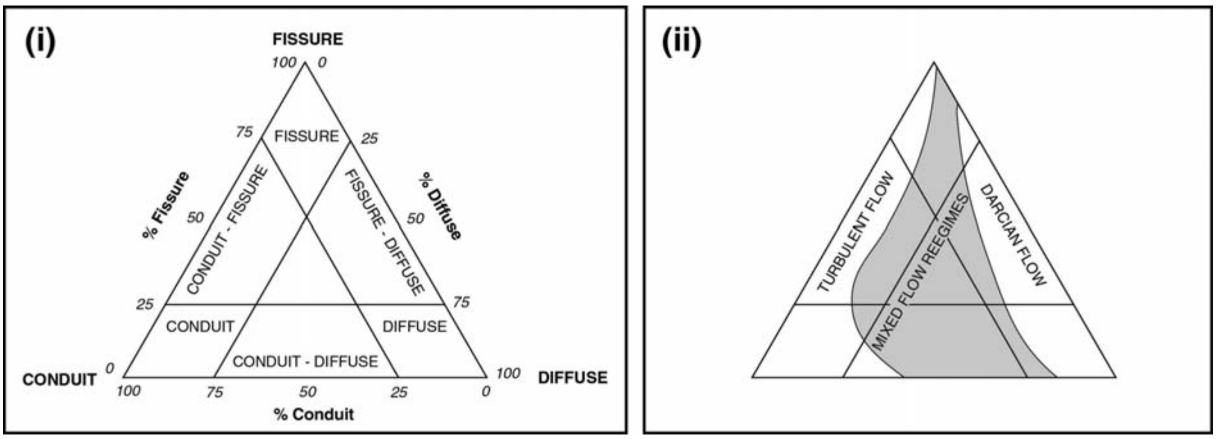


Figure 4.18 Karst aquifer classification according to f ow type. *(From Atkinson, 1985.)*

aquifer shown in Figure 4.19. Manorhamilton (Figure 4.20) is a highly karstified aquifer (type A), Cregduff (Figure 4.21) has a less flashy regime (type B) and Kilmaine (Figure 4.22) exhibits an even more subdued regime with discharge responding to wet spells rather than to individual rainfall events. Such attempts at classification, whilst inevitably somewhat arbitrary, are useful in assisting hydrologists to conceptualise what is happening in the particular aquifer under investigation and in particular to compare springs.

Geological Survey Ireland's classification for karst aquifers is outlined in Chapter 5.

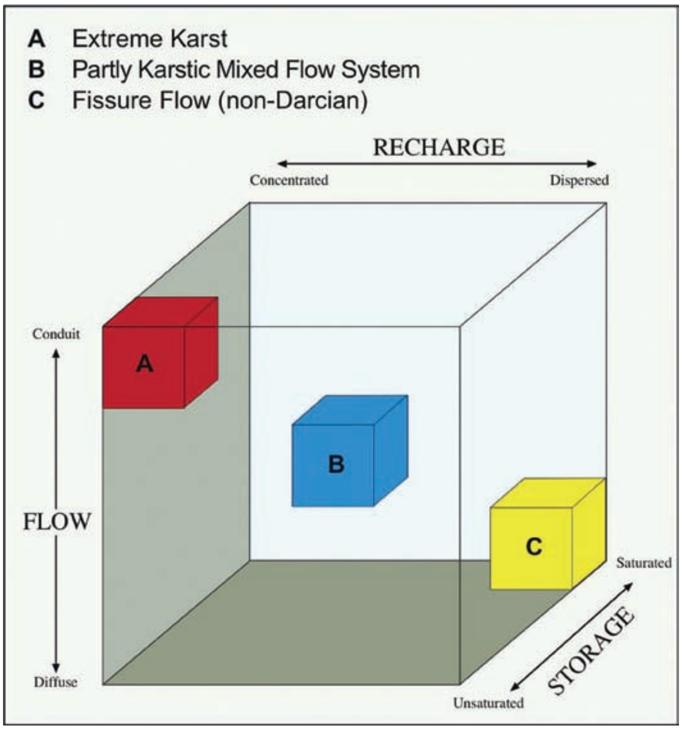


Figure 4.19 A classification of carbonate aquifers based on recharge, storage and flow characteristics. *(From Smart and Friederich, 1987.)*

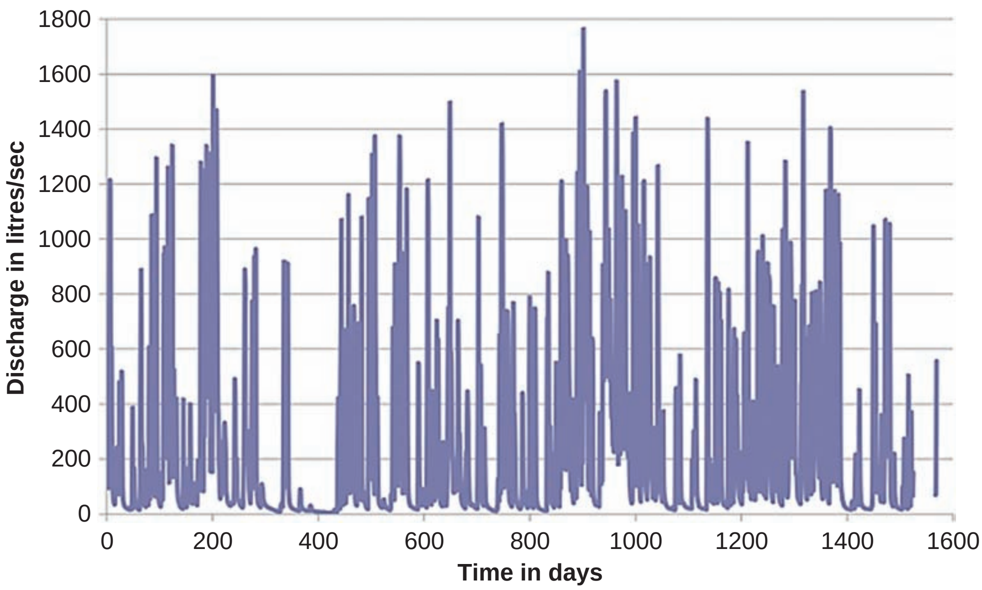


Figure 4.20 Sample hydrograph from Manorhamilton spring (County Leitrim). *(Data from the Environmental Protection Agency, EPA.)*

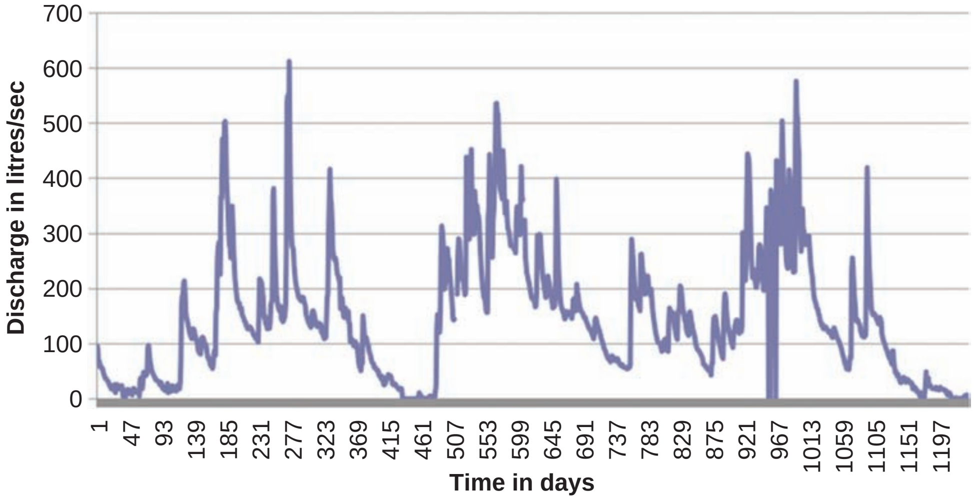


Figure 4.21 Sample hydrograph from Cregduf spring (County Mayo). *(Data from the EPA.)*

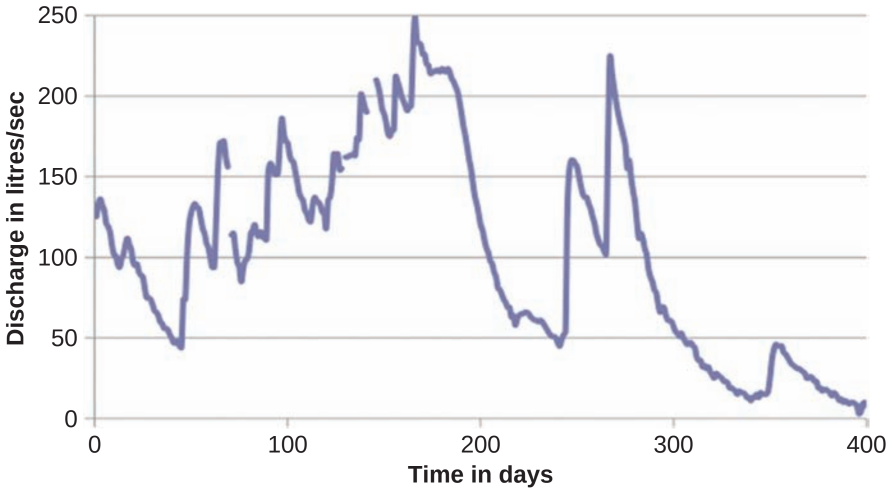


Figure 4.22 Sample hydrograph from Kilmaine spring (County Mayo). *(Data from the EPA.)*

Chapter 5

AN OVERVIEW OF KARST IN IRELAND

5.1 Introduction

Carbonate rocks underlie approximately 40% of the island of Ireland and 45% of the Republic of Ireland. By far the most widespread carbonate rock is Carboniferous limestone but karst also occurs (for example) in the Ordovician limestone at Portrane, County Dublin (Figure 5.1), the Cretaceous Ulster White Limestone Formation in County Antrim (Figures 5.2 and 5.3), the Dalradian limestone in northwest County Mayo, the metamorphosed limestone in Connemara and Donegal and the Triassic gypsum/anhydrite near Kingscourt, County Cavan. However, only the karst developed in Carboniferous limestone is described in any detail in this book.

The distribution of Carboniferous limestone in Ireland is shown in Figure 5.4 together with the distribution of younger and older rock types. Carboniferous limestone is the dominant bedrock over the midlands but is largely absent from the north, southeast, southwest and western extremities.

Figure 5.1 Karst development, modern littoral zone karren and ancient caves, in Ordovician limestone at Portrane, County Dublin. *(Photograph by David Drew.)*

Figure 5.2 Karst development in the chalk in Antrim. A line of enclosed depressions and swallow holes runs along the base of the Knocklayd Mountain at the contact between the younger, overlying volcanic rocks, on the hill, and a thin outcropping band of chalk. *(Source Bing Maps, 2016, https://bing.com/maps/.)*

Figure 5.3 (A) Loughareema swallow hole in Ulster White Limestone at the northeastern margin of the Antrim Plateau and (B) the same feature in flood. *(Photographs by Kirstin Lemon, BGS.)*

Younger strata of Namurian and Upper Carboniferous age overlie the limestone in west Clare and Limerick, in the plateau karst of the northwest (Sligo, Leitrim, Cavan and Fermanagh) and on the Stradbally–Castlecomer–Slieveardagh upland in the southeast. In these areas, the non-limestone strata are being stripped away by fluvial and, previously, glacial erosion. The resulting contact zone between calcareous and non-calcareous rocks becomes the focus of intense karstification – for example, at the southwestern margins of the Burren (Figures 5.5 and 5.6) and at the periphery of the Cuilcagh massif.

At the contact between older strata and the Carboniferous limestone that is around the rim of the central lowlands and at the edges of inliers, such as Slieve Bloom, there is less evidence

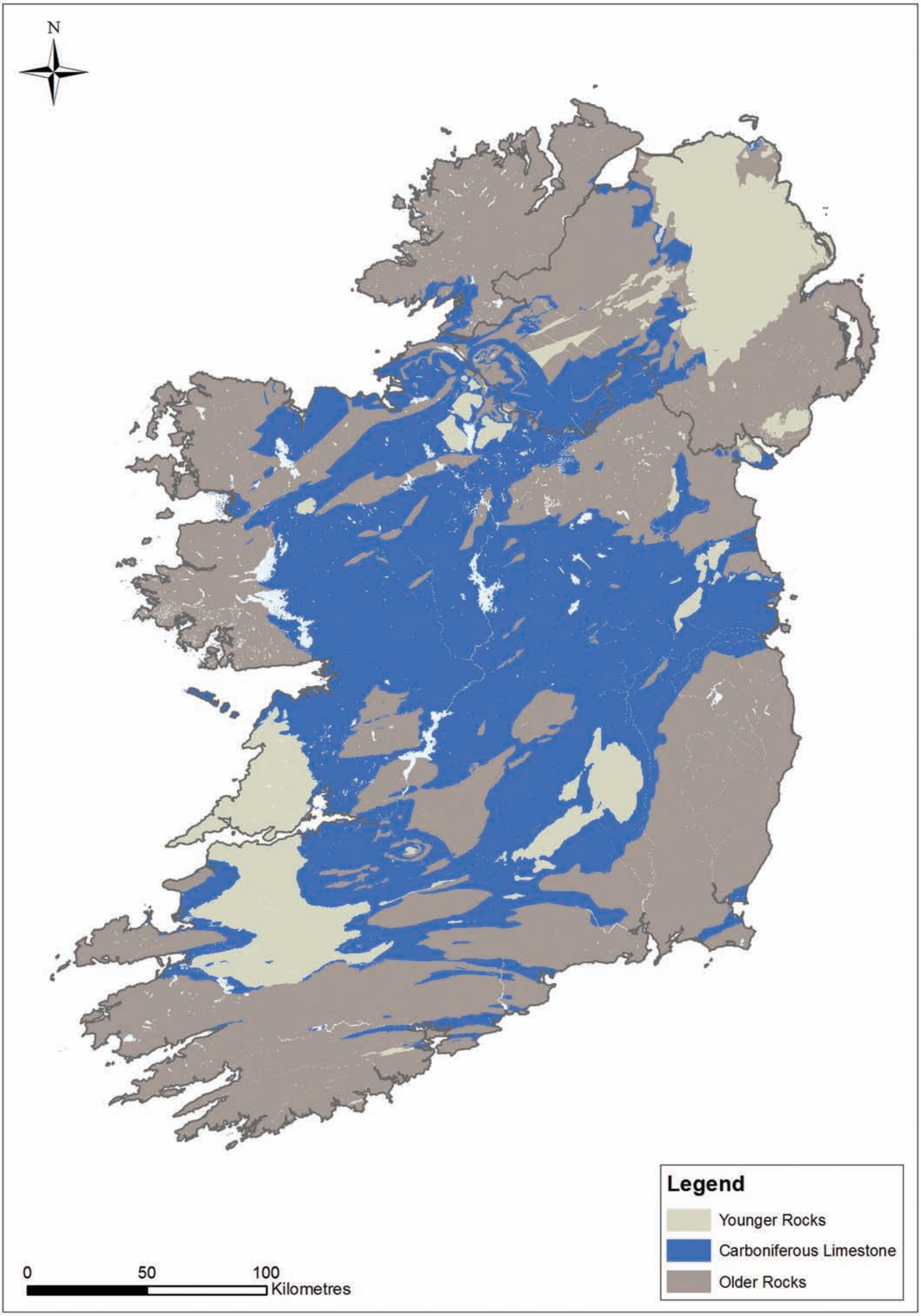


Figure 5.4 The Carboniferous limestone rocks of Ireland and younger and older rocks (simplified). *(Adapted from GSI data.)*

Figure 5.5 The margin of the karstified limestone at the contact with overlying Namurian strata (Burren, County Clare). *(Photograph by David Drew.)*. In the foreground and middle ground are the pavements and green pastures of the limestone terrain. The steep, heather and forest covered scarp in the background marks the outcrop of overlying, non-limestone, Namurian rocks.

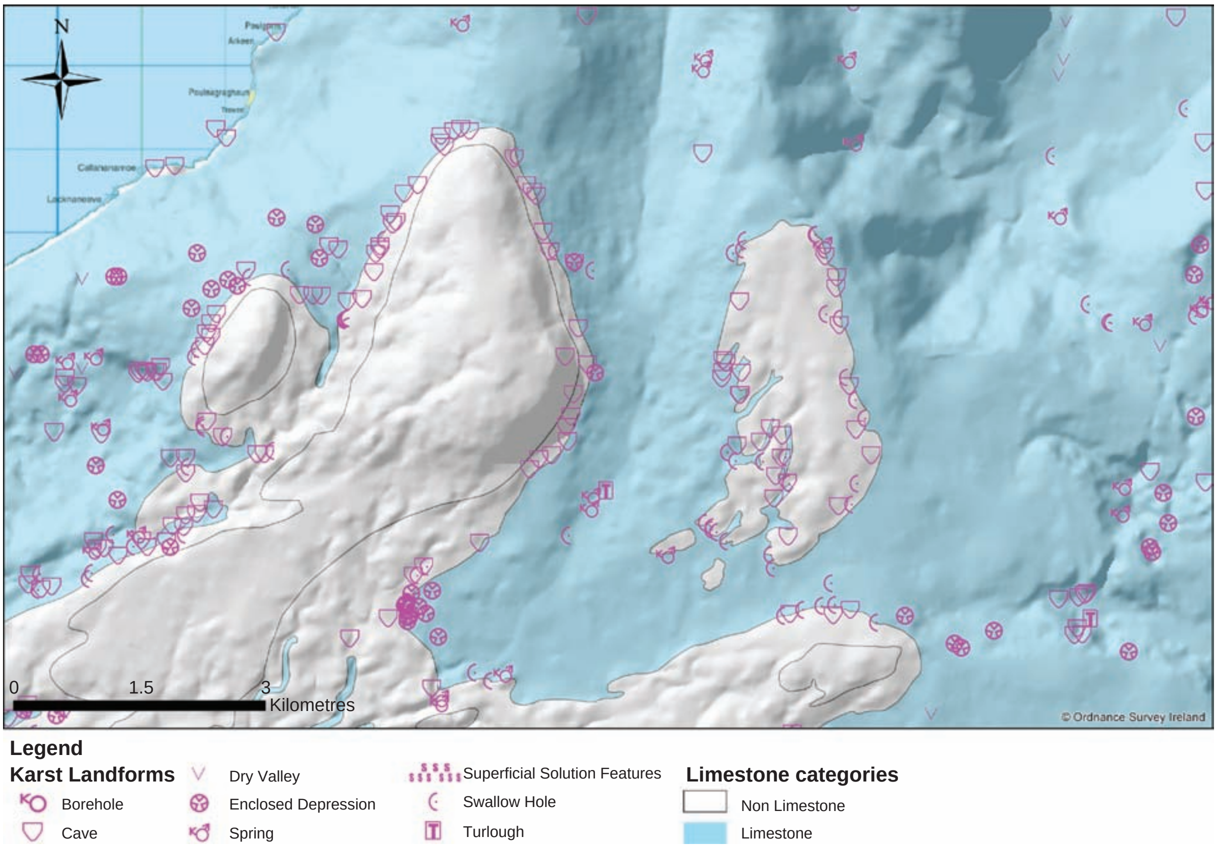


Figure 5.6 Karst landforms, mostly caves, developed at the boundary between the pure bedded limestones and the overlying younger Namurian sandstones and shales (western Burren, County Clare). *(Data adapted from GSI.)*. A detailed view of the cave passages on Poulacapple Hill is shown in Figure 7.88.

for accelerated karstification with the exception of the swallow holes and conduit systems developed on the western flanks of Slieve Aughty in the Gort area of County Galway. In these areas the limestone outcrop has been progressively reduced through time to the extent that, in Counties Cork and Waterford, the limestone outcrop is confined to narrow bands occupying valley floors and, in some instances, the limestone now comprises outliers. In these situations, karstic groundwater circulation may be inhibited and karstification processes are relatively weak. Fossil karst landforms are predominant.

5.2 Classification of Ireland's Karst Rock

5.2.1 Hydrogeological Rock Unit Groups and Limestone Lithologies

Geological Survey Ireland's Rock Unit Groups (RUGs) were created to generalise over 1,400 different geological formations and members found in Ireland, which are delineated by various factors, few bearing relevance to the hydrological properties of the aquifer. The RUGs categorise all these geological divisions into 27 different rock unit types, based on groundwater flow properties (e.g. limestone purity, degree of bedding and/or jointing, degree of deformation). Figure 5.7 shows the RUGs for Ireland.

Seven of these RUGs include limestone bedrock and these were further simplified into four main limestone lithologies, for the purposes of this book: pure bedded limestones, dolomitised limestones, pure unbedded limestones (The Waulsortian Limestones) and impure limestones. The first three of these limestone lithologies, used in this book, are the same as the RUGs of the same name. The impure limestone lithology encompasses impure limestones from all other RUGs containing impure limestone, but principally the Dinantian Lower Impure Limestones RUG (mainly the Ballysteen Limestone) and the Dinantian Upper Impure Limestones RUG (mainly the Calp Limestone). These simplified limestone lithologies are used as the geological base maps for most of the maps used in this book and are shown in Figure 5.8. A brief summary of the main characteristics of the four main limestone lithologies is given below:

The pure bedded limestone lithology and Dinantian Pure Bedded Limestones

The limestones in the Dinantian Pure Bedded Limestone Rock Unit Group (and pure bedded limestone lithology) are generally pure, pale grey, well bedded and fine to coarse-grained. The absence of clay minerals within the limestone beds makes these rocks more brittle than the impure limestones, resulting in a high degree of fracturing, and hence permeability. The degree of bedding, jointing and deformation of these limestones has allowed a high degree of karstification to develop. These limestones are associated with low density surface drainage networks, a high degree of interconnectivity between surface and groundwater and the presence of numerous high yielding springs (>25 l/s). These limestones are deformed in the south of Ireland, resulting in mainly NNE to SSW folds and faults, and are generally flat bedded forming extensive lowlands in the west of Ireland.

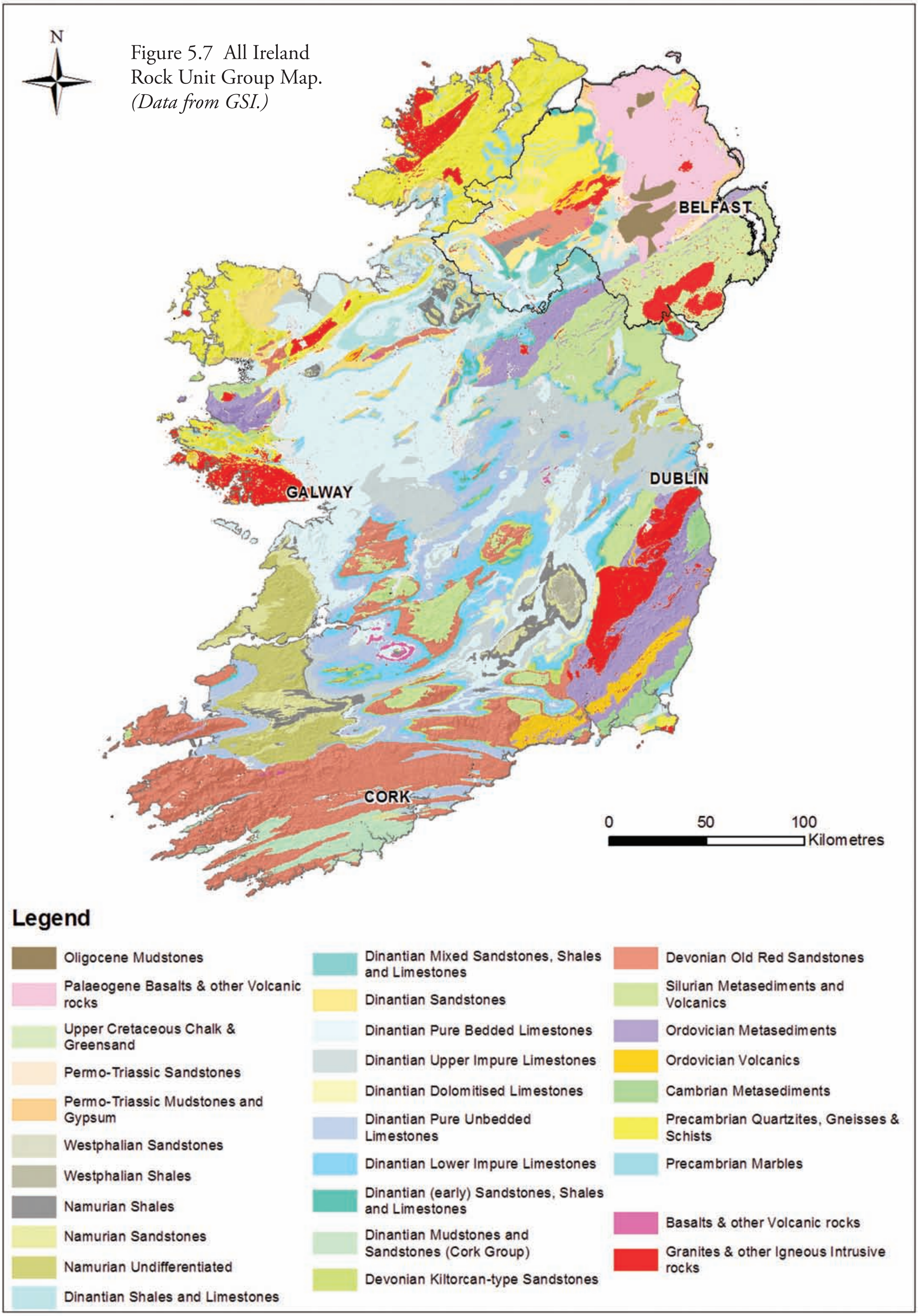


Figure 5.7 All Ireland Rock Unit Group Map. *(Data from GSI.)*

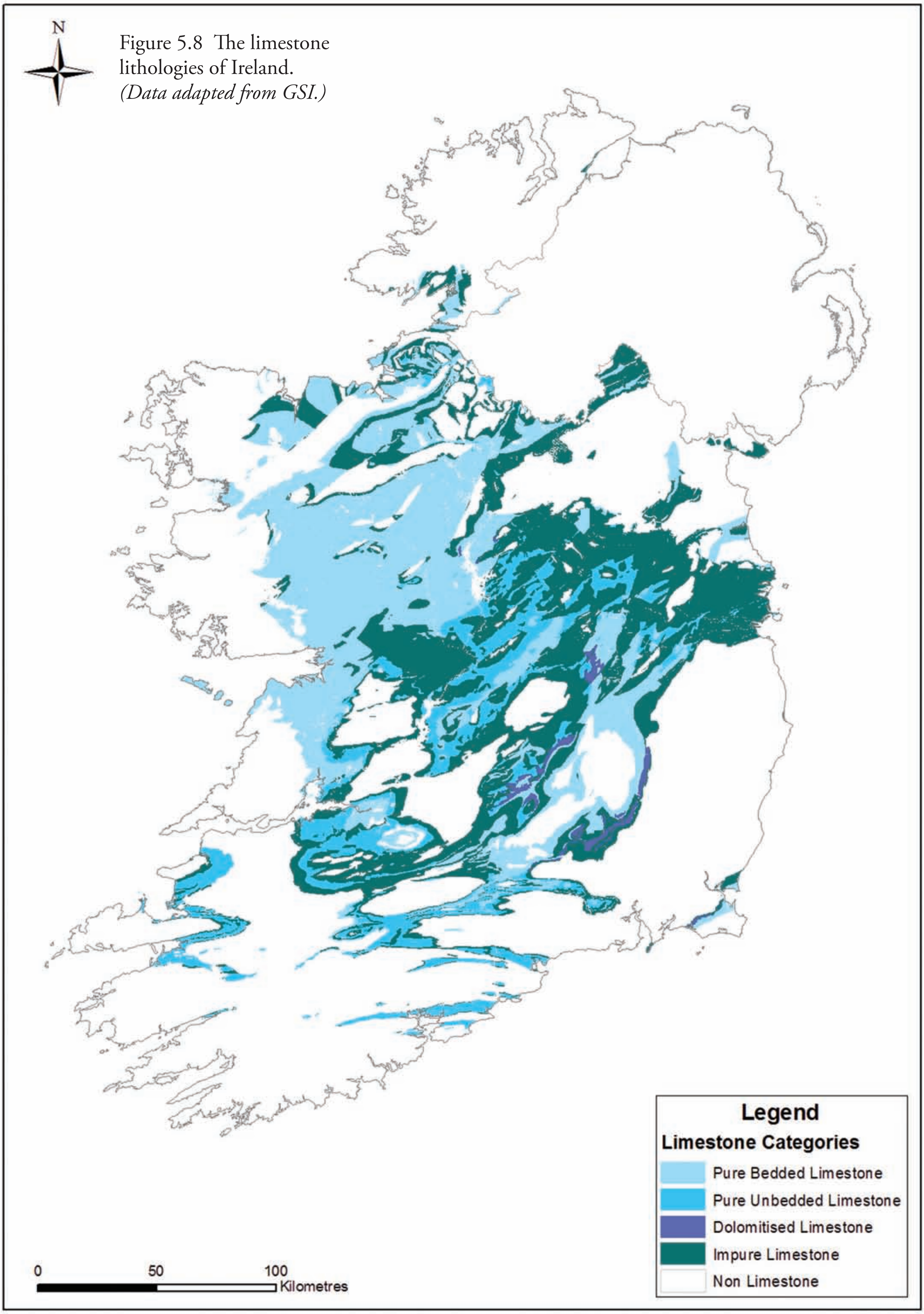


Figure 5.8 The limestone lithologies of Ireland. *(Data adapted from GSI.)*

The impure limestone lithology

The impure limestone lithology encompasses impure limestones from all other RUGs containing impure limestone, but principally the Dinantian Lower Impure Limestones RUG and the Dinantian Upper Impure Limestones RUG. The Dinantian Lower Impure Limestones contain substantial amounts of clayey material and are therefore not very susceptible to widespread solution or karstification. Groundwater movement is frequently restricted to the shallow, weathered sub-surface zone, along faults and other zones of weakness. Due to this low bulk permeability, the limited depth of fracture development and low porosity, these rocks have a poor capacity to accept recharge. In general, flow paths are short and shallow, frequently discharging to small springs or effluent streams.

The Dinantian Upper Impure Limestones encompass a range of limestones that are mostly very impure, dark grey to black, very well-bedded and fine-to-coarse grained. They have a considerable range of grain sizes and contain chert and shale bands. Karst landforms are uncommon. Relatively high surface drainage densities are typical. Flow paths between the recharge and discharge zones are usually short and groundwater is normally restricted to the weathered sub-surface zone near the ground surface. There is little evidence for significant permeability at depth. The water table closely mirrors the topography and, in low-lying areas, is often only 1–2 m below ground level. The Dinantian Upper Impure Limestones are mainly flat-lying and extensive in the midlands from east Galway to Dublin. In the northwest and along the border with Northern Ireland, these limestones are more tilted, outcropping in thin strips and in complex patterns.

The unbedded limestone lithology and the Dinantian Pure Unbedded Limestones

The Dinantian Pure Unbedded Limestones or the Waulsortian Limestones rock unit group are commonly pale grey, fine-grained, massive, pure fossiliferous limestones with calcite in-filled cavities. They developed as calcite 'mud mounds' on the sea floor and are consequently unbedded. Thus, their permeability is dependent on the extent of fracturing and subsequent enlargement of fissures by karstification. In the south of Ireland, these rocks experienced intense deformation. Further north, fissuring is not widely developed, except within isolated fault zones and the near surface extent. Here there is much less evidence of karstification, and groundwater flow patterns generally correspond to surface catchments. Although the limestone is pure and karstification does occur, it is not extensive.

The dolomitised limestone lithology and The Dinantian Dolomitised Limestones

The fourth, wholly limestone rock unit group is the Dinantian Dolomitised Limestones. The process of dolomitisation increases the porosity and permeability of the rock as the crystal lattice of dolomite occupies about 13% less space than that of calcite (Freeze and Cherry, 1979). Dolomitised rocks are usually highly weathered, yellow/orange/brown in coloured and are usually evident in boreholes as loose yellow-brown sand with significant void space and poor core recovery. Dolomitisation is often very localised, occurring at large fault zones and more commonly in purer limestones.

5.2.2 Geological Survey Ireland's (GSI's) Aquifer Classification and Irish Limestones

GSI's aquifer classification

All of the Republic of Ireland's land surface is divided into nine aquifer categories, based on the hydrogeological characteristics and on the value of the groundwater resource. They are as follows

Regionally Important (R) Aquifers:
- karstified bedrock (**Rk**)
- fissured bedrock (**Rf**)
- extensive sand and gravel (**Rg**)

Locally Important (L) Aquifers:
- karstified bedrock (**Lk**)
- sand and gravel (**Lg**)
- bedrock which is generally moderately productive (**Lm**)
- bedrock which is moderately productive only in local zones (**Ll**)

Poor (P) Aquifers:
- bedrock which is generally unproductive except for local zones (**Pl**)
- bedrock which is generally unproductive (**Pu**)

Irish limestones and aquifer category

The Geological Survey's aquifer map distinguishes between limestones with and without a high degree of karstification. All limestone categories, depending on their permeability, storage capacity and areal extent, are categorised into Regionally Important (R); Locally Important (L); and Poor Aquifers (P). Regionally important limestone aquifers are sub-divided into three categories. Where karstification is slight, the limestones are hydrogeologically similar to fissured rocks and are classed as Rf, although some karst features may occur. Aquifers in which karst features are more significant are classed as Rk. Within the range represented by Rk, two sub-types are distinguished, termed Rkc and Rkd.

Rkc are those aquifers in which the degree of karstification limits the potential to develop groundwater resources. They have rapid flow velocities and a significant proportion of flow is concentrated in conduits focussed on large springs. Storage is low and locating areas of high permeability is difficult; therefore, groundwater development using bored wells can be problematical. Such aquifers are common in, for example, the pure limestones in the Burren, mid Galway, south Mayo and Roscommon.

Rkd aquifers are those in which flow is more diffuse, storage is higher, there are many high yielding wells and the development of productive bored wells is less difficult. These areas may also have caves and large springs, but the springs flow regimes are less flashy than those in Rkc aquifers. Examples of Rkd aquifers include those in the pure limestones in Cork, Kilkenny, Offaly and Waterford.

Figure 5.9 shows the sub-divisions of the Carboniferous limestone with respect to its hydrogeological characteristics (aquifer types), which in turn correspond to the extent

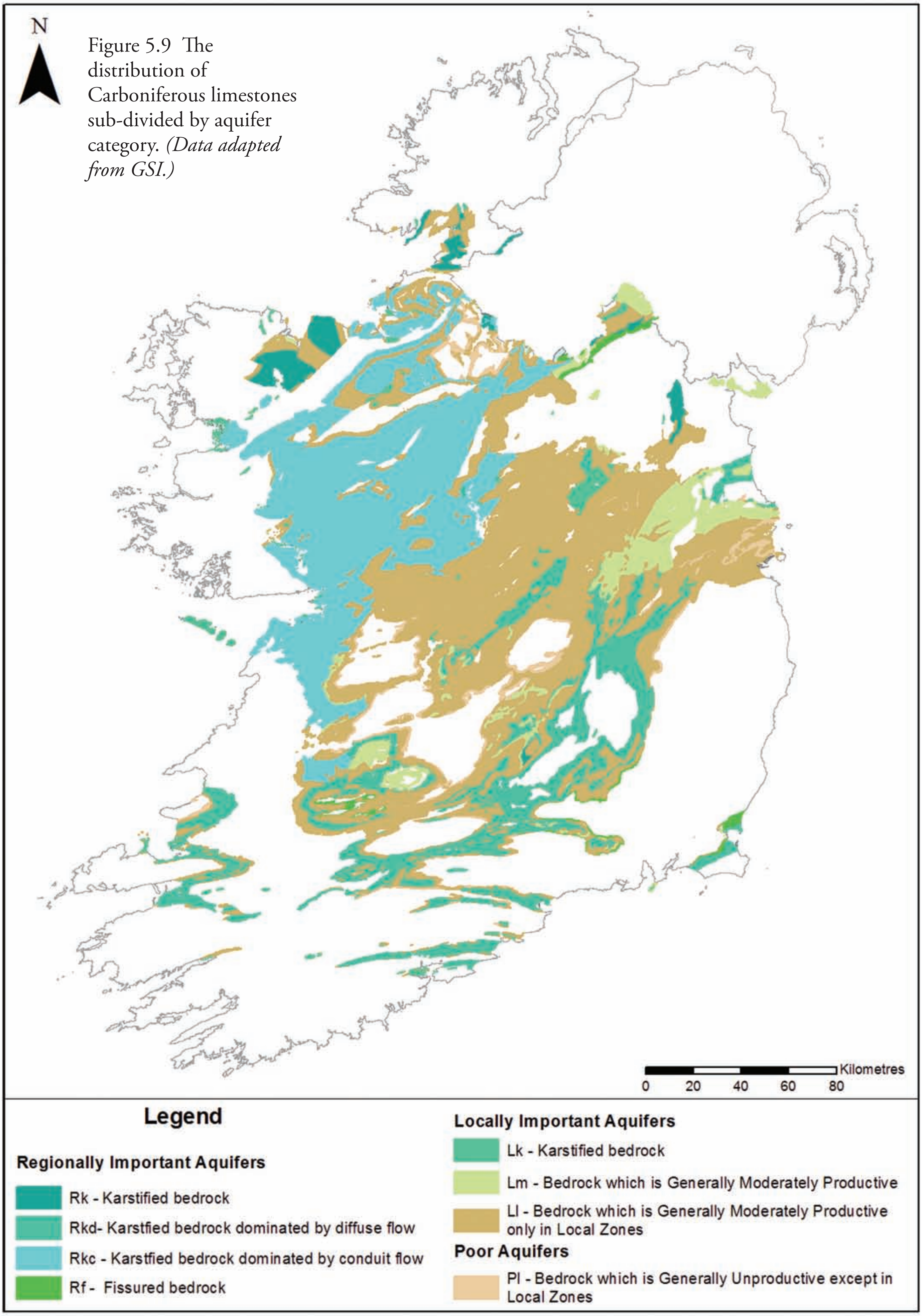


Figure 5.9 The distribution of Carboniferous limestones sub-divided by aquifer category. *(Data adapted from GSI.)*

to which the limestones are presumed to be karstified. The map shows that most Irish Carboniferous bedrock is classified as either Regionally Important (45%) or Locally Important (52%), with 3% classified as Poor aquifers.

More details on Geological Survey Ireland's aquifer classification and the hydrogeology of Irish limestones are given in Chapter 8.

5.2.3 Extent of Karstification

The extent to which the limestone in Ireland is karstified is uncertain but it is probable that all of the limestones have experienced solutional weathering and so the relevant question is not '*Is this outcrop of limestone karstified*?' but rather *'To what extent does the aquifer system behave karstically rather than as a fractured rock aquifer?'*

If the lateral extent of karstification is uncertain then the vertical extent is even more problematic. It has been remarked that lower sea levels during the Quaternary have allowed deep karstification in the limestones adjacent to the coast in the south of Ireland (e.g. Wright, 1979) but with limited concrete evidence (Chapter 8).

Presumably lower base levels would also have influenced the depth of karstification in other areas (e.g. Kerry, Limerick, Clare, Sligo, Donegal, Wexford) where the limestone outcrop extends to below sea level. Examples of karst developed below present sea level are given in Chapter 8.

Carboniferous limestone comprises approximately 31,000 km^2 of the bedrock in the Republic of Ireland. Within this area a wide variety of karstic landscapes are found, some of them not obviously karstic. These differences are due in part to differences in the lithology and structure of the limestone, but also due to the nature and intensity of other geomorphic

Figure 5.10 An inlier of Devonian and Silurian rocks (Galtee Mountains, County Tipperary), surrounded by the limestone lowland. *(Photograph by David Drew.)*

processes operating now and in the past. The length of time for which the karst has been developing is also important, as is the nature and thickness of the sub-soil.

Figures 5.11–5.16 show some examples of these varied 'karsts' found in Ireland. The Burren upland karst with its extensive areas of bare rock (Figure 5.11) contrasts markedly with the plateau karst of the northwest with thick peat blanketing the limestone and heather the dominant vegetation (Figure 5.12). The lowland karsts are even more varied, encompassing some of Ireland's richest agricultural land with no obvious evidence for karstification (Figure 5.13); the western lowlands with thin soils and obvious karst features (Figure 5.14); large areas of limestone pavement virtually at sea level (Figure 5.15) and seasonally watery karsts in which lakes rather than karst drainage dominate (Figure 5.16); a remarkable diversity of limestone landscapes within a relative small country.

Figure 5.11 Rocky plateau karst, the Burren, commonly regarded as a typical karst, though many aspects of the landscape owe their appearance as much to glacial as to karstic processes. *(Photograph by David Drew.)*

Figure 5.12 Peat covered plateau karst in County Leitrim. Bedrock exposures are almost wholly absent but the absence of surface drainage, despite >2,000 mm of annual precipitation, and the presence of numerous dolines (middle foreground) in the peat testify to the karst nature of the groundwater system. *(Photograph by Caoimhe Hickey.)*

Figure 5.13 Lowland karst in County Tipperary, an unobvious karst. (A) Karst features are blanketed beneath the relatively thick topsoil but the well-developed epikarst in the motorway cutting at the same location (B) shows that the bedrock is highly karstified. *(Photographs by David Drew.)*

Figure 5.14 Lowland karst in County Galway with the bedrock covered by a thin veneer of rendzina soil. *(Photograph by David Drew.)*

Figure 5.15 Lowland limestone pavement in County Clare. *(Photograph by David Drew.)*

Figure 5.16 Fluvio-lacustrine karst near Gort (County Galway). Complex interactions between surface and underground water characterise this karst. *(Photo by OPW.)*

Chapter 6

THE DEVELOPMENT OF KARST IN IRELAND

In the 360 million years since the Carboniferous limestone began to be laid down, there are known to have been several episodes of karstification and there may have been many more of which nothing is known at present. Some elements of these ancient karsts are still apparent, as relict karst landforms, in the Irish landscape; others have been, in part at least, re-activated or influence present-day hydrological processes in other ways.

Karstification of the limestone took place during some of the periods in the Lower Carboniferous when the land was above current sea level and sub-aerial processes could operate. The superficial karstic solutional landforms, infilled by non-carbonate deposits and subsequently buried by later lime sediments, are apparent at many locations in Ireland. Now they commonly function as barriers to groundwater movement and, hence to karstification, an example being the clay wayboards in the Burren (Figure 6.1 and Chapter 8).

Apart from the Namurian and Upper Carboniferous strata that blanketed the limestones, and still do over wide areas, uncertainty prevails as to the extent to which the limestones were buried and then re-exposed during the vast period of time spanned by the remainder

Figure 6.1 Karstification during the mid-Carboniferous Period. Solutionally enlarged joints and karst runnels developed below a bedding plane surface during a period when the limestone was exposed to sub-aerial weathering and subsequently infilled by wayboard (volcanic ash?) material, limestone of Brigantian age, Whelan's Quarry (Ennis, County Clare). *(Photograph by David Drew.)*

of the Palaeozoic, the Mesozoic and the greater part of the Cenozoic (Appendix B), and hence the times during which karst processes could operate. Such evidence for ancient karstification is confined to the Cenozoic Era and comprises both negative landforms, such as enclosed depressions, enlarged fissures/sinks and caves, sometimes with dateable sediment infills (Figure 6.2), and positive landforms such as karst towers.

Figure 6.3 shows the location of dated and undated sediments infilling karst features in Ireland, together with the location of known and inferred buried features (located by core drilling or by geophysics), large-scale enclosed depressions and 'karst towers' (single or groups of steep sided hillocks similar in appearance to those characteristic of present day mature tropical karsts). Some relict caves are also shown – only those caves which are thought, with some degree of confidence, to be mid-Pleistocene or earlier in date, which is a very small sample of the over 300 relict caves known in Ireland. Dated sediments are so limited in number (two each of Oligocene, Oligocene-Miocene, Miocene and Pliocene, Appendix B) as to preclude any meaningful interpretation of type or distribution.

Similarly, the (minimum) age of a very few of the relict caves has been established (using uranium-thorium series dating). With the exception of Aillwee Cave in the Burren (Figure 6.4), all dates acquired from speleothems have been of Holocene or last inter-glacial age. However, many of the caves, particularly those in hydrogeologically anomalous positions

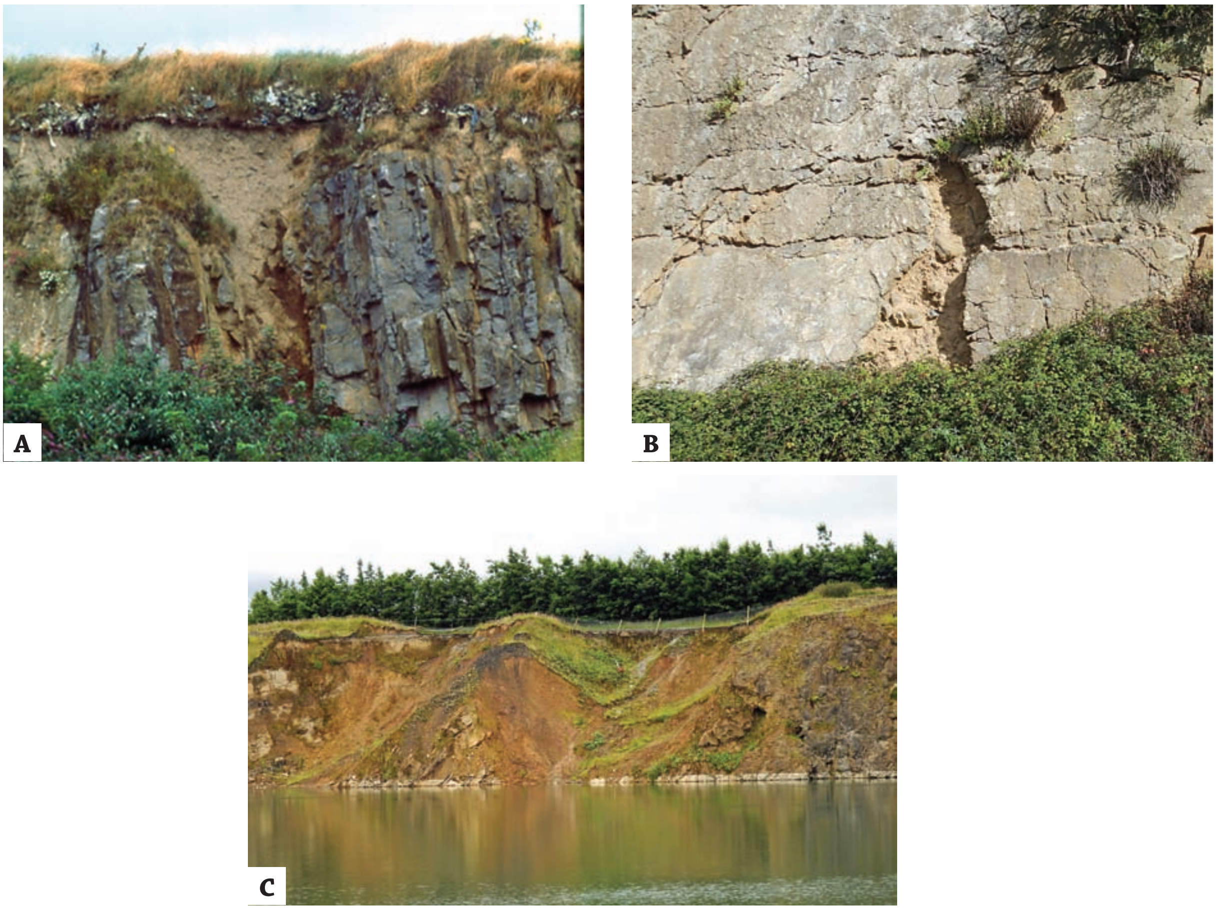


Figure 6.2 Palaeokarst features. (A) Infilled pipe (Tullyallen, County Louth). *(Photograph by David Drew.)* (B) Infilled cave (Tullyallen, County Louth). *(Photograph by Robert Meehan.)* (C) Infilled doline (Carrickboy, County Longford). *(Photograph by David Drew.)*

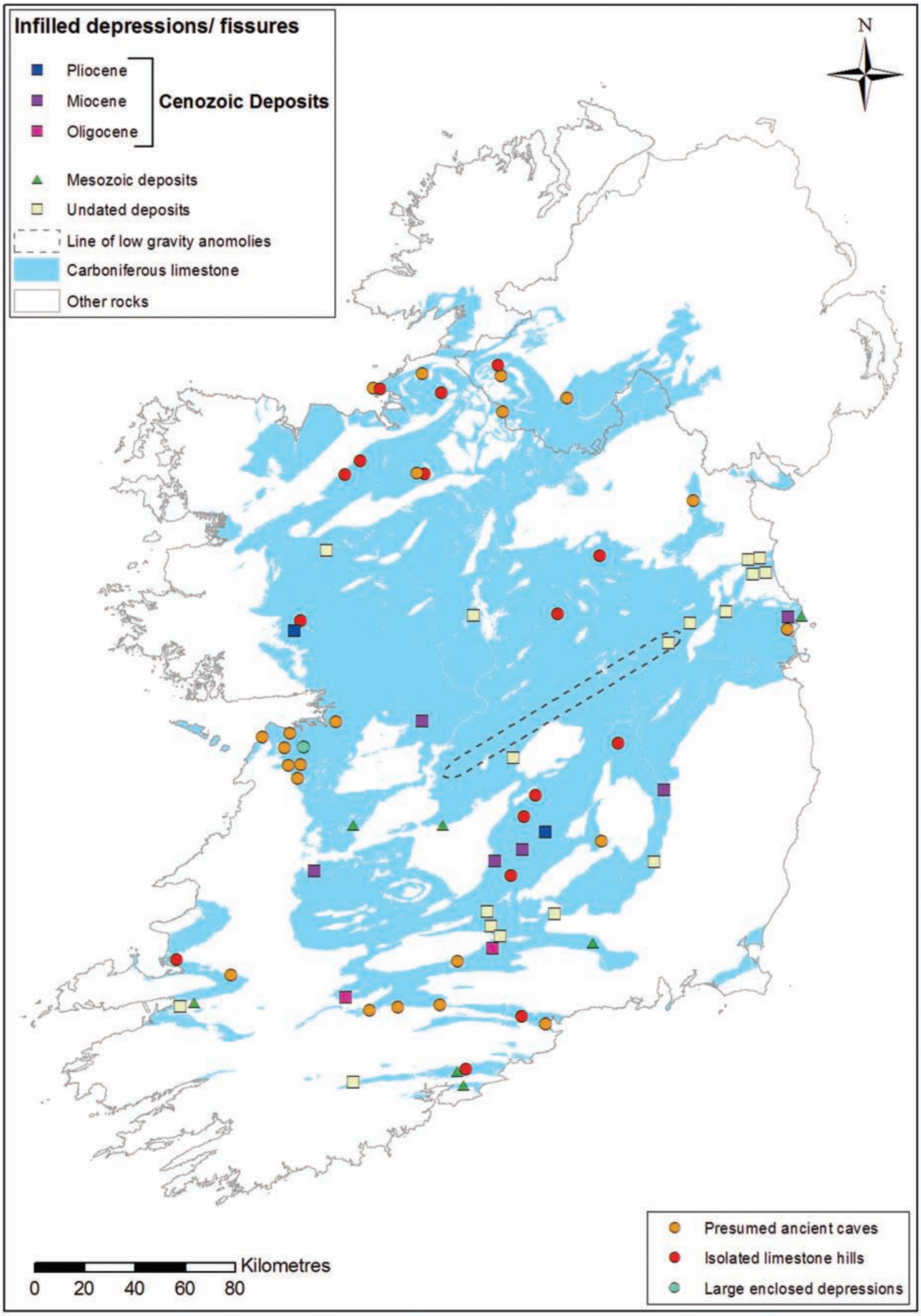


Figure 6.3 Location of dated and undated Mesozoic and Cenozoic deposits infilling karst features and presumed ancient karst landforms (caves, karst towers and large-scale enclosed depressions) in Ireland. *(Modified from Drew and Jones, 2000 as adapted by Coxon, 2006.)*

(Figures 6.5–6.7) such as Maze Holes in the Burren, Kesh Caves (Figure 6.7) and Dermot and Grainne's Cave in County Sligo, and many of the caves of Cork and Waterford, are almost certainly of great vintage. A small calcite deposit in Aillwee cave has been dated to greater than 440,000 years old and possibly one million years old and seems to relate to a time when the cave had already been formed and partially infilled.

No age has been assigned to any of the 'karst cone/tower' landforms (Figures 6.8 and 7.98). There are no obvious structural or lithological explanations for the towers so it is credible that in some areas they represent the isolated remnants of a cone-karst topography, largely destroyed by lateral solutional erosion on the karstic plain of the Irish lowlands. However, in other areas they may represent a former karst upland dissected and almost destroyed by glacial processes.

Figure 6.4 Abandoned stream passage (Aillwee Cave). *(Photograph by Colin Bunce.)*

Figure 6.5 Abandoned former sub-water table conduit (Desmond Cave Tipperary). *(Photograph by Robert Mulraney.)*

Figure 6.6 Fragments of a phreatic cave system near the summit of Aillwee Hill, Burren, some 250 m above the present zone of saturation. *(Photograph by David Drew.)*

Figure 6.7 (A) and (B) Kesh Corran Caves (County Sligo). *(Photographs by David Drew.)*

Figure 6.8 Isolated limestone hillocks with cave fragments (Dunamase, County Laois). *(Photograph by David Drew.)*

Thus, it is certain that karstification occurred, particularly during the Cenozoic Era under sub-tropical climates and with sea-levels well below present-day. It may be that the karst landscape of Pliocene, or even earlier times, may have been similar to that of the present day as argued by Williams (1970), Coxon and Coxon (1997) and others.

The Pleistocene Epoch has profoundly influenced karst geomorphology and hydrogeology in Ireland, but our lack of detailed knowledge of events in any but the latest glacial and interglacial times means that landscape evolution can only be discussed in generalised and largely speculative terms. During the interglacials and shorter warmer periods, karstification presumably took place at least on the scale of that in the Holocene, and it might be that some of the relict karst features date from these episodes rather than from pre-Quaternary times.

Glacial and glacio-fluvial deposits blanket the pre-Pleistocene landscape of the limestone lowlands of Ireland to varying depths, masking the karstic landforms, particularly east of the River Shannon. Basal tills, if sufficiently thick, may have effectively confined pre-existing aquifers, whilst caves and smaller conduits such as those found in the epikarst aquifers may have been sealed with intruded glacial or fluvioglacial deposits (e.g. Aillwee and Glencurran Caves respectively, County Clare). However, in more elevated sites with shallow subsoils, such as the Hill of Uisneath in County Westmeath, doline fields probably pre-dating at least the last glaciation, are preserved (Figure 6.9).

Glacial erosion is unlikely to have removed major karst landforms such as medium or large dolines, but may have inactivated them hydrologically or modified them physically. Sub-glacial or glacier marginal meltwaters may have created or modified karst drainage systems in what now seem to be topographically improbable locations, for example Aillwee and Vigo caves in the Burren.

Although the mean value for solutional erosion of limestone in Ireland during the Holocene amounts to only 160 mm of surface lowering, this average masks great differences ranging from zero where the limestone bedrock is buffered by calcareous till to values of greater than 1 m where highly aggressive water has access to limestone. In some instances glacial features have become partially karstic features – for example glacial grooves enlarged into elongate corridor karst, kettle holes functioning as dolines (in the lower Deel valley, County Mayo) and moraine-dammed valleys impounding what are now turloughs (Lough Aleenaun, County Clare).

There are also landforms that are wholly Holocene in age, such as some of the simpler swallow hole caves in the Burren; sinks located at the edge of raised bogs and at points where till deposits are thin or absent on the western limestone lowlands; collapse dolines on all scales and, probably, turloughs. Most karren forms must be assumed to be of Holocene age even though some limestone pavements and associated grikes may have survived at least one glacial cycle.

Karrenisation may be rapid. The extensive areas of bare limestone on the southeastern shore of Lough Mask in County Mayo are pitted with small solution hollows (kamenitza) and other solution hollows (Figure 6.14), which are clearly of Holocene age and which are located in the zone of seasonal fluctuation of lake water level. There are also a suite of kamenitza developing on lower rock surfaces that have only been in the zone of fluctuation since water levels in Lough Mask were lowered by the construction of the Cong Canal in the middle of the nineteenth century. Rising sea-levels in post-glacial times have modified karst drainage systems in coastal karsts such as eastern and southern Galway Bay as is evidenced by cave conduits now below sea-level, for example the Blue Holes at Doolin, County Clare.

Figures 6.10–6.14 are examples of karst features which have almost certainly been developed during the Holocene.

Figures 6.15 and 6.16 show the geomorphological features of a 200 km^2 area of the limestone lowland south of Tuam, County Galway and illustrates the complexity of karst in (at least) the lowland limestones. The area is considered to be an ancient (possibly Miocene) karst surface with the isolated limestone hill of Knockmaa rising from the plain to the north and to the southwest, gorges (less than 20 m deep) and karst caves infilled with non-carbonate sediments of Pliocene age at Pollnahallia. Numerous dolines of various dimensions and of

Figure 6.9 (A) The Hill of Uisneath (County Westmeath). *(Photograph by David Drew.)* and (B) the doline field on its summit. *(Photograph by Archaeology Department NUIG.)*

unknown age pit the land surface, whilst a drainage pattern of turloughs and (largely artificial) river channels is the surface expression of a complicated surface water-groundwater karst system. Such a karst palimpsest may be characteristic of wide areas of lowland karst in Ireland.

Many of the karst locations and features mentioned in this section are also referred to in Chapter 7 – Karst regions of Ireland.

Figure 6.10 Solution pits c.10–15 mm in diameter in the seasonally inundated areas on the southeastern shore of Lough Mask (County Mayo). They have developed since the mid nineteenth century when water levels in the lake were lowered following the construction of the Cong Canal. *(Photograph by David Drew.)*

Figure 6.11 Notch in a limestone boulder developed by solutional erosion in the zone of seasonal water level change in what was formerly an extension of Lough Ree (Cornaseer, County Roscommon). *(Photograph by David Drew.)*

Figure 6.12 Sinks and dolines on the margin of a bog (County Roscommon). *(Photograph by Aerpas for Caoimhe Hickey.)*

Figure 6.13 A 2.5 m deep vadose trench that may have developed during post-glacial times (Cullaun 2 Cave, County Clare). *(Photograph by Colin Bunce.)*

Figure 6.14 A 1 m high pedestal developed in the Holocene, beneath an erratic (Leean Mountain, County Sligo). *(Photograph by Richard Thorn.)*

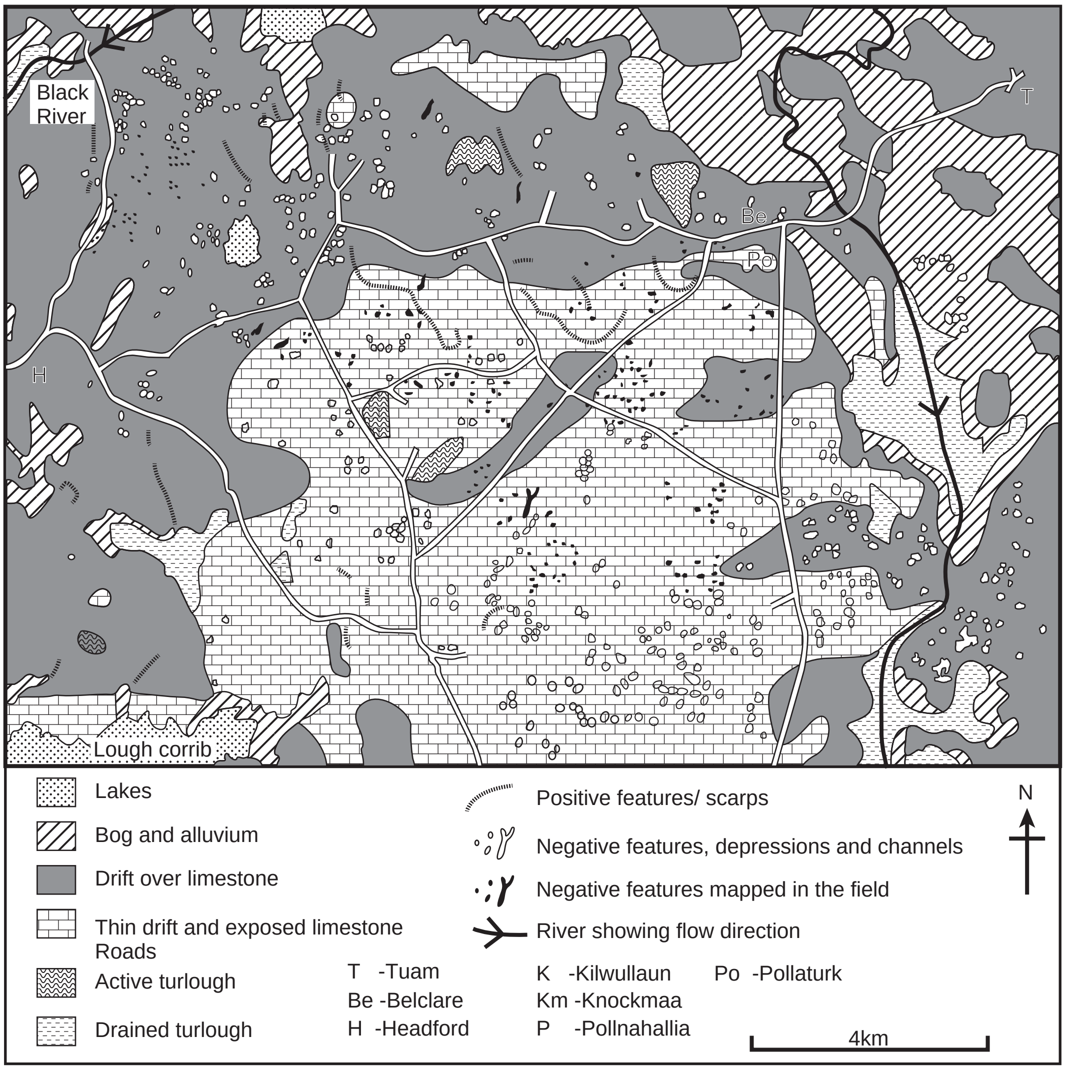


Figure 6.15 Geomorphological features in a 200 km^2 area of limestone lowland south of Tuam (County Galway). *(From Coxon, 2005).*

Figure 6.16 (A) The featureless till plain southwest of Tuam (County Galway) with the residual limestone hill of Knockmaa in the background, (B) The infilled karst gorge at Pollnahallia in the same area. *(Photographs by David Drew.)*

Chapter 7

KARST REGIONS OF IRELAND

7.1 The Distribution of Karst in Ireland

Carboniferous limestone outcrops in all the counties of the Republic of Ireland with the exception of County Wicklow. Geological Survey Ireland's karst database shows that karst features have been recorded for all other counties except for Wexford and Carlow, both of which have only very small areas of limestone bedrock. However, it is probably the case that all limestone of reasonable purity in Ireland has been karstified to some degree, though without this necessarily being manifested in terms of karst landforms, particularly in areas where bedrock is overlain by thick subsoils.

Figure 7.1 shows the distribution of recorded karst features in relation to the outcrop of the four main limestone lithologies (Section 5.2). Caution is needed when interpreting these maps as they represent the current state of knowledge of the existence of karst features and the detail in which various areas have been mapped varies considerably. Also, a karstified limestone does not necessarily exhibit many surface karst features if the subsoil cover is thick. This may explain the greater abundance of karst features mapped in the lowland areas west of the Shannon where Quaternary deposits are generally thinner than further east. However, it is apparent that in general terms the greatest concentration of karst features and, therefore, possibly the most intensive karstification, is on pure bedded limestones to the west of the River Shannon. Extensive outcrops of impure and unbedded limestones in the northeast and midlands of Ireland have few recorded karst landforms.

Figures 7.2 and 7.3 show the numbers of different types of karst landforms (and the total numbers) located on each aquifer category (Chapter 5.2.2). It can be seen from this that there are over 11,200 landforms recorded in the database of which the most abundant landform type are enclosed depressions, accounting for 65% of the total. Springs are the next most common landform type (13%) followed closely by swallow holes (11% of landforms). However, it can be seen from Figure 7.1 that the landforms are not evenly distributed across all aquifer types, with the regionally important karstified aquifers hosting 89% of all mapped landforms. The remaining 10% are found in locally important karstified aquifers (in the Lk and Ll category). However, some aquifer types underlie far greater areas than others and so karst landforms were also plotted per 100 km^2 of each aquifer type (Figure 7.3). From this, the dominance of the karst aquifers, over all others, can be seen.

The lithology of the limestone was also assessed in terms of karst landform type and numbers. Figure 7.4 shows the numbers of each karst landform type, for each principal limestone lithology. The dominance of the pure bedded limestones can be clearly seen across all landform types with 83% of all landforms (Figure 7.4). Somewhat surprisingly, 9% of all karst landforms are found in the impure limestone category, and pure unbedded and dolomitised limestones account for only 8% and 1%, respectively. However, the impure limestones account for 44% of the limestone types by area, whereas, the pure unbedded and the dolomitised limestones account for 15% and 1% respectively.

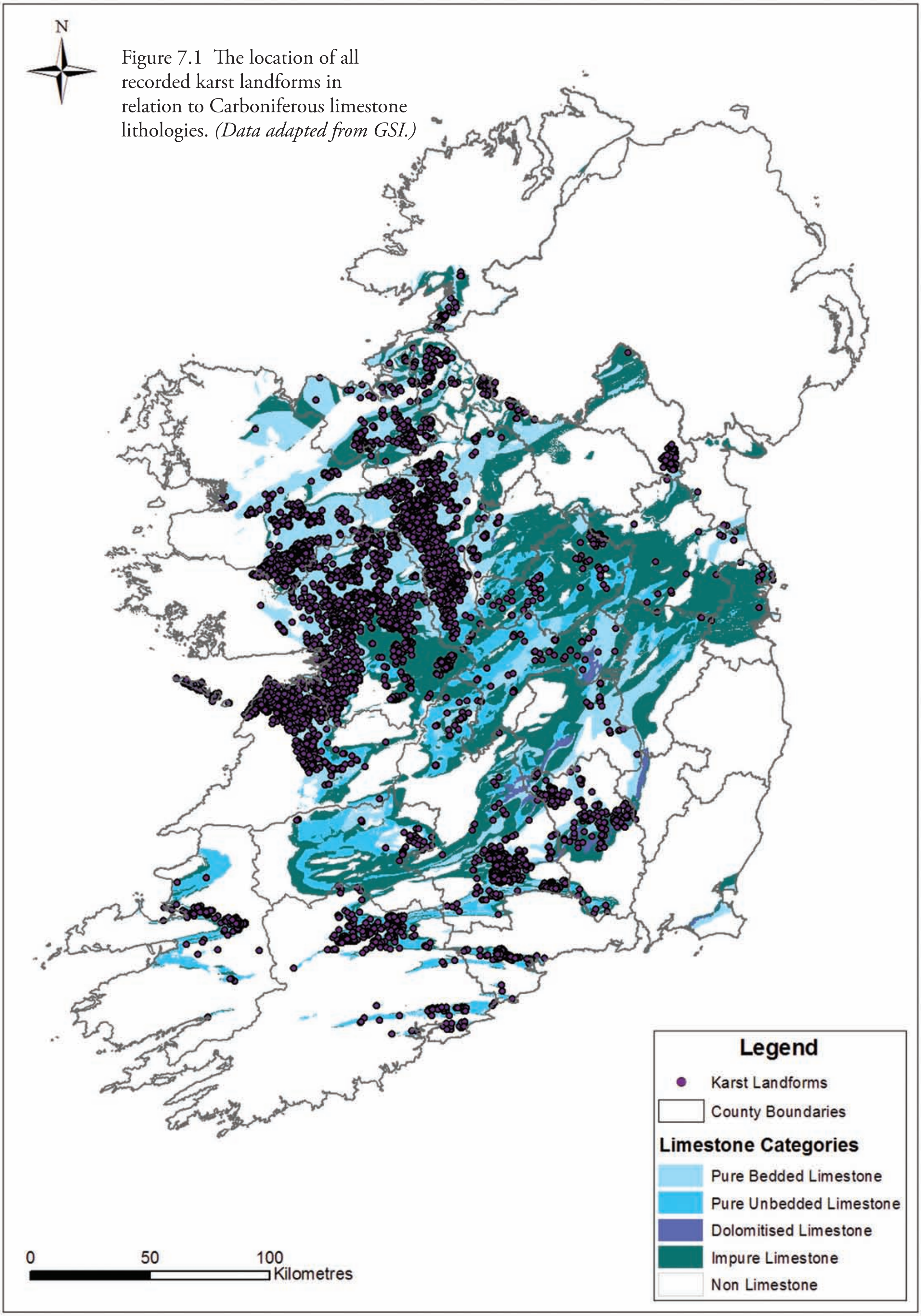
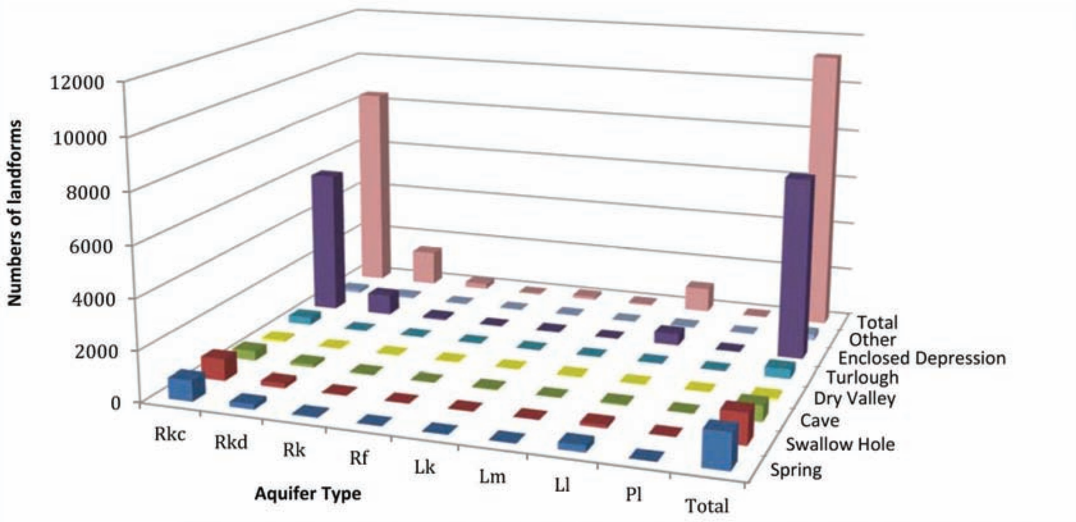
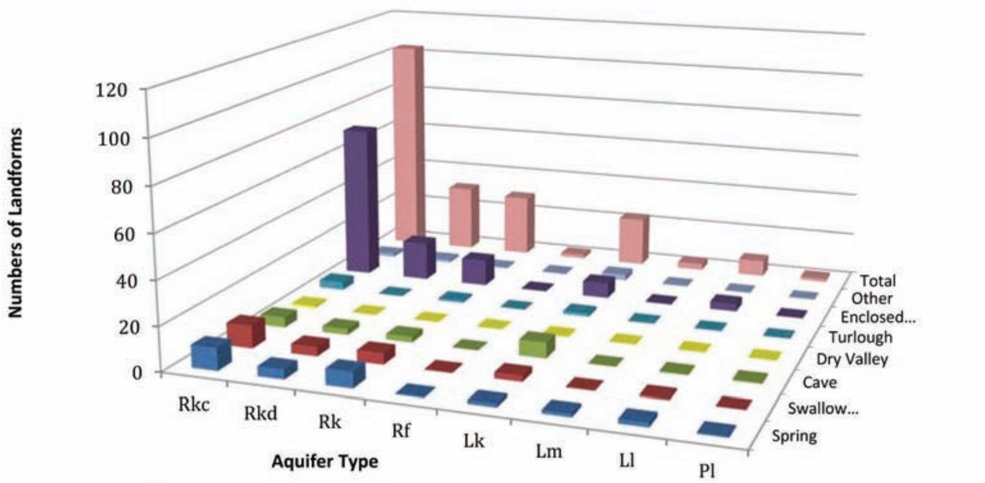


Figure 7.1 The location of all recorded karst landforms in relation to Carboniferous limestone lithologies. *(Data adapted from GSI.)*



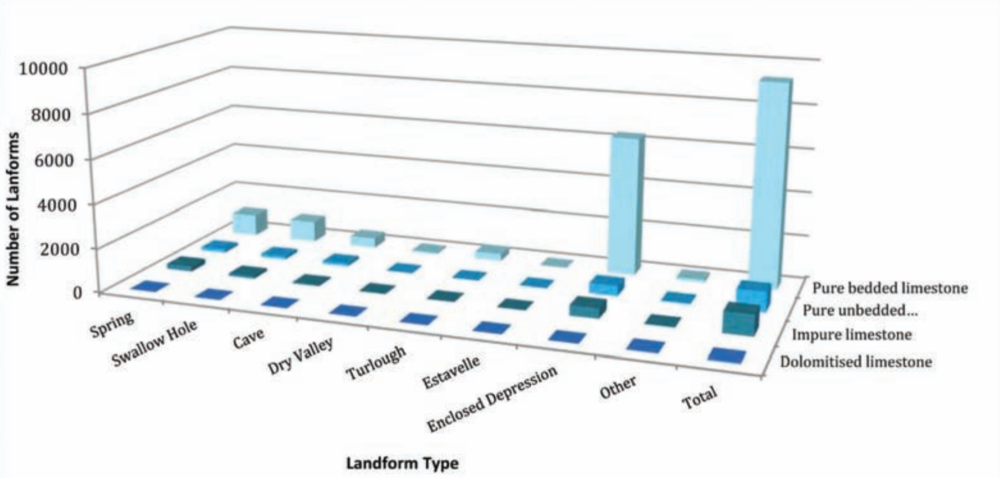
	Rkc	Rkd	Rk	Rf	Lk	Lm	Ll	Pl	Total
Spring	836	204	53	1	9	27	270	7	1407
Swallow Hole	850	198	38	1	15	6	125	0	1233
Cave	387	127	20	0	39	1	59	6	639
Dry Valley	67	0	0	0	0	0	0	0	67
Turlough	311	10	8	0	8	4	24	0	365
Enclosed Depression	5847	826	90	1	39	7	478	2	7290
Other	121	62	3	1	15	7	40	0	249
Total	8420	1427	212	4	125	52	995	15	11250

Figure 7.2 Number and type of karst landforms per aquifer category. *(Data from GSI's Karst Database.)*



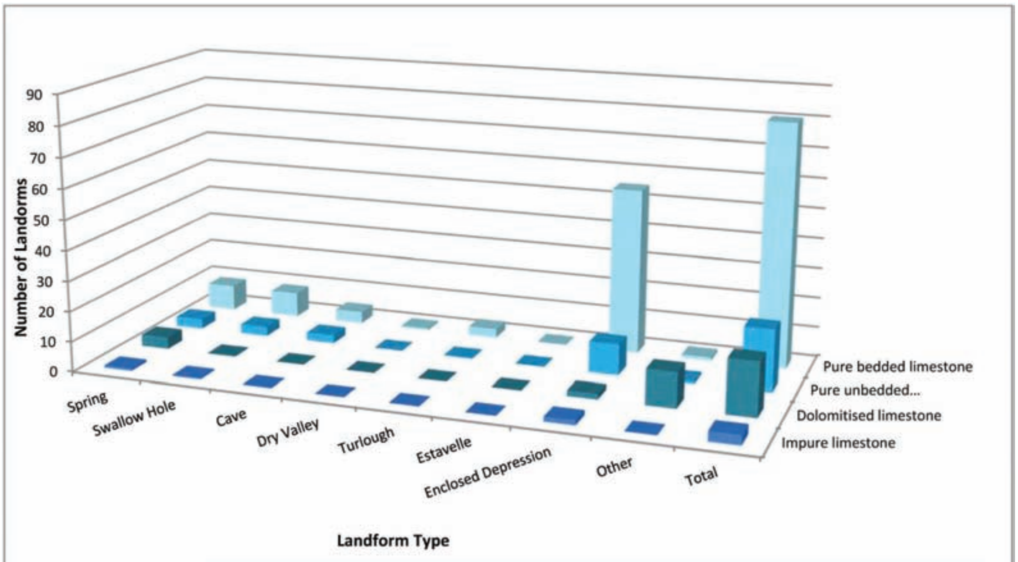
	Rkc	Rkd	Rk	Rf	Lk	Lm	Ll	Pl
Spring	10	4	7	0	2	2	2	1
Swallow Hole	10	4	5	0	3	0	1	0
Cave	5	3	3	0	7	0	0	1
Dry Valley	1	0	0	0	0	0	0	0
Turlough	4	0	1	0	1	0	0	0
Enclosed Depression	72	18	12	0	7	0	4	0
Other	1	1	0	0	3	0	0	0
Total	104	31	29	2	23	3	8	2

Figure 7.3 Number and type of karst landforms per 100 km^2 of aquifer category. *(Based on data from GSI's Karst Database.)*



	Spring	Swallow Hole	Cave	Dry Valley	Turlough	Estavelle	Enclosed Depression	Other	Total
Dolomitised limestone	15	1	0	0	0	0	7	44	67
Impure limestone	244	130	59	0	20	0	476	35	964
Pure unbedded limestone	148	138	125	1	9	0	463	40	924
Pure bedded limestone	995	965	454	67	336	11	6337	119	9284

Figure 7.4 Number and type of karst landforms per limestone lithology. *(Data from GSI's Karst Database.)*



	Spring	Swallow Hole	Cave	Dry Valley	Turlough	Estavelle	Enclosed Depression	Other	Total
Impure limestone	1	0	0	0	0	0	2	0	3
Dolomitised limestone	4	0	0	0	0	0	2	12	18
Pure unbedded limestone	3	3	3	0	0	0	10	1	20
Pure bedded limestone	9	8	4	1	3	0	55	1	80

Figure 7.5 Number and type of karst landforms per 100 km^2 of limestone lithology. *(Based on data from GSI's Karst Database.)*

Figure 7.5 gives a more realistic idea of the potential for each limestone lithology to contain karst features. The number of each landform (and the total number) is shown per 100 km^2 of each limestone lithology. This indicates that the pure bedded limestone lithology still dominates, with a karst landform density of 80 karst landforms per 100 km^2, but that the impure limestones have a density of only 3 per 100 km^2. Each 100 km^2 of pure unbedded limestones has a density of 21 landforms and each 100 km^2 of the dolomitised limestones has an average of 18 karst landforms. There are relatively large numbers of landforms in the 'other' landform category found in the dolomitised limestones and these are mainly karst cavities intersected by boreholes. Karst cavities are more commonly encountered in the dolomitised limestones than the other three categories put together. More on this topic is given in Chapter 8.2.

Another index of karstification is the density of drainage channels (drainage density) on the land surface. A mature karst is characterised by wholly underground drainage. Drainage density is affected by precipitation amounts, by subsoil character and by topography as well as by the character of the bedrock and these factors need to be taken into account when interpreting Figure 7.6. However, the absence of extensive fluvial systems over large areas of the pure limestones of the west and northwest midlands contrasts to adjacent areas of impure limestones which have a similar precipitation amount. Drainage density on non-limestone strata averages 1.2 km of channel/km^2, on impure limestones 1.0 km/km^2 and on pure bedded, unbedded and dolomitised limestones 0.8 km/km^2.

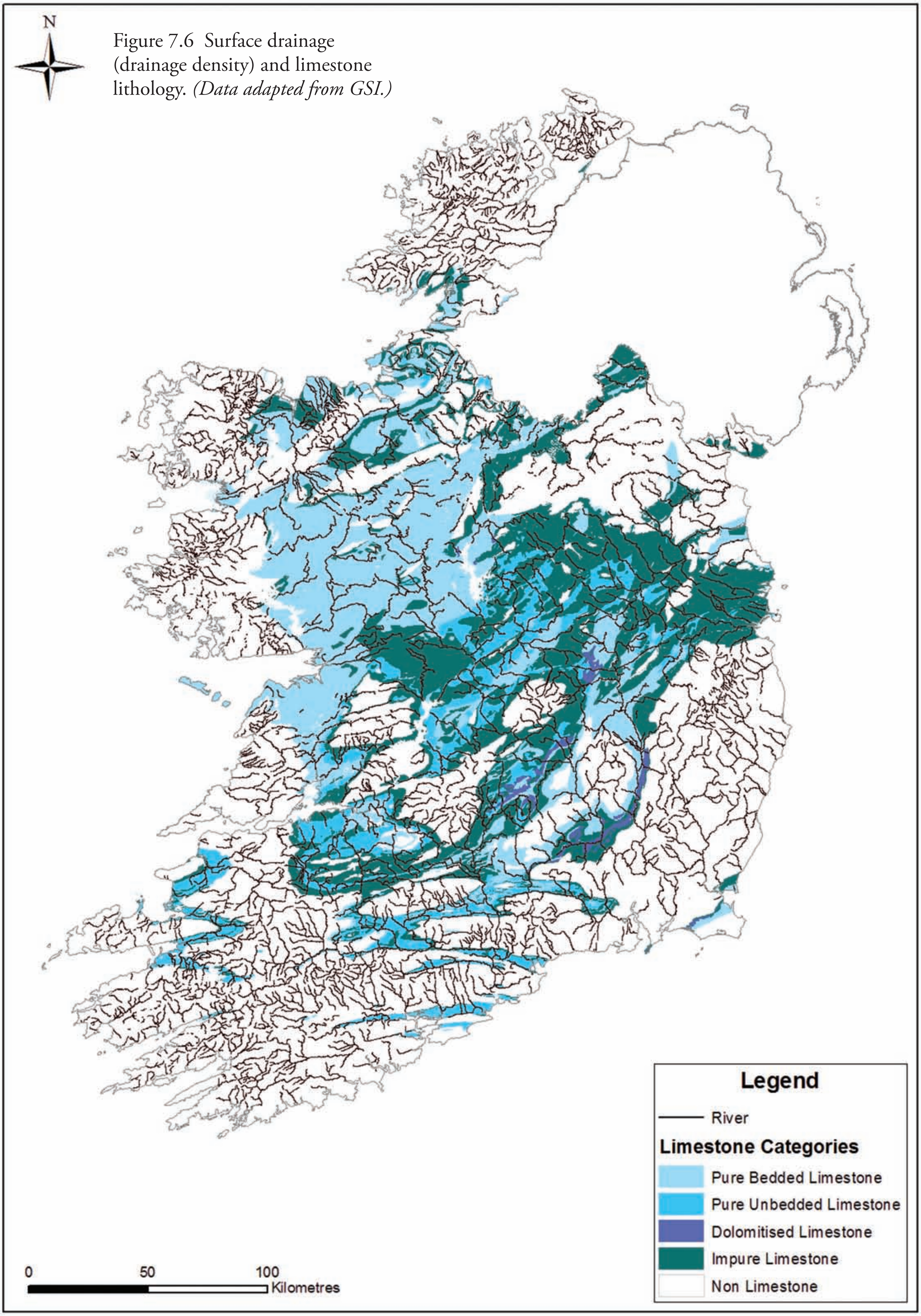
There is an obvious distinction is between lowland and upland karsts in Ireland. Lowland karsts are the more extensive: approximately 80% of the outcrop of Carboniferous limestone lies at an altitude of less than 100 m O.D. and approximately 95% at an altitude of less than 150 m O.D. The upland, or plateau, karsts (the Burren and the uplands of Sligo, Leitrim, Cavan and Fermanagh) are located at the margin of the lowland karsts. These karsts are simultaneously developing as the overlying, younger and predominantly non-calcareous strata are removed by non-karstic processes and are being destroyed as the lowlands encroach. Sinking streams at the contact between limestone and non-limestone strata are common, as are steep hydraulic gradients, rapid flow rates and (sometimes) relatively simple groundwater flow systems. These are also lightly populated areas of relatively limited economic significance, at present.

The lowlands, particularly west of the River Shannon, are blanked by Quaternary and earlier deposits over much of their extent, with the cover thinning westwards. Lowland karsts are probably the most developed and complex karst regions of Ireland, comprising a mixture of re-activated, pre-glacial and inter-glacial karst and Holocene karst. Despite the fact that lowland karst underlies many of the most economically significant areas of the country, with the most developed agriculture and the highest demands for water, its hydrogeology is apparently complicated and is less than fully understood. Characteristic of the lowland karsts are:

- low hydraulic gradients but with flow rates, typically 50–100 m/h (though almost all the flow velocity data are from Rkc aquifers and do not necessarily apply to Rkd aquifers where velocities may be lower)
- numerous springs with discharges of 10–100 l/s and with contributing areas, not always easy to delimit, of tens of km^2
- flow paths from recharge to discharge areas of hundreds of metres, to tens of kilometres
- complicated interactions with surface drainage systems, lakes and rivers

It is also possible, if not necessarily helpful, to distinguish other 'distinctive' types of karst such as areas with fossil or relict karst, the karsts developed on interfluves between major

Figure 7.6 Surface drainage (drainage density) and limestone lithology. *(Data adapted from GSI.)*



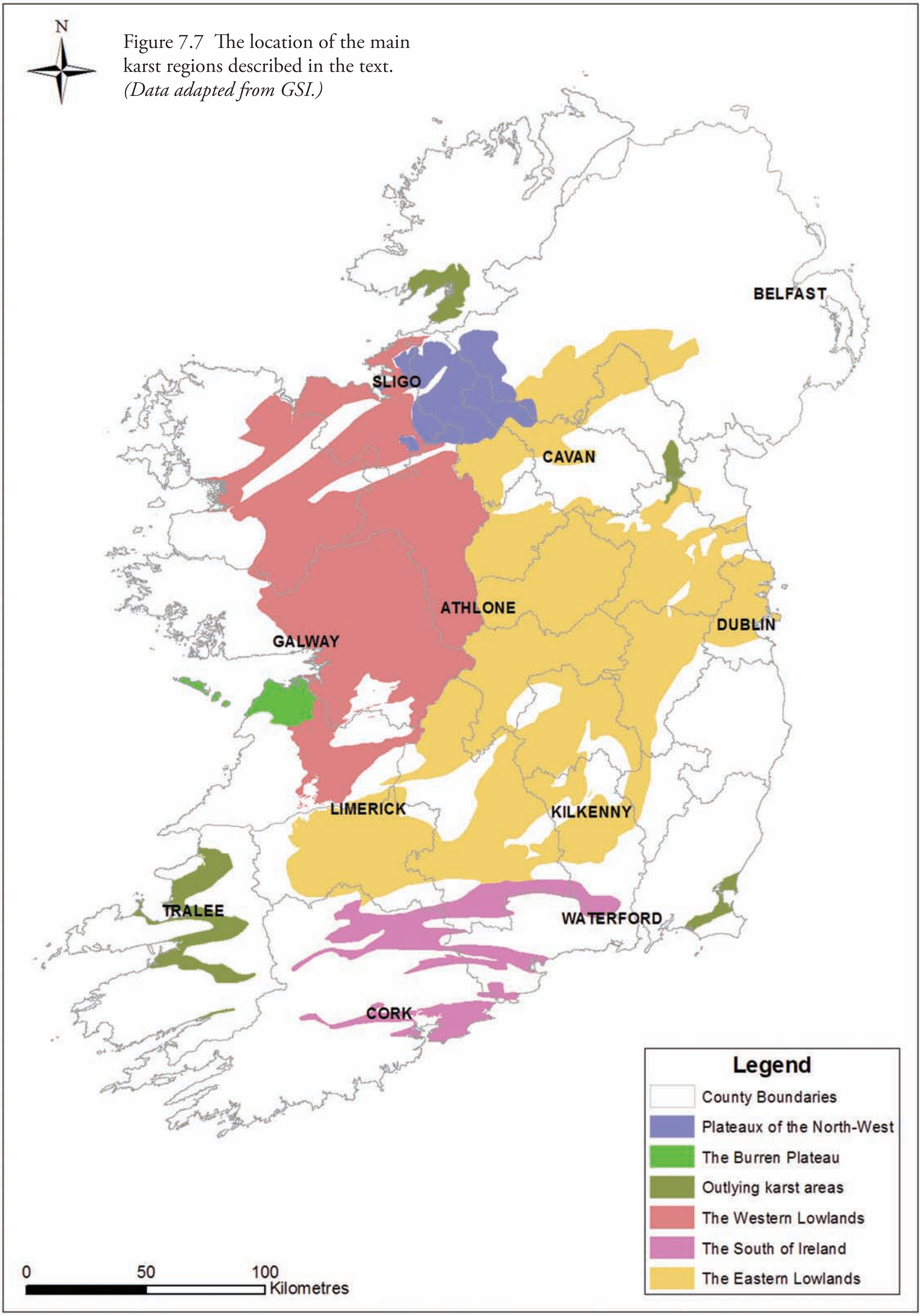


Figure 7.7 The location of the main karst regions described in the text. *(Data adapted from GSI.)*

rivers e.g. in the south of Ireland and karsts in the enclosed or semi-enclosed outliers of limestone in Munster. The subdivision of karst in Ireland used in the succeeding sections is essentially based on the appearance and the location of the karst rather than its age or its functioning – two upland and three lowland 'regions' being recognised together with some small outliers worthy of note (Figure 7.7). The subdivisions of the lowland karst are to some extent arbitrary and to a degree reflect the amount known about the areas. The descriptions given are summaries, with mentions of characteristic or special features; more systematic hydrogeological detail is given in Chapter 8.

7.2 Plateaux of the North-West (Counties Sligo, Leitrim, Cavan and Fermanagh)

The largest upland karst in Ireland is located between the towns of Sligo, Drumshanbo, Enniskillen and Manorhamilton (Figure 7.8). The total area is approximately 1,800 km^2, of which 37% is underlain by Namurian strata and the remainder by Carboniferous limestone. Figure 7.9 shows the main karst landforms and main rivers in the area.

Limestone outcrops over the western part of the plateau and as a narrow rim around the margins of the Namurian strata further east and north. Much of the plateau lies above 400 m O.D. with the highest points being Truskmore (647 m OD) in the west and Cuilcagh (666 m OD) in the east (Figure 7.8).

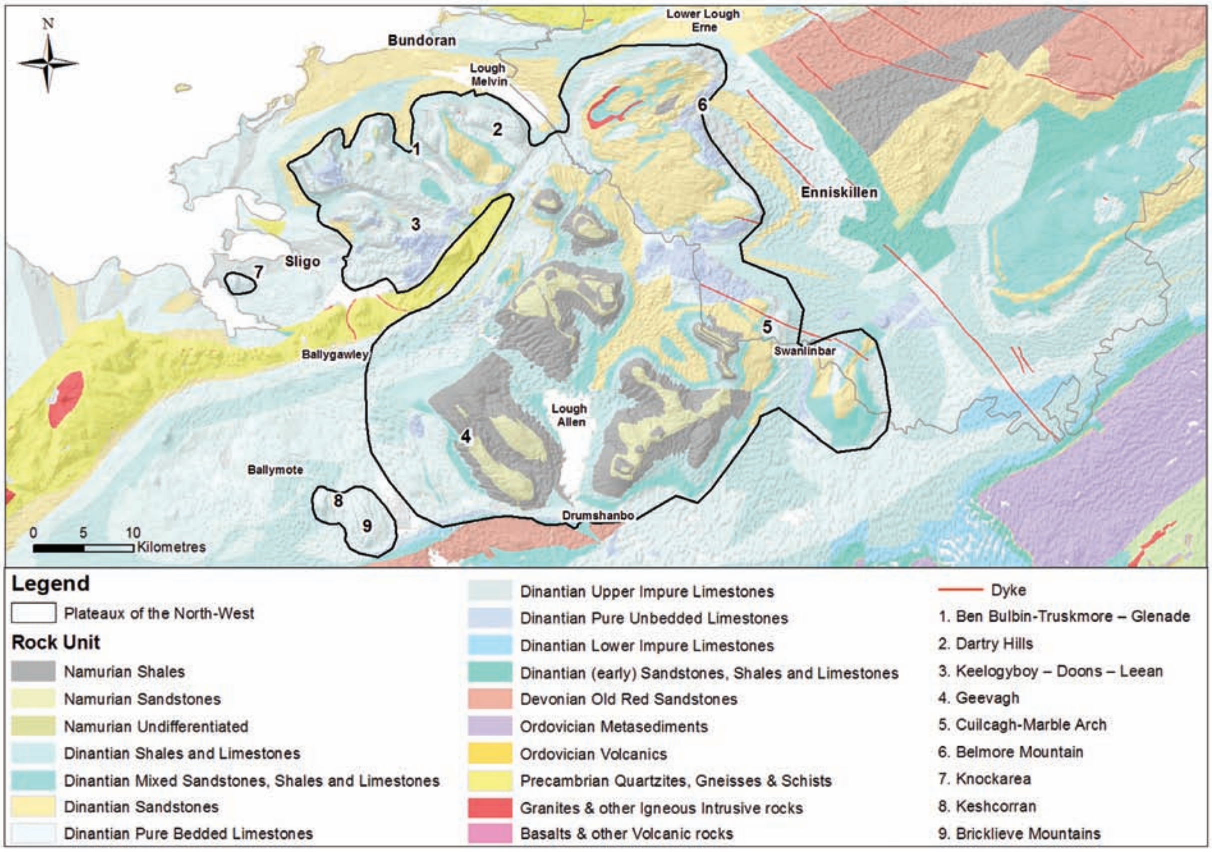


Figure 7.8 Plateau karsts and outliers of northwest Ireland: Counties Sligo, Leitrim, Cavan and Fermanagh. *(Data adapted from GSI.)*

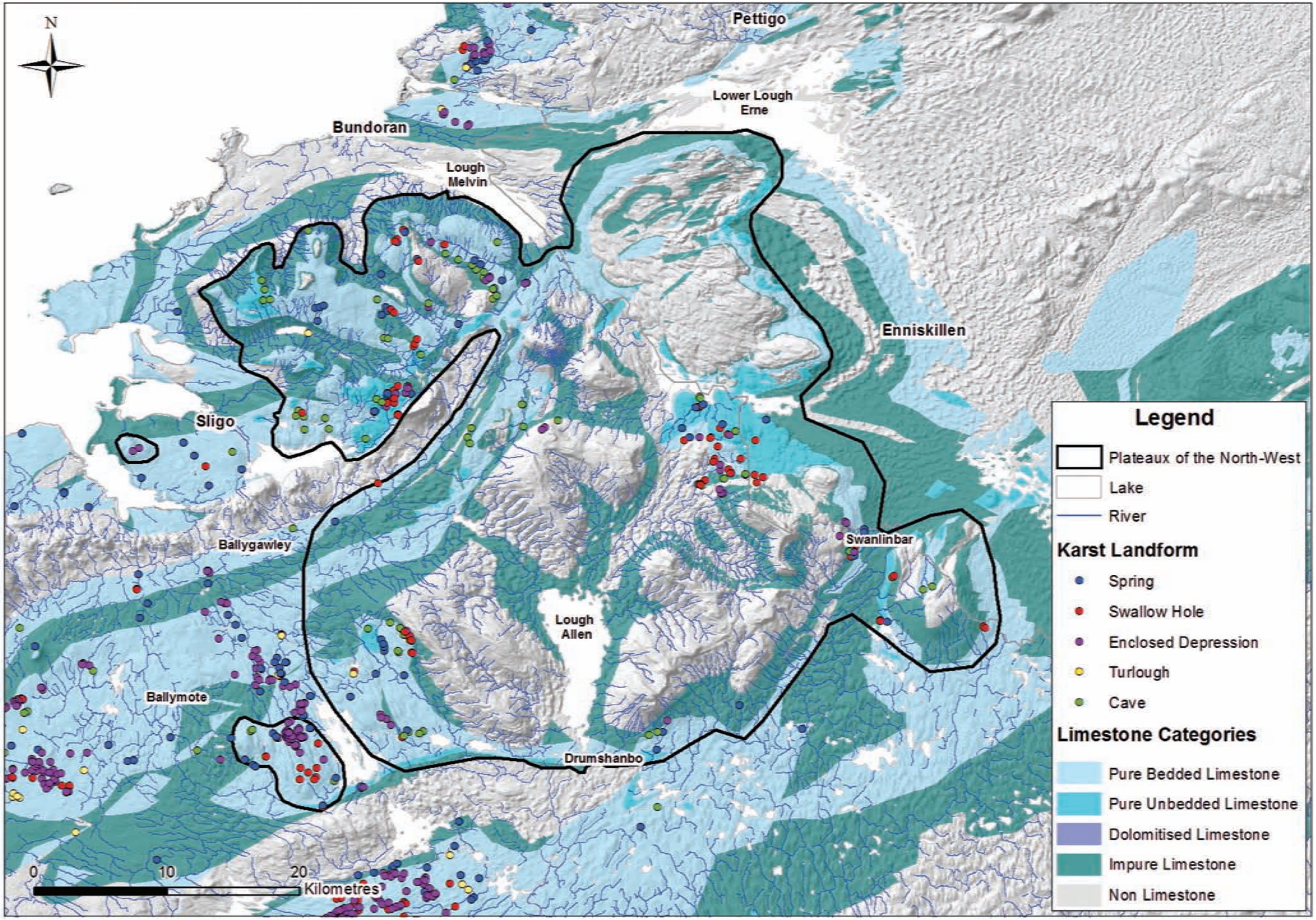


Figure 7.9 Drainage, karst landforms and limestone geology of the plateau karst of the northwest (note there is no drainage shown in Northern Ireland). *(Data adapted from GSI.)*

Annual precipitation exceeds 2,000 mm over much of the upland. Unlike the other upland karsts of Ireland, exposures of the limestone are uncommon and blanket bog is widespread, often underlain by up to 2 m of rubbly insoluble residue from the decalcified limestone. The Dartry Formation comprises massive (reef) limestones in its upper part with bedded chert-rich limestone below. Beneath is the Glencar limestone with thinner bedding, shale layers and closer jointing. At the base of the Glencar Formation are the relatively impermeable Glencar shales, the boundary commonly marked by an abrupt break of slope (Figure 7.10).

The plateau has been dissected in varying degrees by glacial and, to a lesser extent, fluvial erosion that presumably continued throughout the Pleistocene and seems to have been particularly intense in this area, in comparison with other upland karsts such as the Burren. The last ice advance was from southeast to northwest across the area and this is reflected in erosional features such as the parallel gorges (ailts) of the Bricklieve Mountains and the deep, oriented till deposits on the lowlands (Figure 7.20). Glacial troughs such as Glenade, Glencar (Figure 7.11) and Glenaniff, all oriented approximately SE-NW, have compartmentalised the plateau into long ridges such as the Crockauns-Keelogyboy-Leean-Benbo upland south of Glencar and, in turn, these ridges are decaying into isolated clusters of limestone hills or mounds such as in the Doons area north of Lough Gill (Figure 7.13). Extensive fragments of the formerly continuous plateau occur at greater distances from the main massif in the Bricklieve Hills (25 km^2 in area), Kesh and Knocknarea in County Sligo (Figure 7.12). Even more remote are isolated hills with no remnant of the flat plateau summit remaining, such as Muckelty and Knocknashee. Figures 7.10–7.13 show the sequence of progressive dissection of the karst plateau of northwest Ireland from an extensive, coherent upland into isolated limestone hills.

The combination of an impure, frequently closely bedded bedrock and the compartmentalisation of the upland has inhibited the karstification of the area, and the

Figure 7.10 The steep scarp separating the limestone lowlands from the karst plateau, County Sligo. The break of slope on King's mountain (extreme left) corresponds to the junction of the Glencar limestone with the underlying shales. *(Photograph by David Drew.)*

Figure 7.11 The glacial trough of Glencar separates the outlying Crockauns-Keelogyboy-Leean upland (right of picture) from the main King's Mountain-Truskmore karst plateau to the north. *(Photograph by David Drew).*

Figure 7.12 Knocknarea, an outlying remnant of the plateau karst of County Sligo. *(Photograph by David Drew.)*

dominant landforms are those of glacial rather than karstic in origin. In addition, thick glacial deposits mask any karst features in the glaciated valleys and peat growth has had the same ef ect on the interf uves. However, the absence of a surface drainage network

Figure 7.13 Dissection of the karst plateau of northwest Ireland into isolated limestone hills: The Doons (County Leitrim). *(Photograph by David Drew.)*

on the plateaux that lack a capping of Namurian rocks, despite the high effective rainfall, demonstrates that karstic drainage is present, albeit on a relatively subdued scale.

Each upland block appears to function hydrogeologically independently of the others, with recharge occurring via numerous small sinks or dolines fed by local drainage (Figure 7.14). Recharge locations are often clustered along the numerous N-S or E-W faults in the area and are often vertical rifts explored to depths of up to 100 m, with little or no horizontal conduit development. These drain to a series of small springs in adjacent valleys: for example the Largy Rifts on Leean mountain (Figures 7.15 and 7.16). Many of the cave systems do not seem to be hydrologically active and/or have extensive fills of glacial till, suggesting that the karst network pre-dates at least the last glacial advance.

There is also evidence for very ancient (pre-Pleistocene?) karstification at locations such as Dermot and Grainne's Cave in Gleniff, which must pre-date the formation of the deep valley (Figure 7.17). Post-glacial karstification is also apparent, for example in the numerous doline-sinks in the peat on the Bricklieve Mountains (Figure 7.18) and is presumably proceeding rapidly given the large supply of highly aggressive water. Thus, locally concentrated autogenic recharge, short, dominantly vertical flow paths and discharge via numerous small springs characterises much of the western part of the area.

Figure 7.14 The contact between the Namurian strata (the elevated background) and the Dartry limestone at Geevagh, County Sligo. Typically, solutional erosion of the limestone has been concentrated (swallow holes) in the area adjacent to the Namurian strata (corresponding to the forestry at upper left) creating a shallow linear hollow parallel to the geological boundary. *(Photograph by David Drew.)*

Even where allogenic recharge does exist for example, at the junction between the Meenymore Formation and the underlying Dartry limestone in the Dartry Hills (Figure 7.19), little integration of underground drainage seems to result, as evidenced by lack of large springs.

Further to the east the plateau is less dissected, particularly the Cuilcagh massif to the south of Lough Macnean Lower. The eastern flank of Cuilcagh has a hydrogeology similar to that of the plateaux of Sligo and Leitrim, with vertical rifts draining the highly cherty limestone. However, the Dartry limestone that outcrops on the northern flank in County Fermanagh is a clean, well-bedded, massive mudbank carbonate rock that has allowed the development of a classical dendritic system of karst conduits focussed on the springs that form the Cladagh River (Jones et al., 1997, Fogg and Fogg, 2001). On the southwestern side of Cuilcagh is another major spring, the Shannon Pot (the putative source of the River Shannon), which drains circa 13 km^2 of the northeastern section of the massif. It emerges through the Meenymore Formation (from a depth of greater than 16 m) and is, therefore, an overflow spring (Figure 7.21). Almost 5 km of major conduit feeding the spring has been explored and surveyed (Brown et al., 2009). Allogenic point recharge accounts for greater than 50% of recharge over these parts of Cuilcagh but for less than 10% of recharge over much of the other plateaux of the northwest.

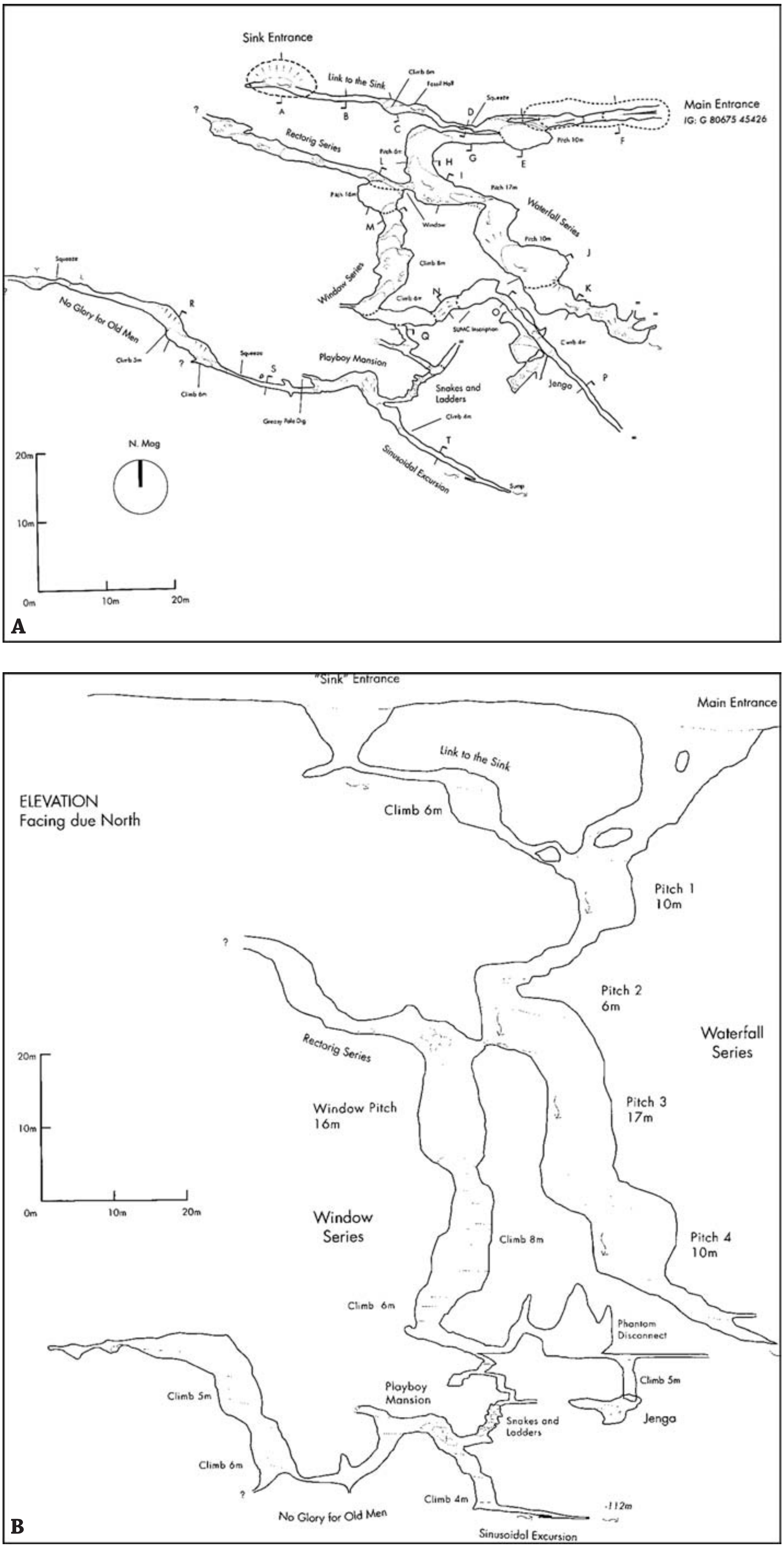


Figure 7.15 Deep Pot, Largy, Glenade, County Leitrim; (A) Plan and (B) Elevation. *(Barry and Kennedy, 2013.)*

Figure 7.16 Deep Pot, Largy, Glenade, County Leitrim, a fault-guided rift passage. *(Photograph by Robert Mulraney.)*

Figure 7.17 Diarmuid and Grainne's cave (yellow circle) located 400 m above the floor of the Gleniff valley, County Sligo and developed in the lower beds of the Dartry limestone Formation. *(Photograph by David Drew.)*

Figure 7.18 Subsidence dolines developed beneath the peat cover on the Bricklieve plateau. *(Photograph by David Drew.)*

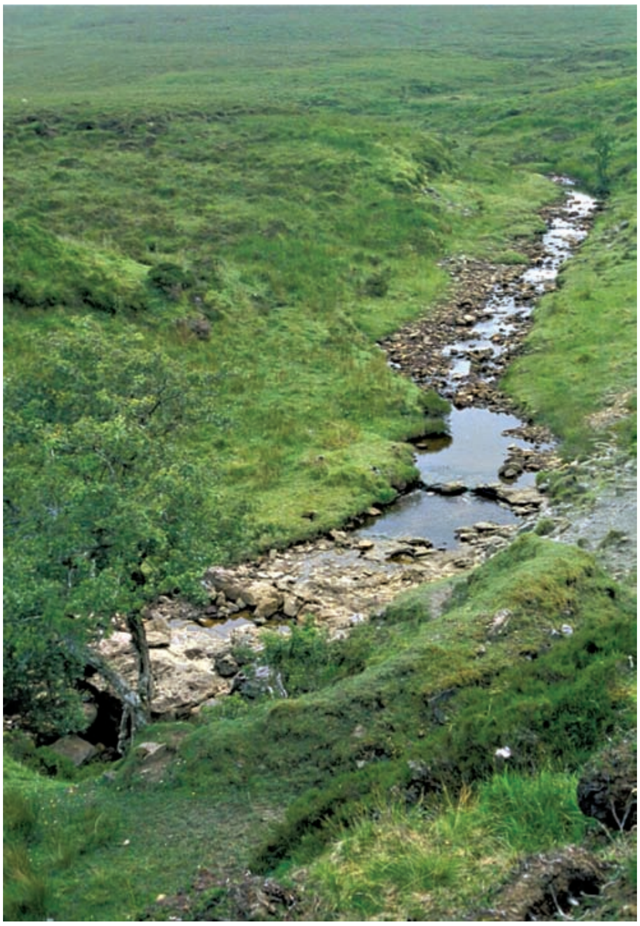


Figure 7.19 Sulphur Pot, a swallow hole at the contact between the Meenymore and Dartry Formations (Glenanif , County Leitrim). *(Photograph by David Drew.)*

Figure 7.20 One of the series of parallel gorges (ailts) which traverse the Bricklieve and adjacent Geevagh uplands from north to south. *(Photograph by David Drew.)*

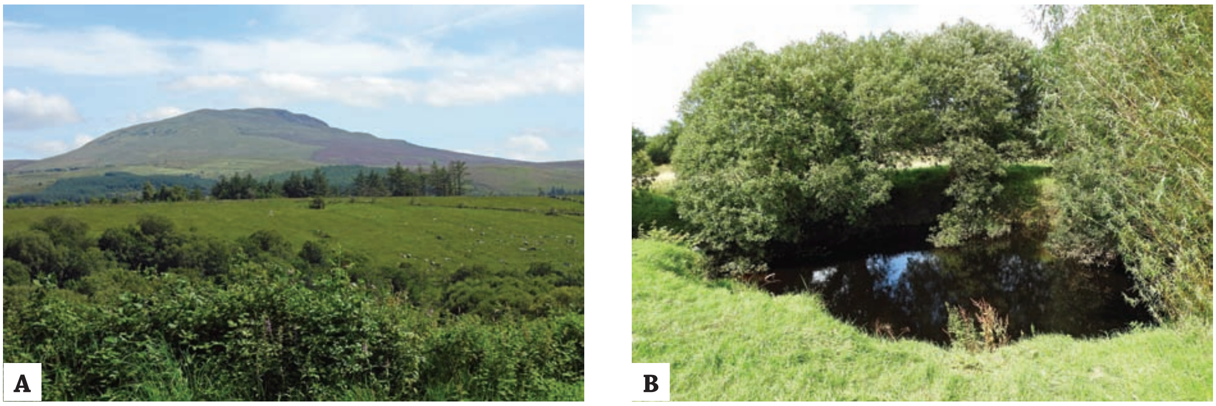


Figure 7.21 (A) Cuilcagh mountain looking eastwards with the break of slope corresponding to the non-calcareous rocks overlying the Dartry limestone. (B) Shannon Pot, which drains the area of Cuilcagh to the northeast of the spring and is located in the trees in the foreground of (A). *(Photographs by David Drew.)*

Although, strictly speaking, Lough Nasool near Riverstown in County Sligo is a lowland karst phenomenon, its location in the corridor between the Bricklieve Hills and the Namurian sandstone and shale capped ridge in the vicinity of Geevagh (Figure 7.22) means that it is probably associated with karstic drainage from the sinking streams at Geevagh or the Bricklieves. Lough Nasool, with a surface area of approximately 0.1 km^2, occupies one of the many hollows in the hummocky, drumlinoid till between the two uplands. The lake has no obvious inlets or outlets but on occasions (in 1883, 1933, 1964, 1985 and almost in 2006 and 2012) the lake completely and rapidly disappears through a swallow hole in its bed. The destination of the sinking water is not known, though Lough Bo, some 200 m to the north and 16 m lower in altitude, does have an outlet (to the River Feorish) but no apparent inlet and is a permanent lake. Lough Funshinagh (Section 7.5) in County Roscommon, behaves in a similar manner.

Figure 7.22 Lough Nasool with the Geevagh upland in the background. *(Photograph by David Drew.)*

7.3 The South of Ireland (South Tipperary, Cork, Limerick, Waterford)

The area of southern Ireland that was significantly affected by the Variscan orogeny, including Counties Cork, Waterford, Kerry and parts of Limerick and Tipperary, has developed a karst topography and hydrogeology distinct from other limestone areas of Ireland. In part this is due to the folding, fracturing and faulting associated with the earth movements, which intensify southwards. It is also due to the fact that the limestone has been eroded from the anticlines and primarily outcrops in the floors of east-west oriented synclinal valleys bounded by anticlinal ridges of older, non-limestone strata (the Galtee Mountains for example). These limestone floored troughs include those between Cork and Midleton (90 km^2 in area), Cloyne and Cobh (17 km^2), Dungarvan-Lismore and Castletownroche, all of which are open to the sea at their eastern extremities, allowing for circulation of groundwater (Figure 7.23). To the north, the Carrick-on-Suir-Cahir-Mitchelstown-Buttevant syncline marks the limit of the main zone of folding and is contiguous with the main outcrop of the Carboniferous limestone of central Ireland described in Sections 7.4 and 7.5.

In some places, erosion of the limestone has proceeded to the extent that the limestone survives only as an inlier surrounded by Devonian rocks. This is the case in a part of the River Bride valley west of Tallow (Figure 7.24) and in more extreme form in the 8 km^2 Araglin outlier between the Kilworth and Knockmealdown Mountains, which is separated by more than 5 km from the main outcrop of limestone to the north. Present day karstification is presumably limited under such slow moving groundwater conditions.

Karst features are widespread in the area and are present in the dominant Waulsortian strata, the pure bedded limestones and, to an extent, the less pure limestones. Unlike further north in the midlands (Sections 7.4 and 7.5) the Waulsortian seems to be the most karstified and productive aquifer (Chapter 8.2). The differences in karst development between the lowland midlands and the south of Ireland may be due not simply to the highly fractured

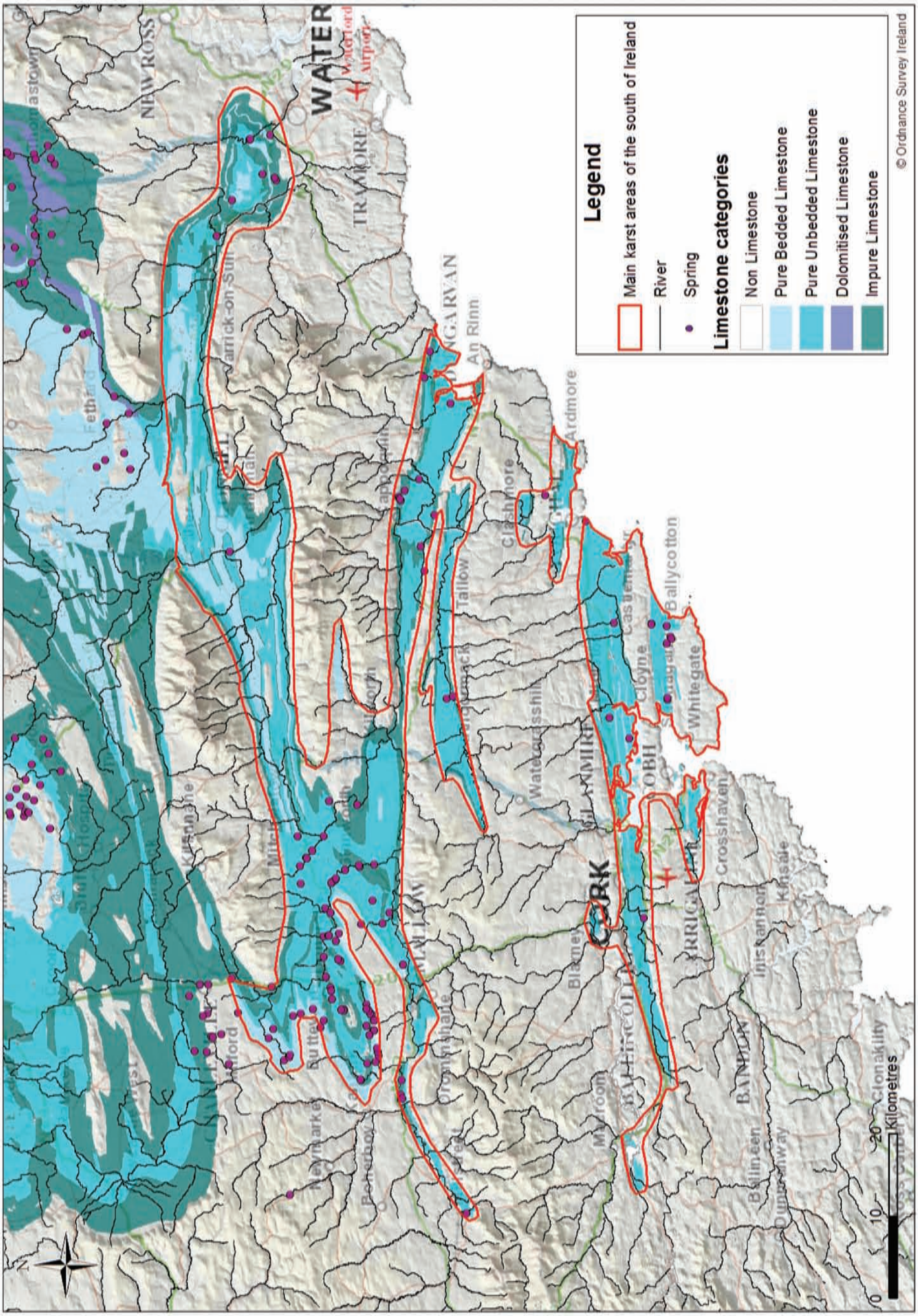


Figure 7.23 Geology, drainage and karst springs of the karst of southern Ireland. *(Data adapted from GSI.)*

Figure 7.24 The outlier of Carboniferous limestone that underlies a part of the River Bride valley to the west of Tallow (County Waterford). *(Photograph by David Drew.)*

character of the folded strata but also to the fact that glacial and glacio-fluvial processes are less dominant in terms of determining the subsoils and landforms.

The southern limestone outcrop more closely resembles a fluviokarst than any other karst in Ireland. There is a well-developed river and valley network, controlled, in part, by the geological structures and an association between major rivers and karst springs, which is largely absent elsewhere in Ireland, where glacial derangement of surface drainage is the dominant feature. This is particularly true of the north-south oriented segments of rivers rather than the west-east flowing reaches (of the Blackwater and Suir rivers in particular; Figure 7.23). For example, the Clashawley River, south of Fethard, is fed by major springs such as Mullenbaun (mean discharge 25 l/s), Kiltinan (160 l/s) from east and west banks respectively. The River Suir, south of Caher, receives significant inflow from Roaring Well spring (Figure 7.25) and from Kedrah spring, the latter being possibly the largest in the area with a mean discharge of circa 250 l/s. West-east flowing tributaries to the Suir such as the Aherlow and Tar (Poulalee Spring) also receive major groundwater inflows. Flow in tributaries to the River Blackwater such as the Funshion, Bregoge and Awbeg (Figures 7.26 and 7.27) is also significantly supplemented by spring flow. The hydrogeology of the Awbeg River is further discussed in Chapter 10.

Figure 7.25 The large karst spring of Roaring Well on the west bank of the River Suir north of Ardfinnan. (A) The River Suir looking south (downstream) towards the Knockmealdown Mountains – the spring is located on the right bank just beyond the bend. *(Photograph by Aerial Eye for David Drew.)*. (B) Close-up of Roaring Well which is presumed to be fed in part from a swallow hole to the northwest. *(Photograph by David Drew.)*

Figure 7.26 The limestone surface into which the Awbeg River is incised <50 m between Shanballymore in the north and the Blackwater River to the south, the photograph is facing south southwest. *(Photograph by Aerial Eye for David Drew.)*

Figure 7.27 Shanballymore spring (mean discharge 150 l/s) is located at centre foreground on the left bank of the Awbeg River just upstream of the previous photograph. *(Photograph by Aerial Eye for David Drew.)*

Even where springs are not apparent, the high baseflow component of many of the rivers of the area (>50 l/s/km^2, Keegan, 1993) suggests that groundwater discharge directly into the river channel is important.

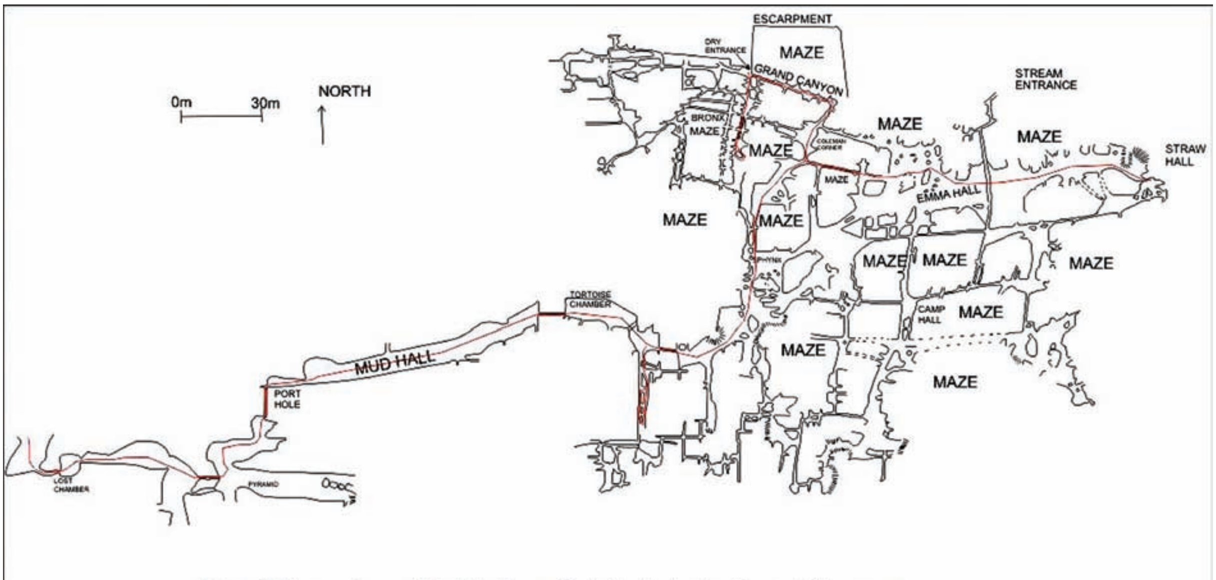
Thus, the rivers of the area do function as hydraulic lows for the karstic groundwater system to some extent, though the precise nature of the flow systems is not fully understood – for example, whether or not groundwater flow passes beneath rivers at depth in some places.

The mode of recharge to the karst aquifers is dominantly dif use in character, with the relatively few swallow holes located either at the contact with the non-calcareous rocks or where streams have been generated on less permeable subsoils. This latter scenario is common on the limestone lowlands particularly west of the River Shannon.

The main east-west synclinally controlled outcrops of limestone dif er to some extent in terms of karstif cation:

7.3.1 Cloyne and Cork – Midleton – Youghal (County Cork)

The most signif cant karst feature in the narrow Cloyne lowland is the eponymous Cloyne Cave (Figure 7.28). The cave is developed in a ridge of Waulsortian limestone and consists of a maze oriented along the dominant joints, of which probably only a small fraction are explorable and, therefore, mappable. Thus far, some 2,800 m of cave passage have been surveyed within a planar area of c.150,000 m^2. It is likely that the cave developed under relatively stagnant groundwater conditions when the valley f oor stood higher than at present.



Map of Cloyne Caves. Modified from Cork Speleological Association map.

Figure 7.28 Plan survey of Cloyne Cave modif ed from the Cork Speleological Association. *(Map by Colin Bunce.)*

Similar solutional network caves have been explored in the western end of the Midleton – Cork limestone outcrop, at Carrigtoohill and further east at Castlemartyr, which is the location for the major karst spring at Dower (mean discharge c.430 l/s), which drains the valley and upland to the north.

7.3.2 Mallow – Dungarvan (County Cork – Waterford)

The River Blackwater (Figure 7.29) follows this limestone outcrop for some 80% of its length, and is the hydraulic base control for a large part of south County Cork, yet evidence for karst drainage into the river is scant, which is in contrast to many of its tributaries.

Figure 7.29 The River Blackwater looking east from Lismore. *(Photograph by David Drew.)*

Figure 7.30 The limestone-floored valley near Dungarvan, the former course of the River Blackwater, now occupied by the misfit Colligan River. *(Photograph by David Drew.)*

The present day Blackwater turns south at Cappoquin to flow to the sea at Youghal and it is in the former valley course, now occupied by the Colligan and Brickey rivers, that evidence of karstification is present (Figure 7.30). This eastern extremity of the limestone outcrop, extending out to sea at Dungarvan, is known to be a highly productive aquifer. For example, more than 13,000 m^3/day is abstracted for drinking water from the Ballynamuck boreholes near Dungarvan in addition to an outflow exceeding 100 l/s from a nearby spring. Remnants of older karst hydrogeological systems are preserved in low ridges and hillocks in the valley floor, as elsewhere in the region. More than forty caves have been surveyed, concentrated in the Whitechurch area.

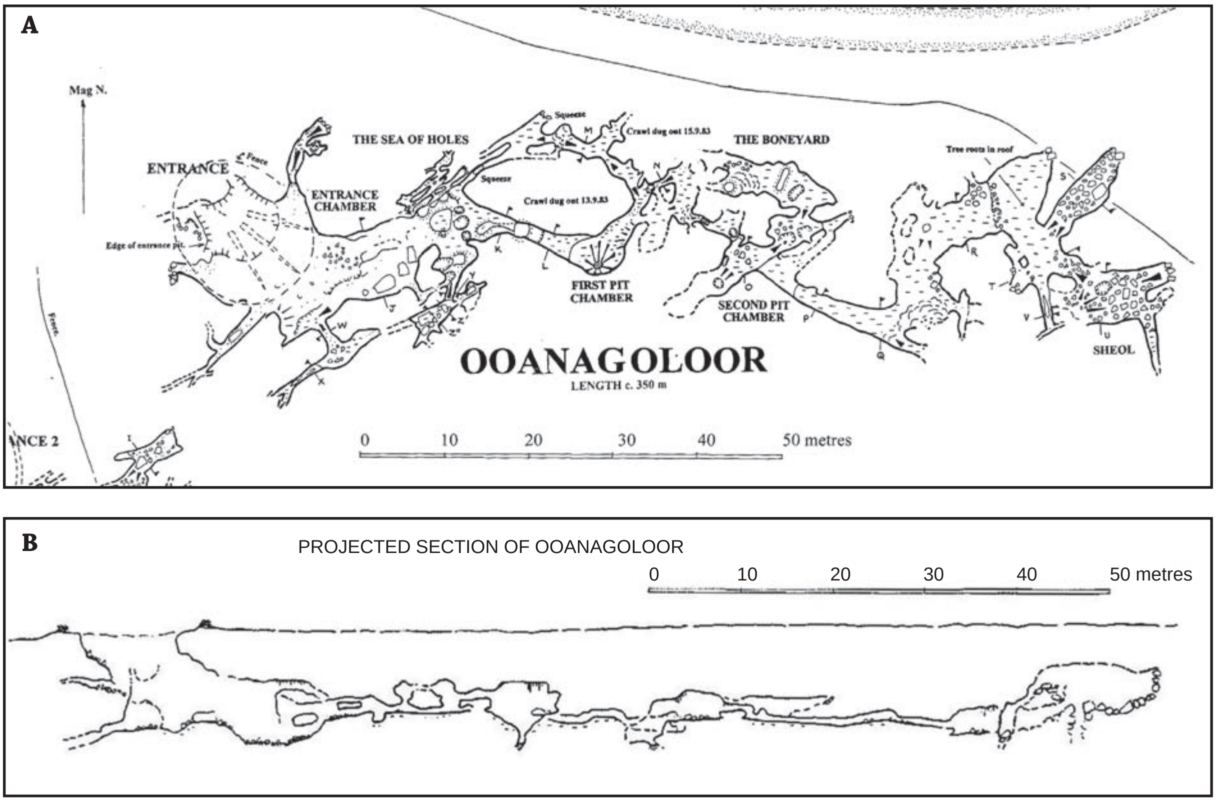


Figure 7.31 Survey of Ooanagoloor Cave (County Waterford). (A) Plan (B) Projected section. *(From Ryder, 2009.)*

The caves are fragments of karst drainage systems, with much breakdown and few natural entrances. Some of the caves were apparently water table controlled – Ooanagoloor Cave, for example, on one level (Figure 7.31), while other caves are formed on two vertical levels. The morphology of the cave passages as shown in Ballynahemery Cave (Figure 7.32) implies a phreatic (sub-water-table) origin with slow moving groundwater.

Figure 7.32 A typical passage in Ballynahemery Cave (Whitechurch, County Waterford). *(Photograph by Matthew Parkes.)*

7.3.3 Buttevant – Clonmel (County Cork – Tipperary)

In contrast to the synclines described above which are typically only 1 km or so in width, the Buttevant-Clonmel feature is 5–10 km wide with gentler dips. For much of its length it is bounded by the Galtee Mountains to the north and the Knockmealdowns to the south (Figure 7.33).

Most of the recorded active karst systems are in the east of the area associated with the River Suir and its tributaries, but the underfit streams and low drainage density elsewhere in the valley, suggest that groundwater flow is significant. A low ridge of limestone at Burncourt near the centre of the valley contains several major cave systems (Figures 7.34–7.36), presumably fragments of a continuous underground drainage system. These (Mitchelstown) caves comprise a series of caverns developed along the strike of the limestone which dips at c.30° to the east-southeast. The caves are largely fossil with little evidence of flow and consist of rifts spaced some 1–6 m apart, but flooded passages extend to a depth of greater than 40 m. The caves seem largely unrelated to present day topography and hydrology and there is nothing to suggest that they were formed by sinking streams generated on the adjacent Devonian rocks.

Near the western limit of this limestone outcrop, active, present day karstification (the Awbeg and Bregoge Rivers described elsewhere) are juxtaposed with fragments of ancient karst, such as the Mammoth (Castlepook) Cave at Doneraile (Figure 7.37 A–C). As with

Figure 7.33 The Buttevant–Clonmel synclinal valley looking west from the vicinity of Caher with Galtee mountains to the north and the Knockmealdown Mountains to the left. The River Suir crosses the lowland from north to south. *(Photograph by Aerial Eye for David Drew.)*

Figure 7.34 Looking west across the broad valley between the Galtee Mountains and the Knockmealdown Mountains (County Tipperary). The Mitchelstown Caves are developed in the low small ridge in the centre of the valley. *(Photograph by Aerial Eye.)*

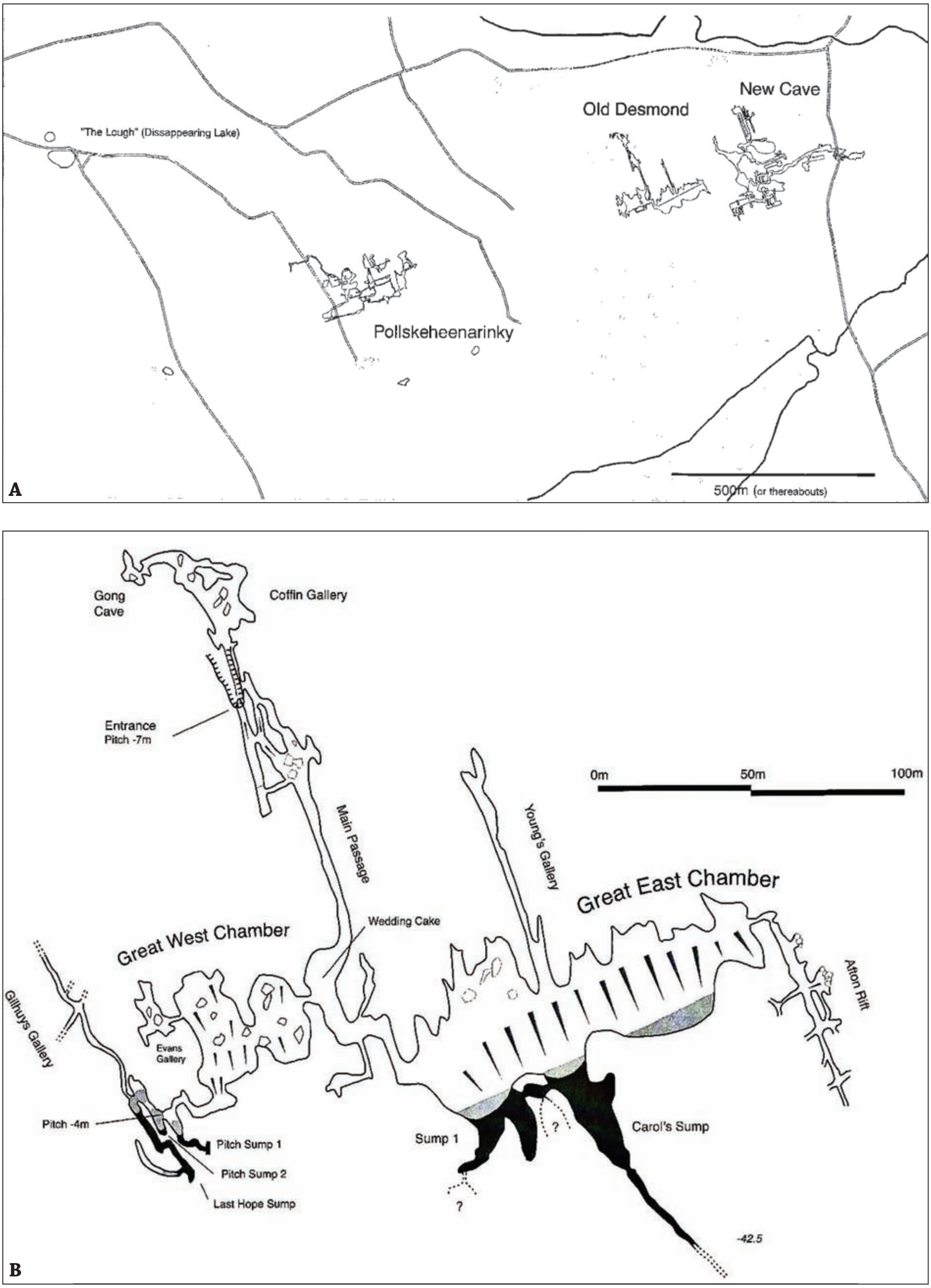


Figure 7.35 The caves near Burncourt (County Tipperary). (A) Plan surveys of the Old and New Mitchelstown Caves and Pollskeheenarinky in relation to one another. (B) Detailed plan survey of the Desmond (Old) Mitchelstown cave. *(From Barry, 2013.)*

Figure 7.36 Cave passage in the Old Desmond Cave, Mitchelstown developed along the strike of the steeply dipping strata. *(Photograph by Robert Mulraney.)*

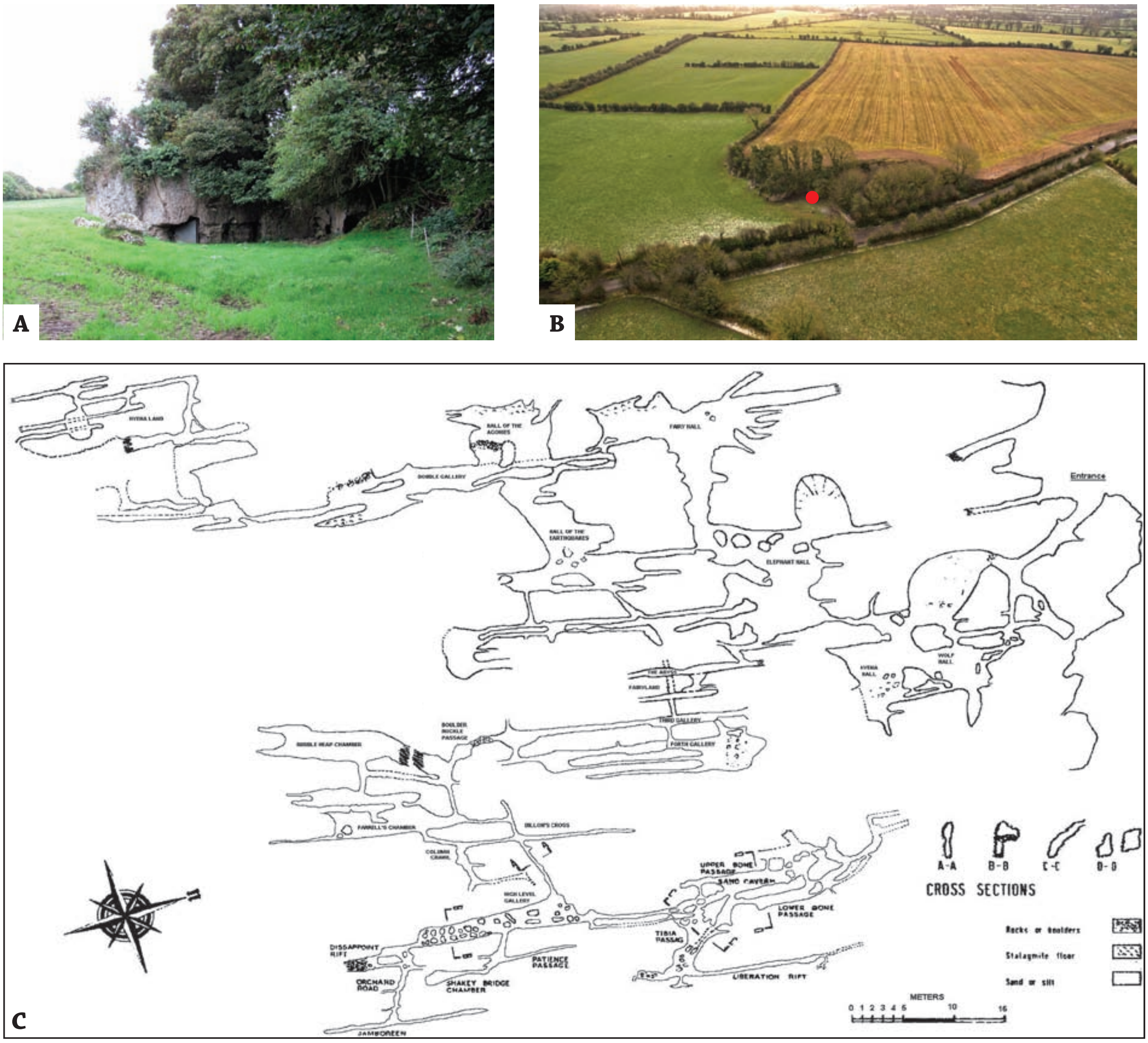


Figure 7.37 Mammoth (Castlepook) Cave (Doneraile, County Cork). (A) The entrance to the cave in an isolated limestone knoll. *(Photograph by David Drew.)*. (B) Mammoth Cave (centre-foreground red dot) in its setting at the western end of the Clonmel-Buttevant syncline. *(Photograph by Aerial Eye for David Drew.)*. (C) Plan survey of the cave. *(From Aherne, 1974.)*

the other surveyed caves of the area, geological controls are very apparent in the network of passages, but an overall dominant orientation north-south is apparent in the survey, suggesting a more defined direction of flow than is the case in the Mitchelstown and Cloyne caves, where folding of the strata is more pronounced.

7.4 The Eastern Lowlands (Meath, Westmeath, Offaly, Laois, North Tipperary)

Lowland, with a muted relief rarely exceeding 60 m and Carboniferous limestone as the dominant bedrock, is characteristic of central Ireland both east and west of the River Shannon. Depositional glacial and glacio-fluvial landforms predominate. East of the River Shannon a coherent surface drainage pattern is present, including the left bank tributaries of the Shannon, the drainage to the Irish Sea and the headwaters of the major rivers of the southeast (Suir, Nore, Barrow and Slaney) (Figures 7.38 and 7.39).

Less is known about karstification in this area than in any other of the limestone areas of Ireland. This may be due to a combination of factors, including the more widespread occurrence of impure limestones, the generally thicker subsoils and the comparative dearth of karst hydrogeological research. Over much of the midlands the water table is within 15 m of the land surface with an annual fluctuation of 3–7 m and up to 20 m under higher ground – a range typical of karstified aquifers. Active karst drainage is probably widespread and is especially apparent in parts of counties Kilkenny and Tipperary, for example the Nuenna catchment (Deakin et al., 2015) and the Mullinahone area (Jones and Gunn, 1982), but significant karst springs are common in the central midlands also (Figure 7.40). Karstic phenomena have been recorded in apparently unlikely areas such as County Meath (Figure 7.41) and County Louth, though without the presence of major springs which are often indicative of significantly karstified aquifers.

Fossil karst features, represented by fragments of ancient cave systems, are known in all counties of the eastern midlands except Longford, Meath and Carlow. However, it is likely that over wide areas, the mantle of subsoil is sufficiently thick to conceal even major karstic bedrock landforms, for example those postulated by Murphy (1962). Two areas in which karst landforms and hydrogeology are well documented are described below.

7.4.1 The Central Section of the Nore Valley

The area between Castlecomer to the north and Kilkenny city to the south is a limestone lowland occupied by the River Nore and its tributary the Dinin, which drains the southwestern part of the Castlecomer plateau (composed of Namurian and Upper Carboniferous rocks, Figure 7.42). Although the Nore system dominates the drainage, there is evidence of ancient, incipient and fully functioning karstic hydrogeology.

Ancient karst is represented by Dunmore Cave (Figures 7.43–7.45). It is the only cave of any significance in the area – the nearest caves of comparable size are those at Mitchelstown some 80 km to the west. Although the cave contains only 300 m of passages, its interest is considerable and it may be that it is one of the oldest accessible

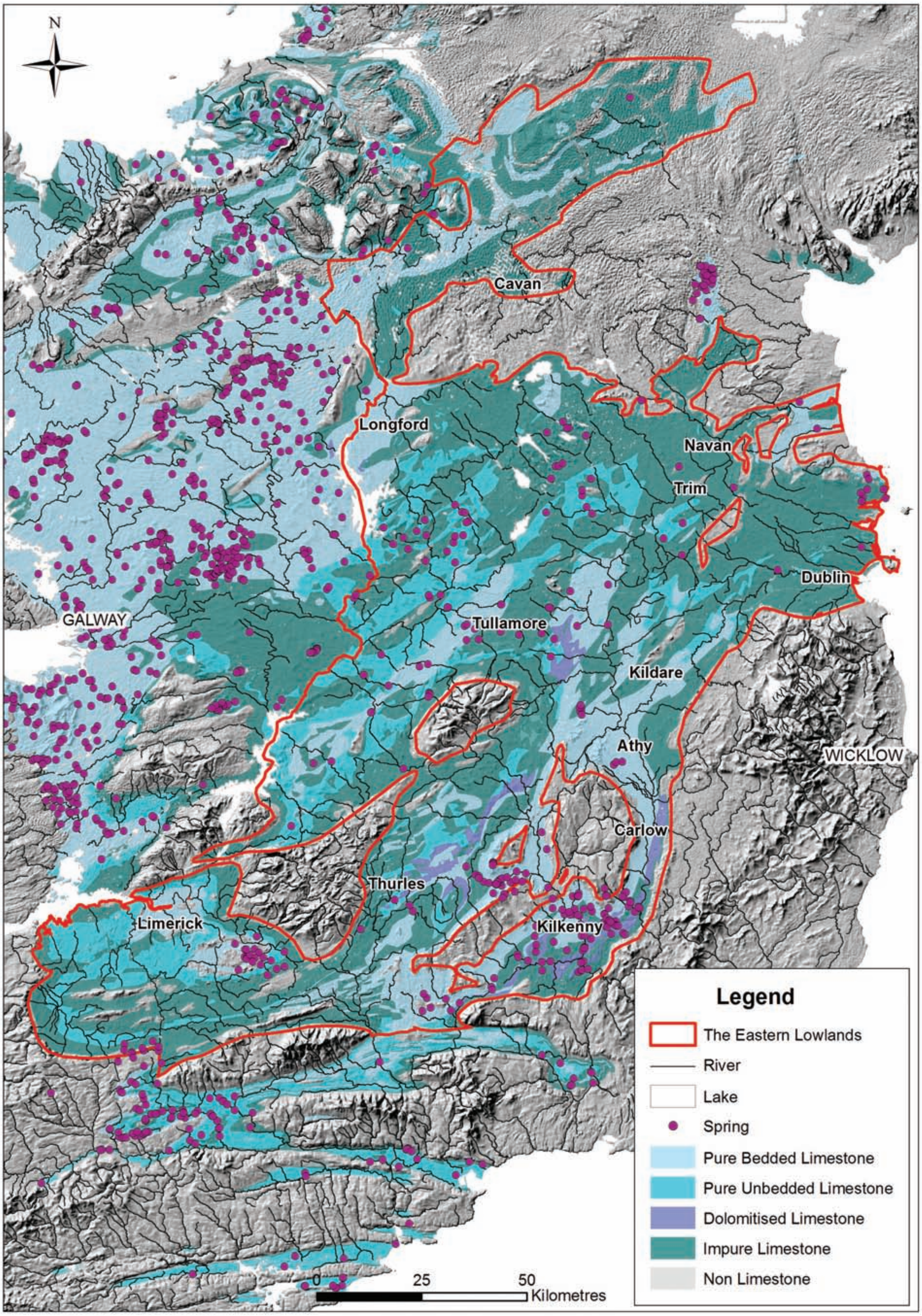


Figure 7.38 Limestone lithology, drainage and karst springs of the eastern lowlands. *(Data adapted from GSI.)*

Figure 7.39 The limestone lowland of County Longford looking east towards the hills of the Castlepollard area of County Westmeath. *(Photograph by David Drew.)*

Figure 7.40 (A) The Ballyhodrid spring on the bank of the Tullamore River at Tullamore (County Of aly). (B) The Tullamore River: the Ballyhodrid spring on the bank in the middle distance (right of image) is fed by from sink holes to the left (south) of the river, the water passing beneath the river course. *(Photographs by David Drew.)*

caves in Ireland. It is located at the northern extremity of a long, narrow inlier of Carboniferous limestone oriented NNE–SSW. The limestone outcrop is 3 km long but averages only 300 m in width, and is surrounded by Luggacurren Shales of Namurian age and the overlying Killeshin Siltstone Formation. More than 2 km separates the limestone from the main limestone outcrop to the west and southeast. The valley of the Dinin River (tributary to the River Nore) lies c.1.5 km west of Dunmore Cave

Figure 7.41 County Meath karst: (A) St Keeran's Well, Carnaross. *(Photograph by Robert Meehan.)*, (B) Poulmore sink near Kingscourt. *(Photograph by Gareth Ll Jones.)*

Figure 7.42 The southwestern flank of the Castlecomer upland with the limestone lowland in the middle ground. *(Photograph by David Drew.)*

and some 40 m lower than the cave entrance, though the lowest passages of the cave contain water which fluctuates in level seasonally and is at the same level as the Dinin valley floor. Little is visible of the original form of the cave that existed when it was a groundwater conduit, apart from solution hollows and bevels in roof and ceiling. The cave seems to have developed along a series of north-south joints under water table conditions, probably when the cover of Namurian rocks was complete. The present-day entrance exists only because of the relatively recent collapse of the uppermost beds of the Carboniferous limestone above the caverns (Figure 7.44).

Active karst groundwater systems integrated into the surface drainage network have been described (Walsh, 2011) in the catchment for the Nuenna River, a west bank tributary of the River Nore to the west of Dunmore Cave. The river receives much of its water from springs that are fed by a series of swallow holes (Figures 7.46 and 7.47) close to the contact between the limestone and the overlying Namurian shales, and also exchanges water with the glacial

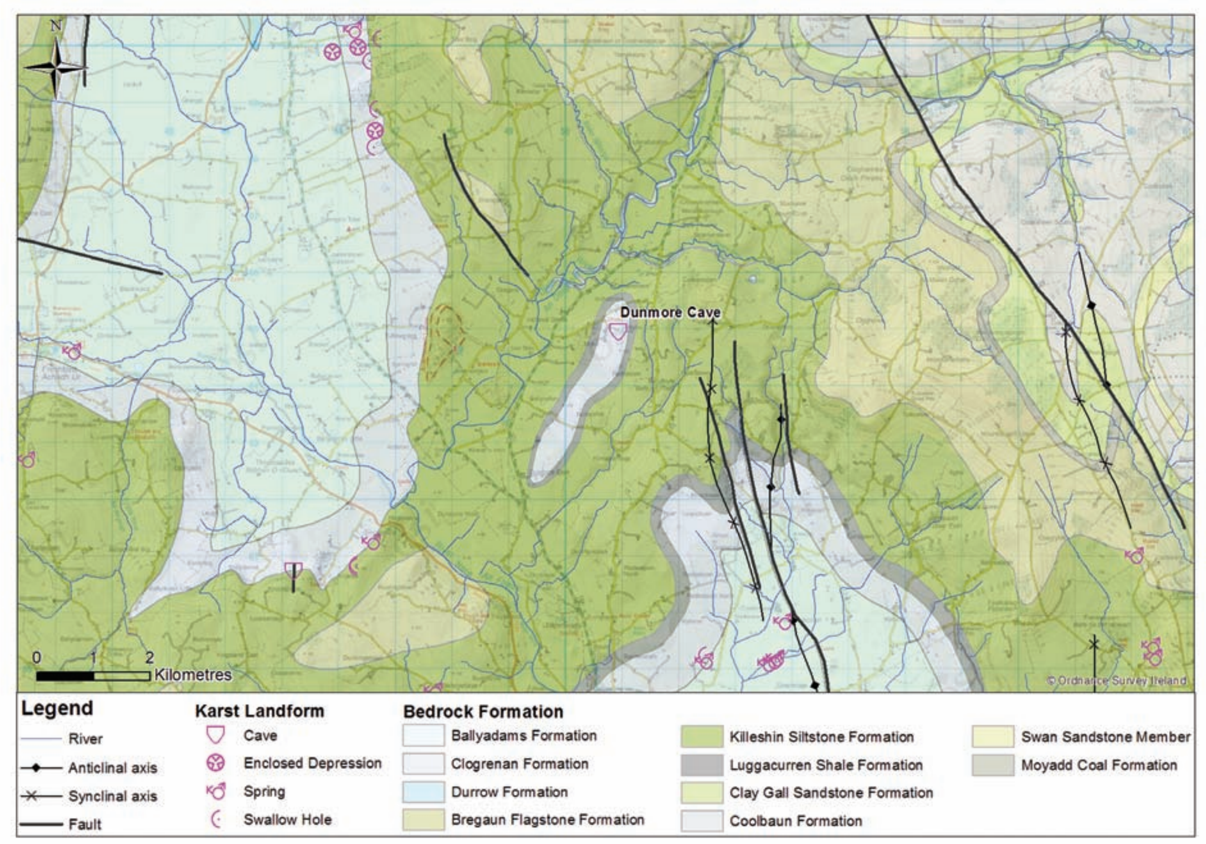


Figure 7.43 Bedrock geology and karst features at the edge of the Castlecomer upland between Kilkenny and Castlecomer. *(Data from GSI.)*

Figure 7.44 The large collapse doline entrance to Dunmore Cave looking NNE along the axis of the limestone inlier to the Namurian strata of the Castlecomer Plateau beyond. *(Photograph by Aerial Eye for David Drew.)*

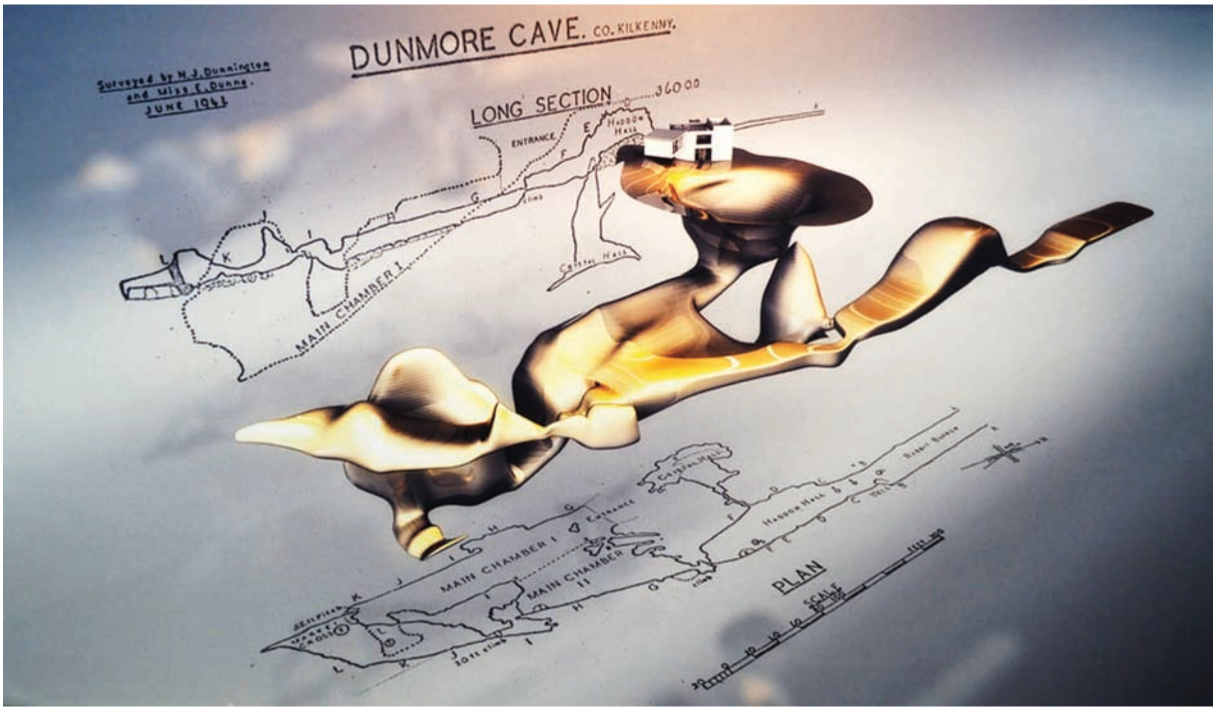


Figure 7.45 3D model and plan and long sections of Dunmore Cave. *(Photograph courtesy of Dunmore Cave.)*

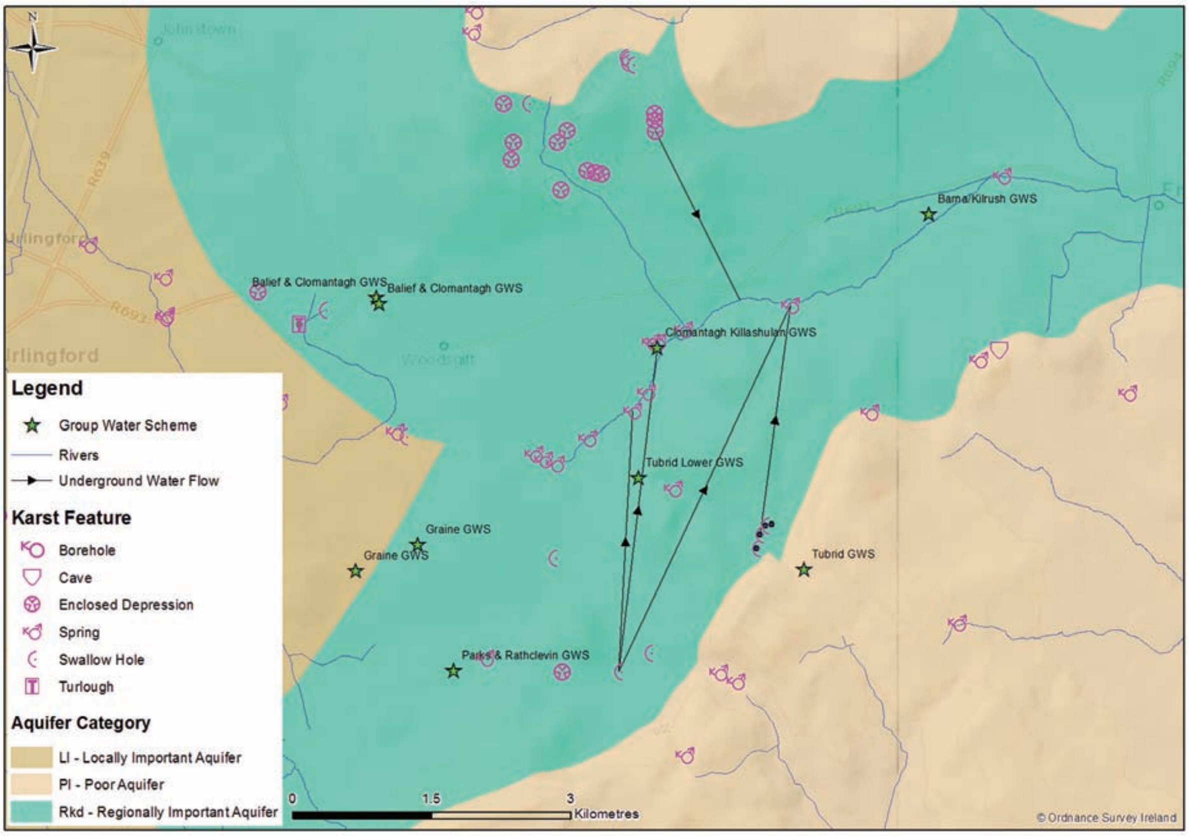


Figure 7.46 Traced connections between swallow holes and springs along the course of the Nuenna River. *(Data adapted from GSI.)*

Figure 7.47 A swallow hole at Killahy in the Nuenna catchment. *(Photograph by David Drew.)*

gravels that infill the lower part of the valley. The Nuenna catchment is an example of the progressive karstification of a diffuse flow groundwater system which has flow directions related to a water table surface as shown in Chapter 8.

Also, as shown on the bedrock map (Figure 7.43), there are a series of small sinking streams and see pages directly related to the present day Namurian-limestone contact at the western margin of the Castlecomer upland (Figure 7.47), which are probably of Holocene age and which drain diffusely into the Nore.

7.4.2 The Westmeath Lakeland

An area of some 100 km^2 on the County Meath-County Westmeath border exhibits landforms and a hydrologic functioning that might be interpreted as a palaeokarst, which is to some degree being reactivated (Drew, 1997, Quinlan, 2010). The area corresponds to the Westmeath 'lakeland' and consists of a cluster of lakes of which the core group are shown in Figure 7.48, but which also includes Loughs Owel and Derravaghagh to the south. There are also more than 30 distinctive isolated hills located to the east of the course of the River Inny, in a band oriented northeast-southwest, which are bounded by Lough Sheelin and Slieve na Calliagh to the north and extending to just southwest of Lough Owel.

To the west of the River Inny the hills cease abruptly and the terrain is almost completely flat as far as the River Shannon. Typically the hills are steep-sided, though the northern flanks are often blanketed by till and/or glacio-fluvial deposits. Vertical rock faces are widespread, for example on the hill south of Fore on the Rock of Curry (Figure 7.49)

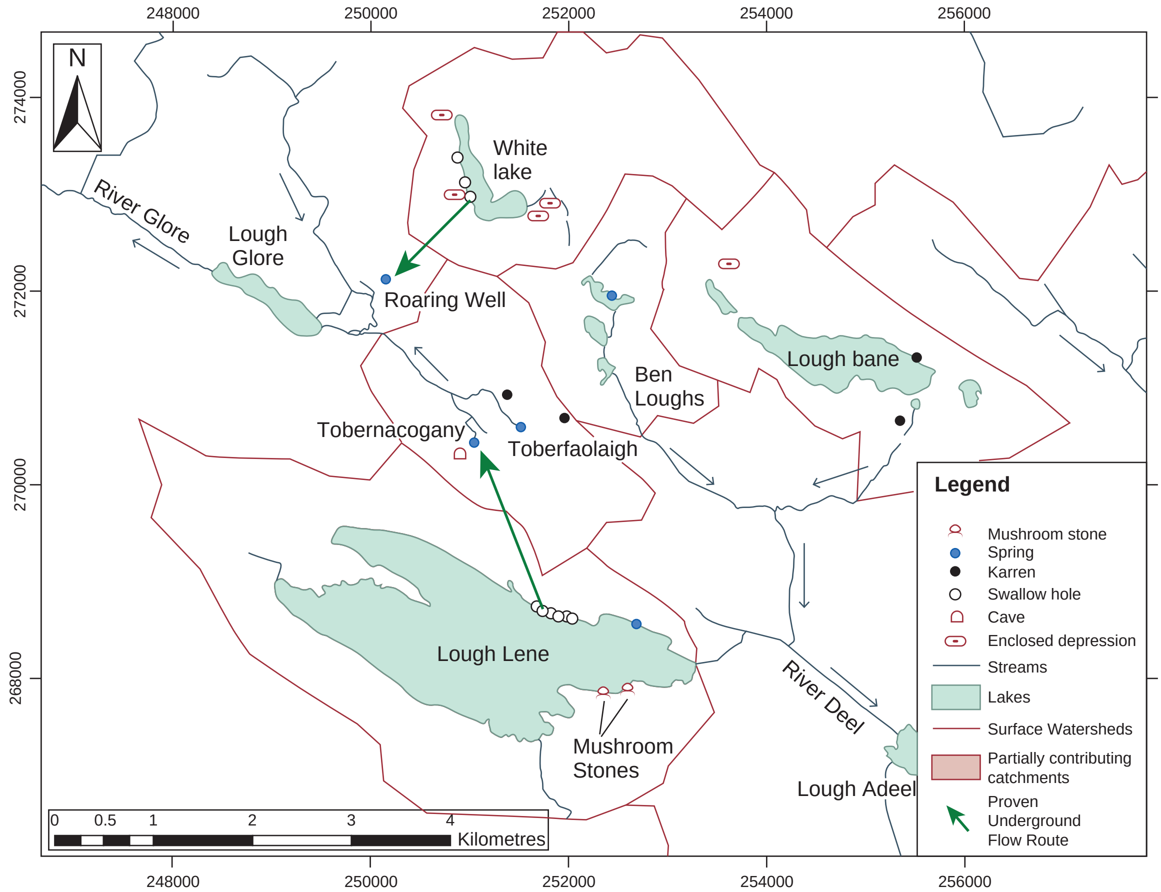


Figure 7.48 Surface and groundwater hydrology in the central Westmeath lakes area. *(From Quinlan, 2010.)*

Figure 7.49 The Rock of Curry, one of the group of steep-sided, isolated hills in the Castlepollard area (County Westmeath). *(Photograph by David Drew.)*

and on Knockeyon on the southeastern shore of Lough Derravaghara. The clif faces are found in all orientations and there seems to be no obvious geological explanation for the occurrence or the morphology of the hills.

Only the elevated portions of the bedrock terrain are visible, the areas between the hills being blanketed with unknown depths of glacial (and other?) materials. An origin for the hills due to glacial erosion of the intervening rock seems less likely in the Irish Midlands than, for example, in the northwestern karsts, and it may be that these are residual hillocks (hums or towers) relating to pre-Pleistocene karst landscapes. The presence of hill-foot caves at the Rock of Curry (Simms, 1991) and fossil phreatic caves high on the hills, for example Poll na gCat (Dowds, 1987) reinforces this hypothesis.

Many of the lakes are losing water to groundwater, having no surface inflows of water. Some have outflow (Loughs Lene and Owel for example), whilst others have no surface inflow or outflow (Bane and White Lough). The lakes straddle the watershed between the Inny (Shannon) and Deel (Boyne) catchments. Lough Lene drains via a surface channel eastwards to the River Deel and underground via sinkholes (Figure 7.50), to the Tobernacogany spring at Fore (Figure 7.51) and hence to the Inny and Shannon, with a flow rate of 80 m/h.

Figure 7.50 Lough Lene looking northeast: the swallow holes are on the lakeshore in the wooded area, far bank, left side. *(Photograph by Aerial Eye for David Drew.)*

Figure 7.51 Tobernacogany spring, fed from the swallow holes in Lough Lene and located at the far side of the hill from the lake at Fore. *(Photograph by David Drew.)*

Lough Lene itself is fed by underwater springs at its west end. White Lake to the north has no surface drainage outlet but at least some of the water drains to the Roaring Well spring, which then joins the outflow from the Fore springs.

Thus, there is a complex and seasonally variable relationship between the lakes and groundwater flow systems and clear differences between surface river catchments and groundwater catchments.

It may be that the existence of present day, shallow underground drainage and numerous springs is evidence for a degree of present-day active and probably post-glacial karstic drainage, but the presence of large springs with stable flow regimes may be evidence of more mature, ancient, fossil conduit systems that are being reactivated to some degree.

7.5 The Western Lowlands (Mayo, Roscommon, Galway, Clare)

The western lowlands are taken to comprise the area bounded by the River Shannon between Carrick-on-Shannon and Limerick, extending as far as Ballina in County Mayo to the west. The total area is 9,650 km^2 (Figure 7.52).

The east of the area is drained by the Shannon and the River Suck and much of the western area by the Rivers Robe, Clare and Moy. However, arterial drainage (Figures 7.53 and 7.54) has considerably modified many of the river courses and other drainage features in this area (Coxon and Drew, 1988). Figure 7.54 shows the surface drainage pattern in an area of approximately 3,700 km^2 in eastern Galway and Mayo, underlain by karstified Carboniferous limestone. Figure 7.54 A shows the present-day drainage, with a series of rivers pursuing somewhat convoluted courses to Loughs Mask, Corrib and the coast, together with a series of large karstic springs, mainly in the vicinity of the eastern shore of the lakes. Turloughs are abundant in the area.

These rivers and turloughs have been subject to extensive arterial drainage since the mid-nineteenth century in an attempt to reduce the extent and severity of seasonal flooding. The drainage pattern prior to arterial drainage, reconstructed from early Ordnance Survey maps, is shown in Figure 7.54 B. It is apparent that originally only two rivers had a surface course to the lakes and none made it overland to Galway Bay and that the area extending 20–30 km east of the lakes drained underground via karst conduits, to the springs. Further east, where Quaternary deposits are thicker, the surface drainage pattern was largely the same as at present. See also Chapter 8.7.

Although karst features are widespread throughout the western lowlands, karst landforms and karst drainage become more dominant towards the western extremity of the limestone and the boundary with Burren upland until, in the area some 20–30 km east of Loughs Corrib and Mask and to the south of Galway Bay, karstic systems are completely dominant to an extent not found elsewhere in Ireland. As with the limestone east of the Shannon, thick subsoils mask much of the bedrock topography, with only isolated exposures of bedrock protruding above the undulating or flat terrain.

Although superficially this is a fluvial landscape, drainage densities are low, reflecting the importance of groundwater (Figure 7.55). Large sinking streams are uncommon, with most

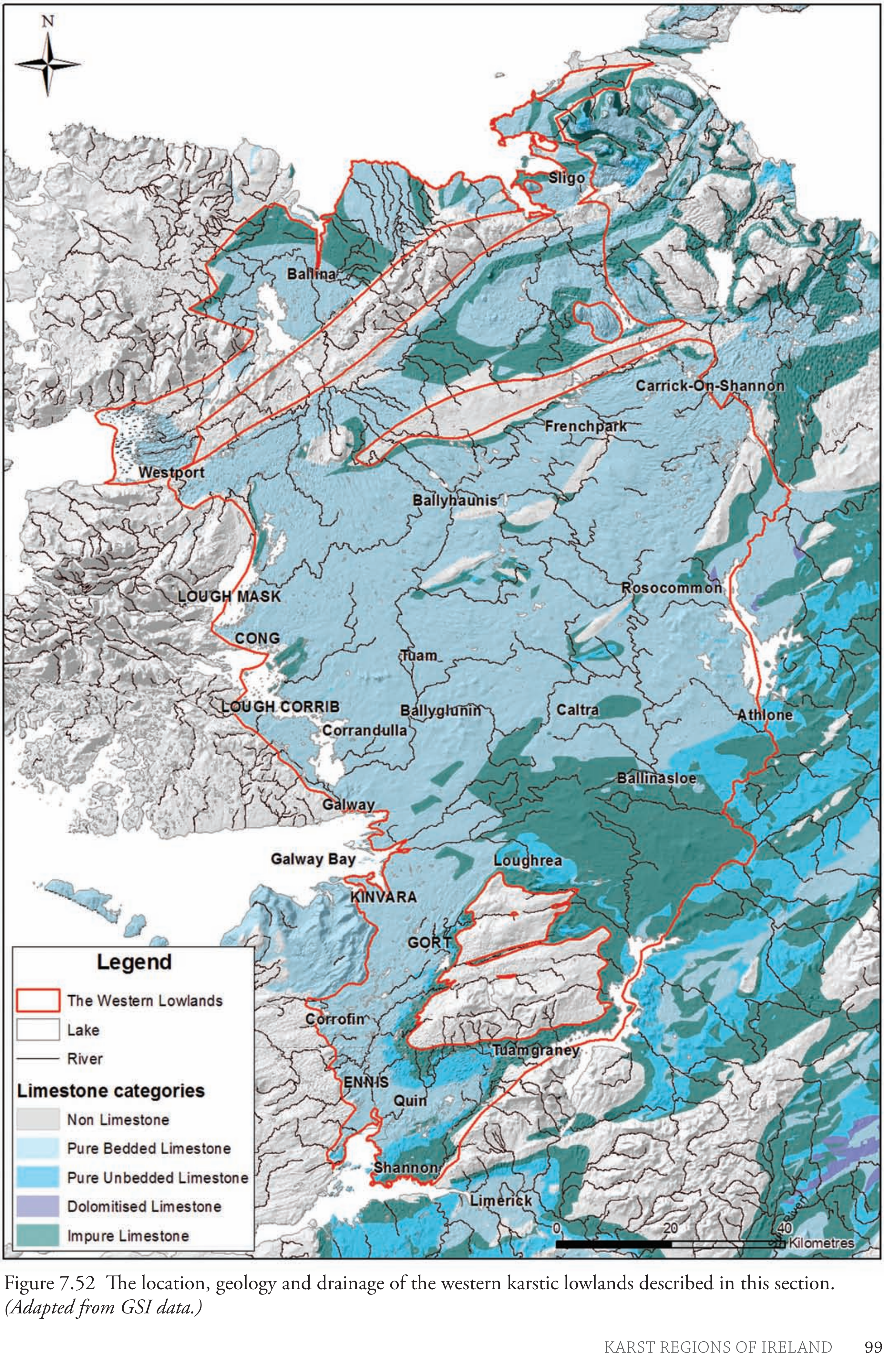


Figure 7.52 The location, geology and drainage of the western karstic lowlands described in this section. *(Adapted from GSI data.)*

Figure 7.53 The artificial channel of the River Clare at Corofin (County Galway). *(Photograph by David Drew.)*

sinking streams having an inflow of less than 10 l/s and a catchment on low permeability subsoils overlying the limestone (Figure 7.56). As elsewhere in Ireland, point allogenic recharge to the limestone aquifer from adjacent older non-calcareous rocks is uncommon, with the exception of the Gort area in County Galway, described later in this section, and the Aille River in County Mayo (Chapter 8.3). Only one such allogenic sinking stream is known in County Roscommon – the Pollnagran Cave system near Frenchpark (Hickey and Drew, 2003).

7.5.1 Roscommon and East Galway

A feature of this area is the existence of tracts of land (mini-plateaux) with areas of up to tens of km^2 elevated 20–40 m above the surrounding lowland, with no integrated surface water channels and draining to small-medium springs around the periphery (Figure 8.37). Catchments for these springs rarely exceed 10 km^2. A more detailed description of one such area in County Roscommon is given in Chapter 10.

Other springs, particularly in the east of the lowlands, have no obvious topographic or geological explanation for their location: for example springs such as Pollifrin (Figure 7.59) and Caltra (Figure 7.60) in County Galway are located in the middle of extensive areas of bog with no obvious catchment and Carnalasson, north of Roscommon town, which overflows from a large, deep pool, again with no obvious surrounding contributing area.

The extensive superficial deposits of Quaternary age and, perhaps, earlier that conceal the bedrock surface over most of the western midlands make it difficult to determine whether the apparently shallow groundwater flow systems feeding springs such as those described above are underlain by older, more developed karst conduits. However, in some locations there is evidence that an older groundwater regime does exist and may be, at least partially, being re-activated.

Figure 7.54A Post-arterial drainage in karstic limestones in western Ireland. *(After Coxon and Drew 1986.)*

Figure 7.54B Pre-arterial drainage in karstic limestones in western Ireland. *(After Coxon and Drew 1986.)*

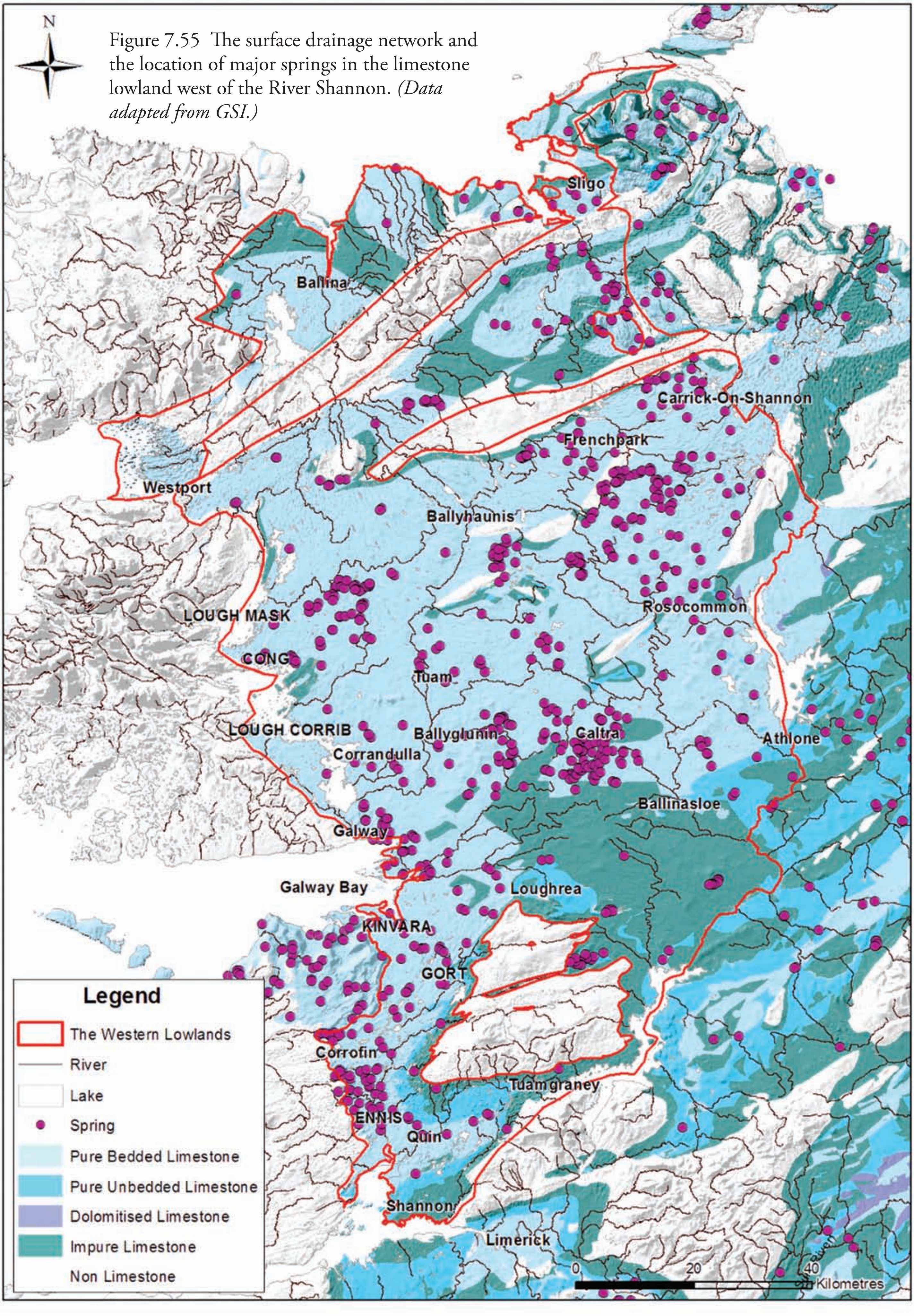


Figure 7.55 The surface drainage network and the location of major springs in the limestone lowland west of the River Shannon. *(Data adapted from GSI.)*

Figure 7.56 One of the many small swallow holes in glacial deposits in the western lowlands, Lough Hackett, County Galway. *(Photograph by David Drew.)*

Figure 7.57 The swallow hole of the Clarin River (County Galway). The sink only engulfs all of the river under low water conditions as higher flows are conduited to the sea by the artificial channel in the background. *(Photograph by David Drew.)*

Figure 7.58 A limestone landscape in eastern County Roscommon. The stony character of the terrain may have been typical of much of the lowland karst west of the Shannon prior to land clearance for agriculture. *(Photograph by Robert Meehan.)*

Figure 7.59 Pollifrin spring, east County Galway. The main spring is at lower centre and an overflow spring is located to the right of the pumphouse. *(Photograph by Aerpas for David Drew.)*

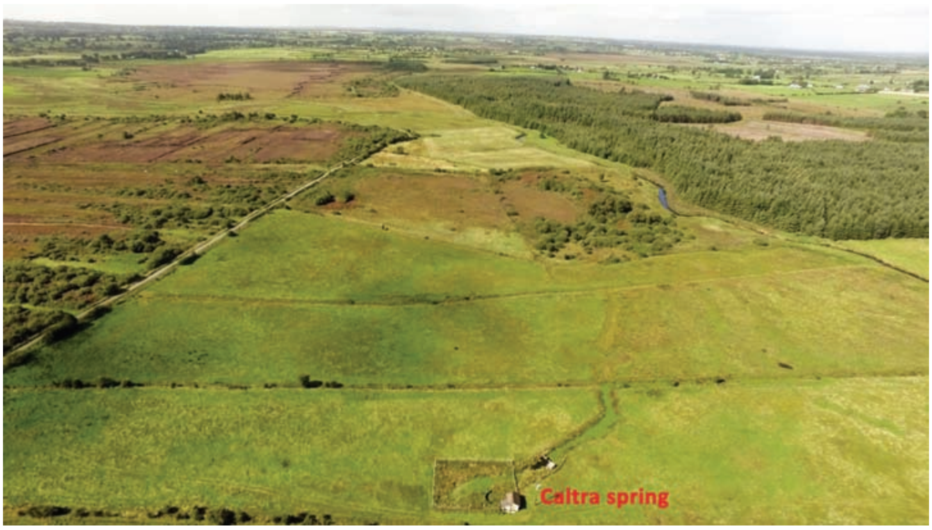


Figure 7.60 Caltra spring, east County Galway. The spring issues from a boggy area surrounded by higher ground but the exact location of the catchment area is unknown. *(Photograph by Aerpas for David Drew.)*

One such location is at Ballyglunin, County Galway where a cave system extends beneath the course of the River Abbert (Figures 7.61 and 7.62) with little (natural) connection between river and cave. Some 1,300 m of cave passage have been mapped, consisting of a set of conduits oriented north-south and generally without water, together with an east-west oriented set of passages containing small streams, probably derived from the Abbert, which have invaded the cave. The north-south conduits are larger and are presumably related to an older flow regime than the east-west set. The water in the cave reappears, under high stage levels, at the Aucloggeen Spring (Corandulla Group Water Scheme), 11 km to the west.

Almost all of Ireland's turloughs are located in the western lowlands (Figure 8.59). Turloughs form part of a spectrum of groundwater bodies ranging from permanent lakes isolated from groundwater to karstic hollows, such as Blackrock turlough in County Galway, which can

Figure 7.61 The River Abbert at Ballyglunin (County Galway). The river loses water in its bed over this reach and Ballyglunin Cave extends beneath the river in the vicinity of the house (at left). *(Photograph by Aerpas for David Drew.)*

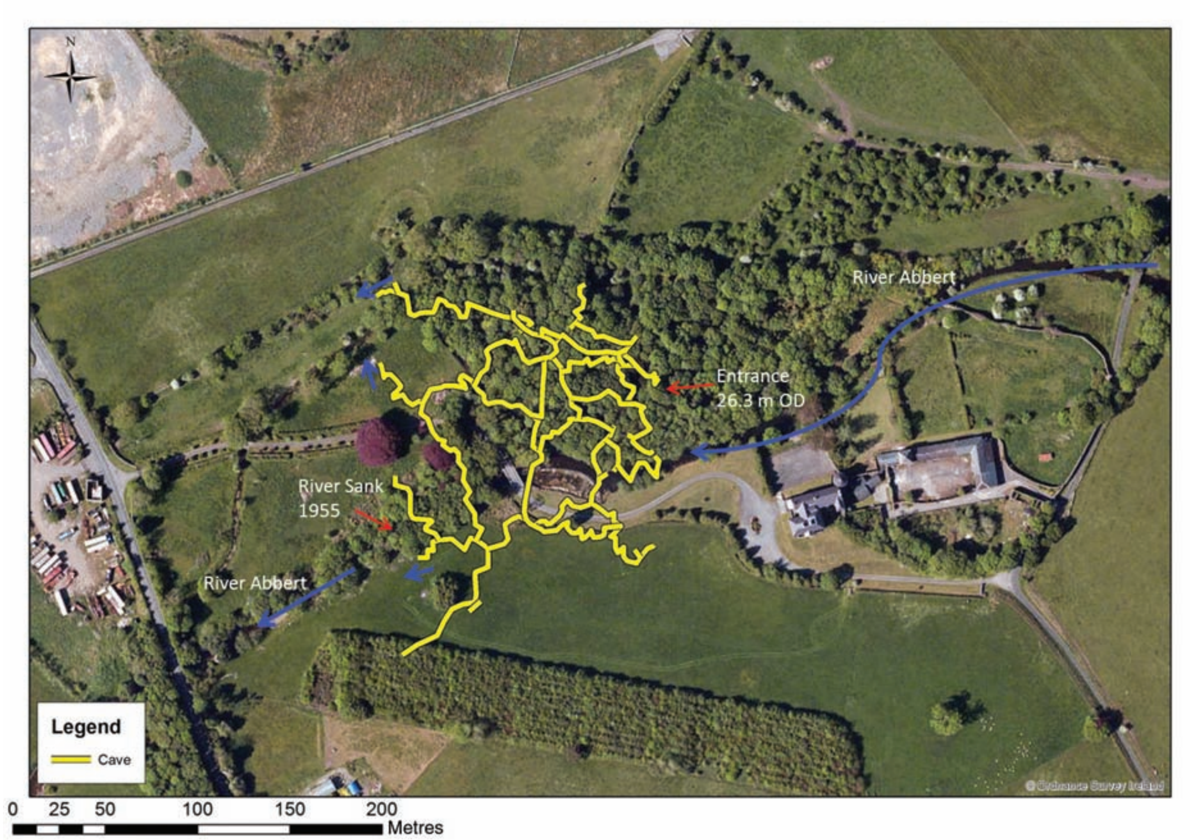


Figure 7.62 Plan survey of Ballyglunin cave in relation to the land surface.

fill and empty with water in a short time. Between the two extremes is Lough Funshinagh (Figure 7.63), located 10 km northwest of Athlone and 5 km west of Lough Ree. Lough Funshinagh is a large-scale (3 km^2) version of Lough Nasool in County Sligo described earlier in this chapter. Funshinagh is fed by two small streams but appears to have no groundwater inflows. The lake periodically empties via a sink on the southeastern shore (in 1955, 1995 and 2010 in recent times) – and almost dries every 4–5 years. The waters are known to drain to a spring in the Cross River some 5 km to the south and 15 m lower. As this lake is very shallow it appears to drain very suddenly.

Figure 7.63 Lough Funshinagh. (A) Under 'normal' conditions. (B) Dry, in 1995. *(Photographs by David Drew.)*

7.5.2 Lough Mask and Lough Corrib

Loughs Mask and Corrib mark the western limits of the karstic lowland of Ireland. Both lakes are located on the boundary between the limestone and the non-calcareous rocks of western Connaught and both lakes function as base levels for the karstic drainage to the east. A series of large springs, east of the lakes, are located at the foot of a low scarp and at the edge of a peaty flatland that extends for some kilometres to the lake shore. These springs may relate to an older long-term lake shoreline but as is described in Chapter 8 (section 8.5), groundwater discharge also takes place directly into Lough Mask at some distance from the present shore.

Loughs Mask and Corrib are separated by a narrow (3–5 km wide) and low isthmus but the lakes are connected by the artificial Cong Canal and also by karst conduits (Figure 7.64). Prior to the construction of the canal the connection was wholly subterranean with estimated underground flows (the runoff from the 877 km^2 catchment of Lough Mask) exceeding 50 cumecs (>50,000 l/s). Nowadays, when the water level in Lough Mask falls below 17 m OD, the outflow, <17 cumecs, all sinks underground.

Lough Mask waters sink at a series of locations on the southeastern shore of the lake from Ballinchalla Bay in the north to Dringeen Bay in the south. The most important swallow holes (60% of the total water sinking) are those in Castle Bay (Figure 7.65), a 1.5 km long inlet of the main lake that becomes separated from the main lake and functions as one enormous sink. In dry weather sinking water becomes progressively concentrated into Castle Bay and below a flow of c.5 cumecs only these sinks are operative (Figure 7.66 B).

The sinking water re-emerges from a group of springs in and around Cong village that combine to form the short Cong River flowing into Lough Corrib. The largest and lowest spring is the Hatchery spring whilst Curreighnabannow and Ellechrissaun springs (Figures 7.64 and 7.67) are overflow springs which cease to flow under dry conditions. Water from small swallow holes in the Clonbur area to the west also drain to the Cong springs. Numerous fissures, up to 50 m deep and often flooded in their lower part, are located on the inter-lake isthmus and it is probable that flow between the lakes is via an extensive network of enlarged joints. Transit time for the underground flows is 6–10 hours (average minimum groundwater velocity of 580 m/h). The main flows are at a considerable depth below the spring outlet levels – up to 40 m below, according to cave divers, corresponding to 25–30 m below sea level. Major karst conduits at similar depths are known from Bunatober Cave further north, near Ballinrobe and in the Aille River Cave, described in Chapter 8. A narrow outcrop of Silurian non-carbonate rock runs along the northern shore of Lough Corrib (the Clonbur fault) and forces the karst water to rise in this area. The springs have presumably migrated north over time to create the Cong River.

Lough Corrib drains into Galway Bay via the short Galway (Corrib) River. However, in the past it may have taken a subterranean route to the sea. According to the Annals of the Four Masters (O'Donovan, 1854) the river ran dry in 1178 and reportedly also in 1191 and 1199. O'Flaherty (1852) reported that the river suddenly dried in September 1647 and in February 1684 citing the *discharging powers of the cavernous passages of Terryland or Castlegar.* The swallow holes may indeed have been at Terryland, where a small distributary of the Galway River now sinks (Figure 7.68), or possibly also in the main river at Menlo where a deep hollow exists in the river bed.

Collapse dolines between Menlo and southeast to Galway Bay may be associated with this underground drainage route. The mean discharge of the Galway River is in the region of 100 cumecs. The water from Lough Corrib may have emerged in the vicinity of Lough Atalia in the eastern suburbs of Galway city, where the tongue of non-limestone rocks along the northern shore of Galway Bay terminates, or further out in Galway Bay, when sea levels were lower in the early Holocene.

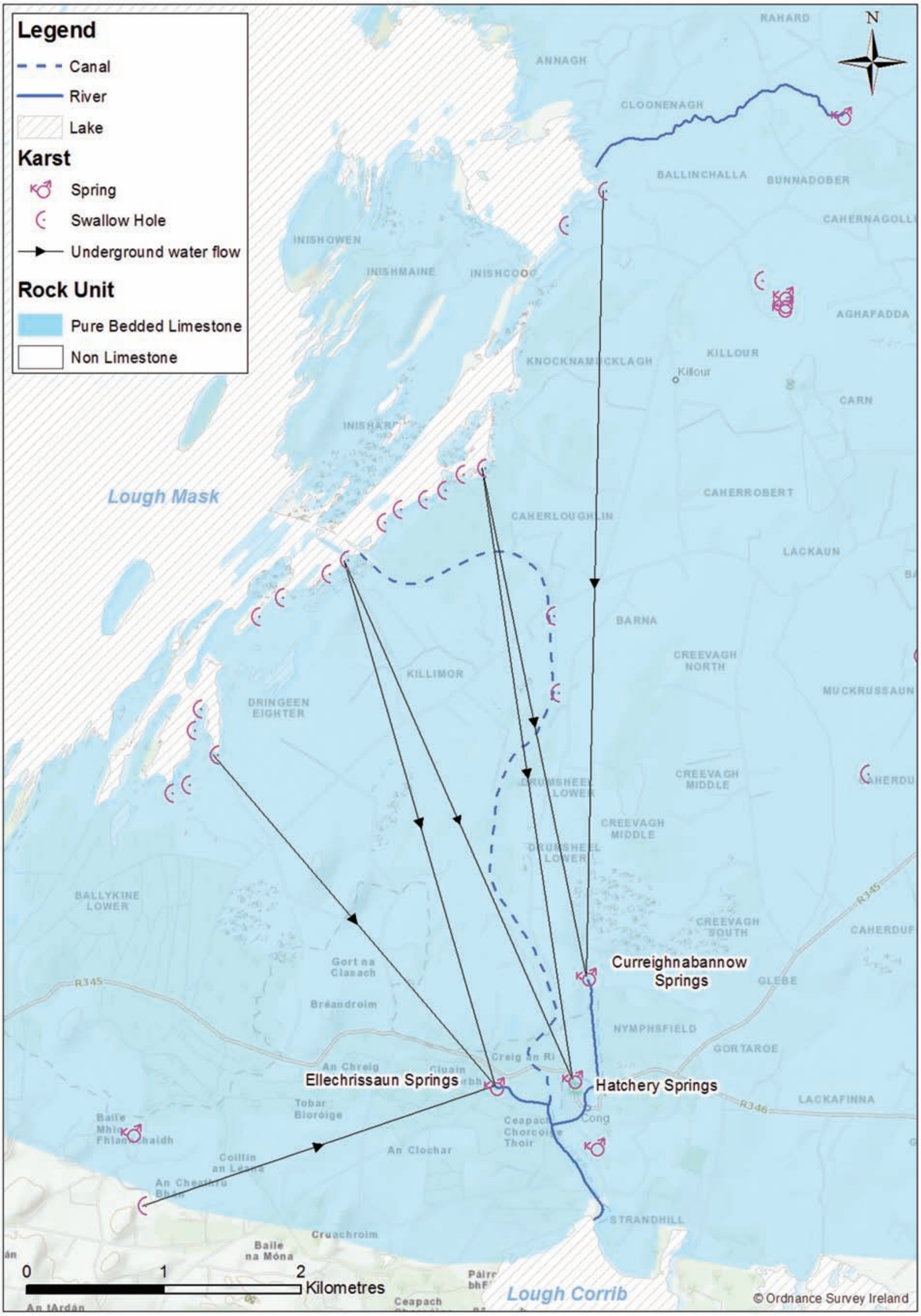


Figure 7.64 Hydrogeology of the Lough Mask-Lough Corrib isthmus. *(Data adapted from GSI and Drew and Daly 1993.)*

Figure 7.65 Castle Bay, Lough Mask, under high water conditions. The entrance to the Cong Canal is on the right. *(Photograph by Aerial Eye for David Drew.)*

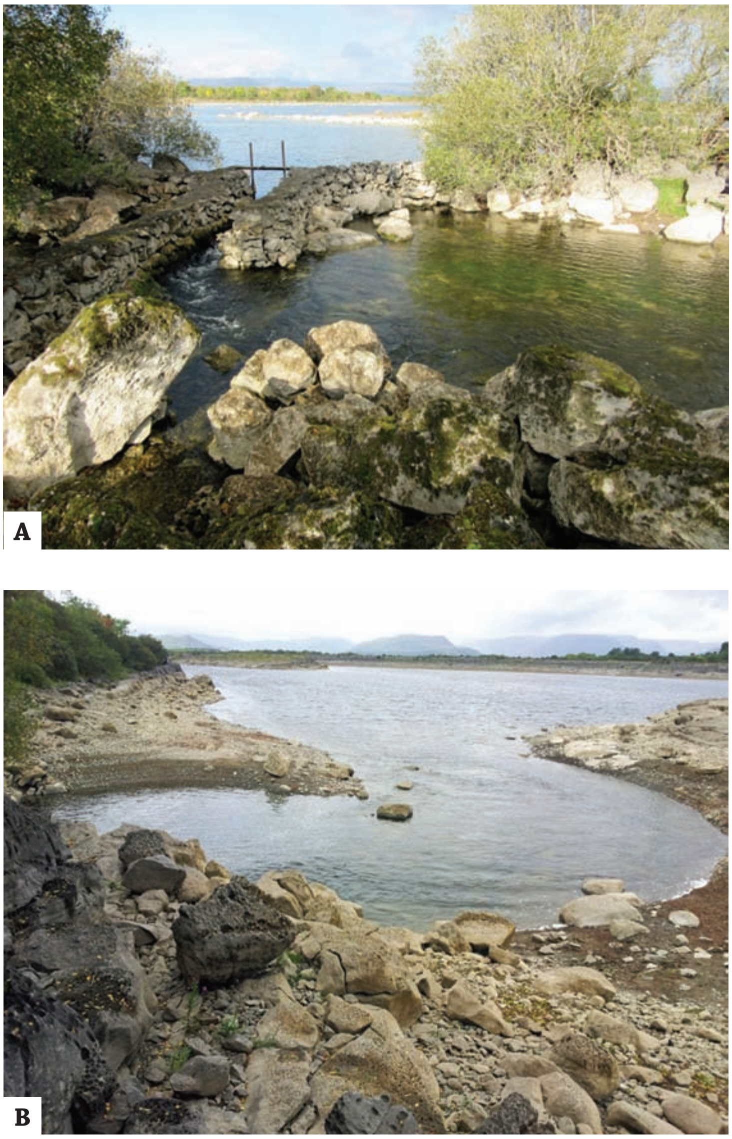


Figure 7.66 Swallow holes in the southeastern shore of Lough Mask. (A) Ballinchalla Bay, (B) Castle Bay. *(Photographs by David Drew.)*

Figure 7.67 The main springs in Cong, Ellenchrissaun to the left and the Hatchery Spring (centre), unite to form the Cong River which drains into Lough Corrib. *(Photograph by Aerial Eye for David Drew.)*

Figure 7.68 The sink of the Galway River distributary at Terryland in Galway city. *(Photograph by David Drew.)*

7.5.3 Karstic Corridor between Galway Bay and the Shannon Estuary

The corridor of limestone running north-south, between the Devonian rocks of Slieve Aughty and Slieve Bearnagh to the east, and the Burren plateau and the Namurian upland of west County Clare to the west, is the southwestern extremity of the western karst lowland (Figure 7.69). The corridor varies in width from 15 km in the central part (Ennis) to 25 km in the north (Gort-Kinvara) and the south (Shannon-Quin). The limestone in this strip receives aggressive runoff waters from both the east and west sides and has been subjected to intense karstification over a long period, resulting in perhaps the most developed karstic landscape in Ireland, particularly in the Gort-Kinvara area. The watershed between the catchment of the River Fergus (1,040 km^2) and the drainage to the springs at Corranroo and Kinvara on the southern shore of Galway Bay (c.500 km^2) is located just south of Gort (Figures 7.70 and 7.71).

The headwaters of the River Fergus, upstream of Corofin, are derived in part from the Burren, and in part from the shales to the west of Kilfenora, and are described in Section 7.6 (the Burren). Between Corofin and Ennis, the course of the River Fergus is partly artificial (Figure 7.72). Originally, much of the flow was underground, short-circuiting segments of the surface course with Lough Keogh, east of Lough Atedaun, acting as the principal swallow hole. Pouladower spring (Figures 7.72–7.74), north of Ennis, is the discharge point for much of the groundwater in the area but its zone of contribution varies greatly depending on water levels in the River Fergus and the lakes along its course. For example, when flow is from Dromore Lough into the River Fergus, the catchment of the spring is approximately 250 km^2 (the area coloured green on Figure 7.73). However, when water level is higher in the River Fergus the flow reverses from river to lake and hence to the swallow holes in the lake, and the catchment area for Pouladower increases by some 130 km^2 (the area coloured mustard on Figure 7.73). In both instances the catchment areas are only partial contributing areas (Coxon and Drew, 2000). Such complex interrelationships between surface and groundwater are characteristic of much of the limestone corridor, and few of the rivers maintain wholly surface courses.

Large conduits are known to exist in the Fergus catchment, for example in the underground segments of the Moyree River and at the Tomeens, a partly unroofed cave system (Figure 7.75) in the headwaters of the Rine River, both being east bank tributaries of the River Fergus. These conduits, together with the presence of large collapse dolines adjacent to the course of the Fergus, suggest that a mature karst drainage system exists which has been dislocated and partially inactivated by cold climate processes.

Karst drainage is much more apparent in the northern third of the corridor. Surface drainage is limited to allogenic streams generated on Slieve Aughty which flow over the limestone for a short distance before sinking underground (Figure 7.76), and to short reaches of surface channel draining the lakes along the eastern flank of the Burren (Figure 7.69).

West and north of Gort, the drainage becomes increasingly subterranean, apart from lakes and turloughs that are linked to the major conduits (Figure 7.77). For 5 km or so inland from Galway Bay there is no surface water, only large collapse dolines such as Poulaloughabo and Pollbehan which access the main conduits draining the area (Figure 7.78).

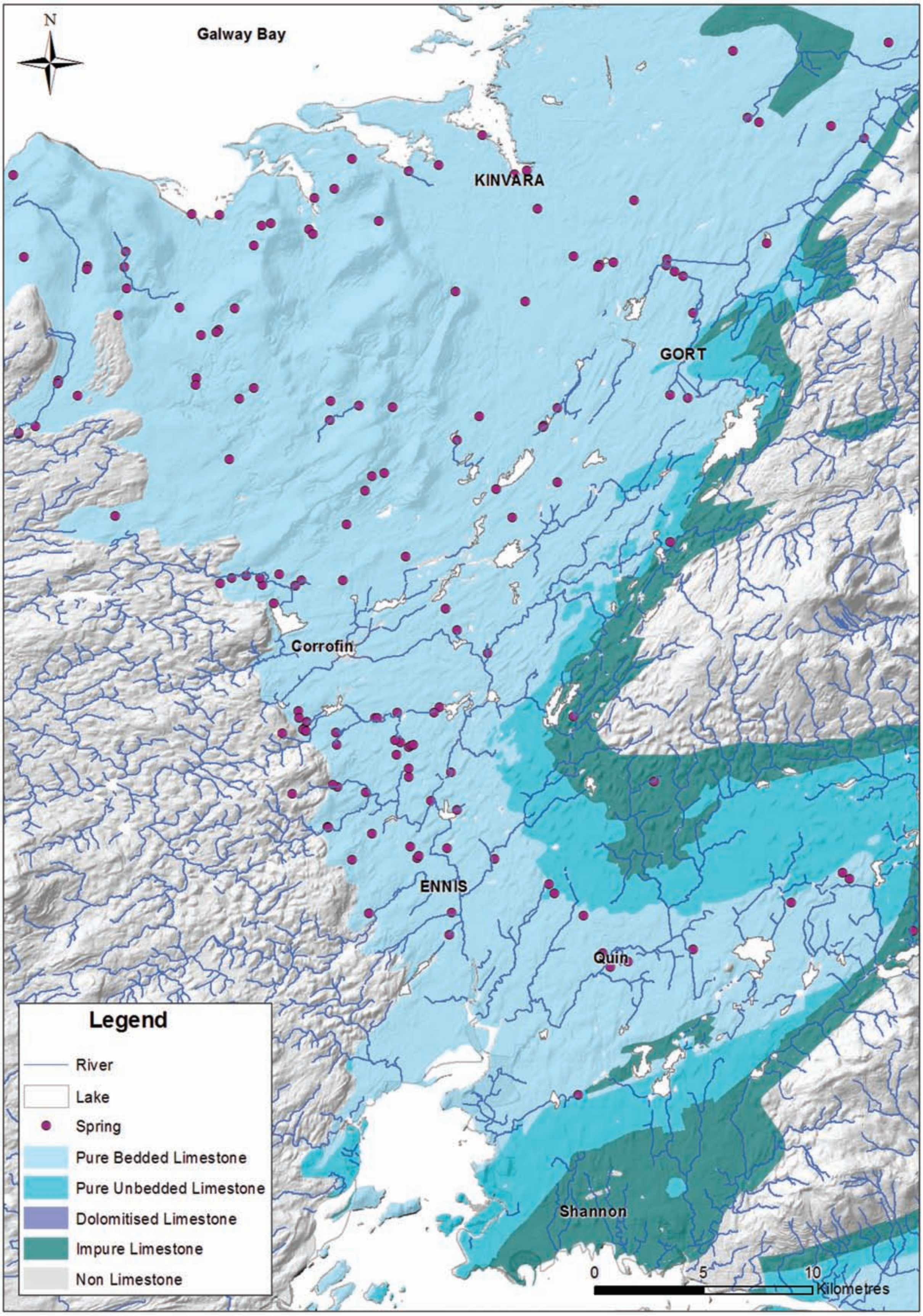


Figure 7.69 The karstic corridor between Galway Bay and the Shannon Estuary. *(Data adapted from GSI.)*

Figure 7.70 Looking east from the Burren across the Gort-Ennis lowland to the Devonian Slieve Aughty Mountains. *(Photograph by David Drew.)*

Figure 7.71 The limestone corridor south of Gort, looking south. The Burren plateau is on the right. In the foreground water discharges from a spring (A) which flows north into Galway Bay at Kinvara. The water originates from Lough Bunny (B) which in turn derives its inflow from groundwater originating at the foot of the Burren at Travaun Lough (C). Muckanagh Lough (D) in the far distance drains subterraneously south to the River Fergus. *(Photograph by Aerial Eye for David Drew.)*

In this highly karstified area, three flow systems are evident: the network of large water-filled conduits with cross-sectional areas just less than 40 m^2, distributed flow within the uppermost 30 m of limestone and a locally significant flow system in the epikarst (Figures 7.79 and 7.80).

At present, most of the groundwater discharge from this area is from the springs in the inter-tidal zone at Kinvara, which have an estimated mean discharge of 12 cumecs (Figure 7.81).

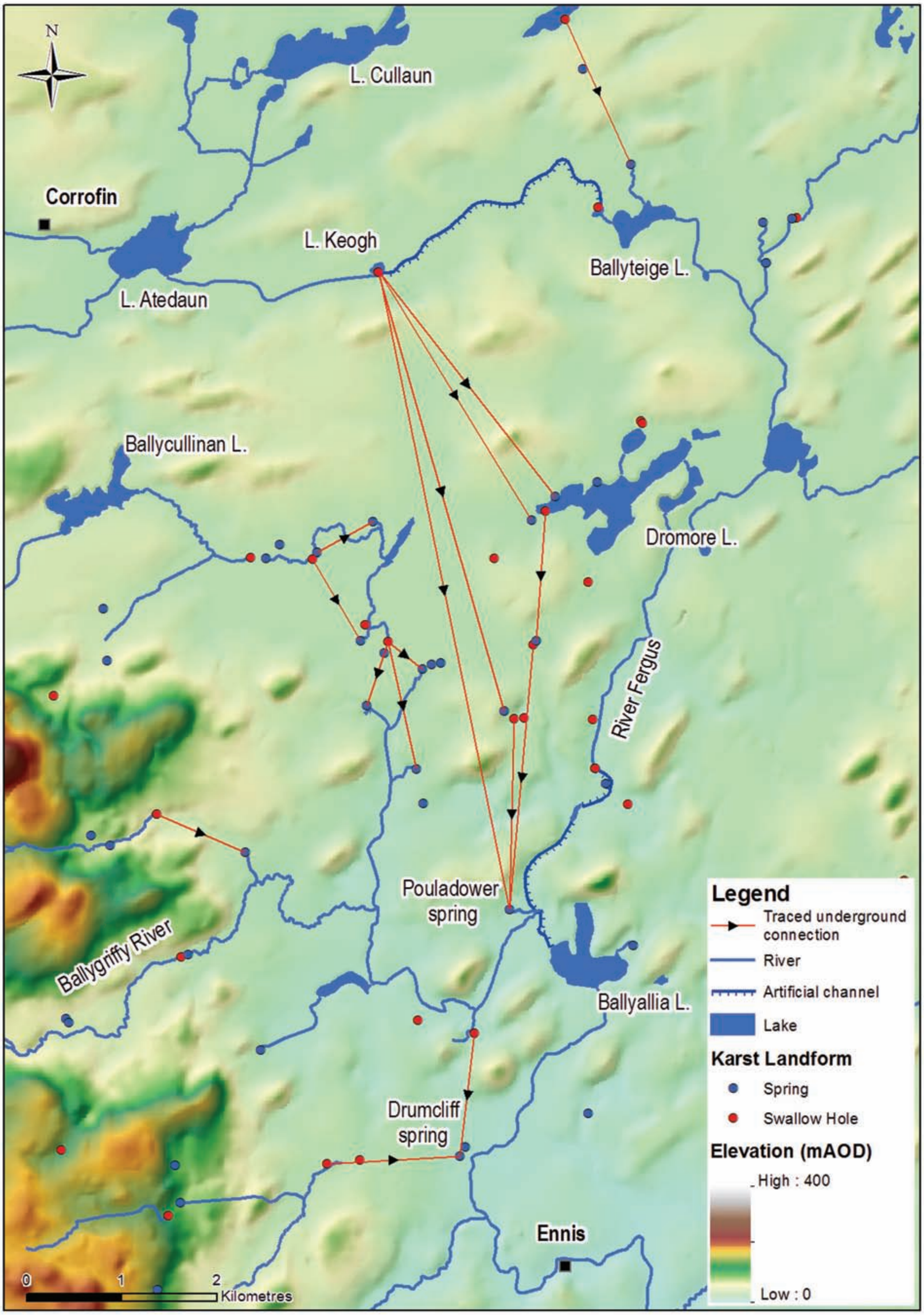


Figure 7.72 Surface drainage systems and proven groundwater f ow connections in the middle and lower course of the River Fergus. *(Modified from Coxon and Drew, 2000.)*

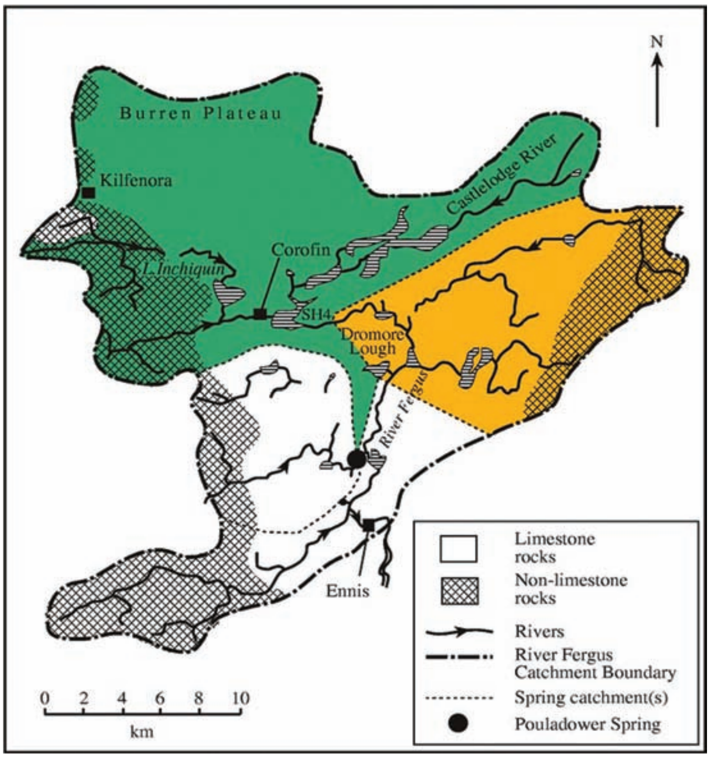


Figure 7.73 Partial contributing areas to the Pouladower spring under diﬀering water levels in the River Fergus (see text). *(From Coxon and Drew, 2000.)*

Figure 7.74 Pouladower spring (Ennis, County Clare). *(Photograph by David Drew.)*

Figure 7.75 The Tomeens caves near the southeastern part of the Kinvara-Ennis karst corridor. *(Photograph by Gareth Ll Jones.)*

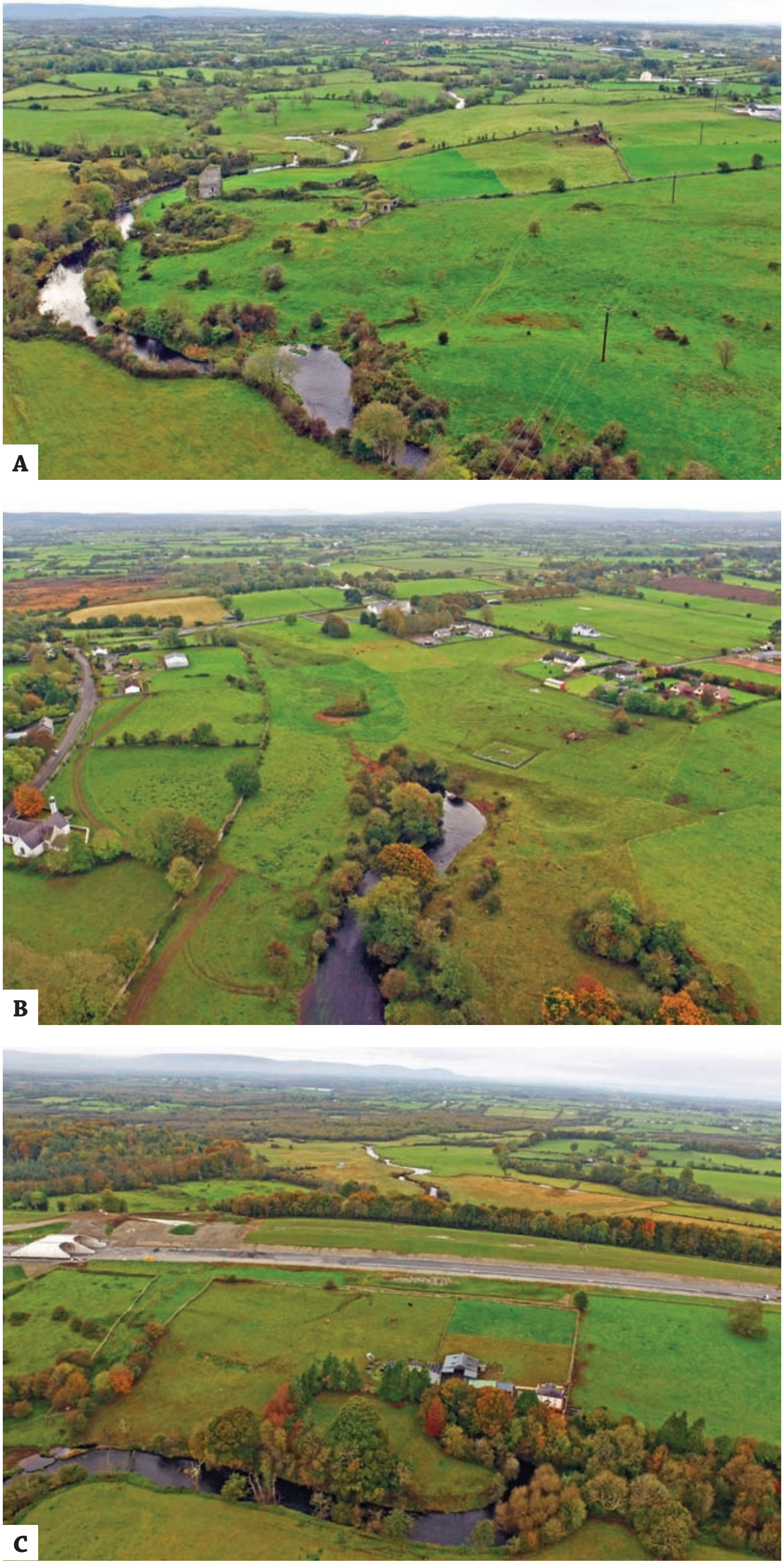


Figure 7.76 Sinks and resurgences of the Gort River upstream of Coole Lough. (A) The Polltoophill sink of the river draining of the Slieve Aughty. (B) The resurgence of the river at Polldeelin spring 1 km to the west. (C) The sink of the Polldeelin water and its resurgence at the far (western) side of the M18 road. The river then f ows into Coole Lough. *(Photographs by Aerial Eye for David Drew.)*

Figure 7.77 Water from Coole Lough and other sources sinks and then flows to the springs at Kinvara and Corranroo on the coast. Some of the water flows by shallow routes via Caherglassaun Lough appearing from epikarst springs at (A) before sinking at (B) and dropping into the main conduit via a collapse. Underground flow directions are shown by the blue line. *(Photograph by Aerpas for David Drew.)*

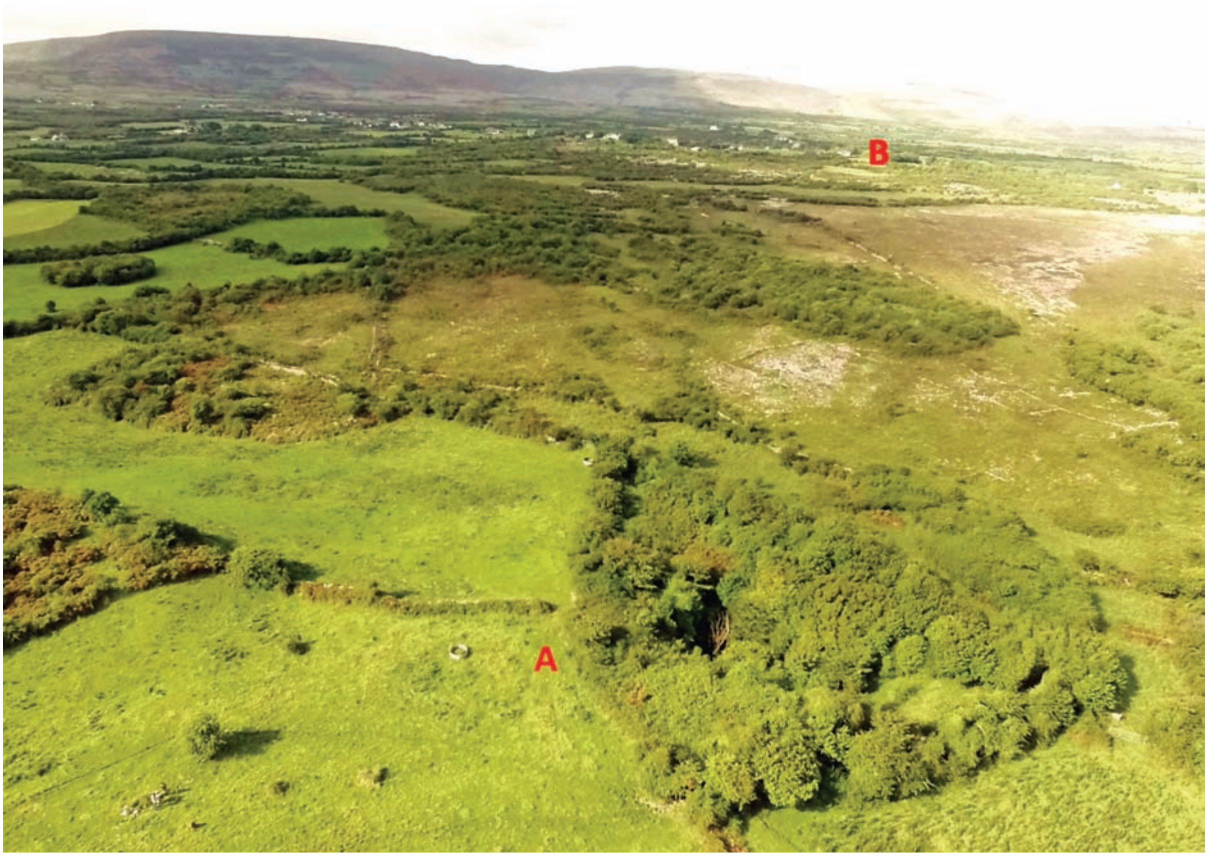


Figure 7.78 The collapse dolines of Pollaloughabo (A) and Pollbehan (B) above the main conduit leading to the springs at Kinvara. *(Photograph by Aerpas for David Drew.)*

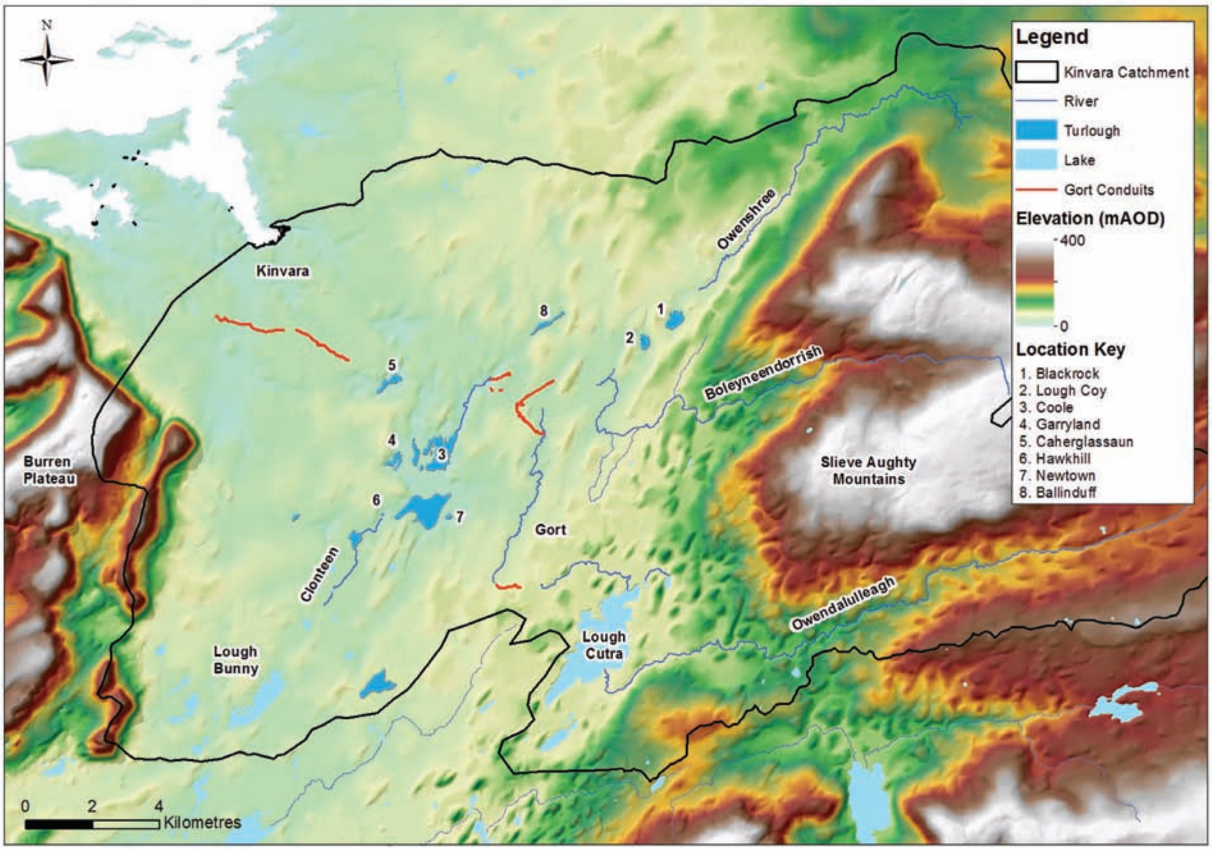


Figure 7.79 The surface hydrological system in the Gort-Kinvara lowland area. *(Modified after Naughton et al., 2017.)*

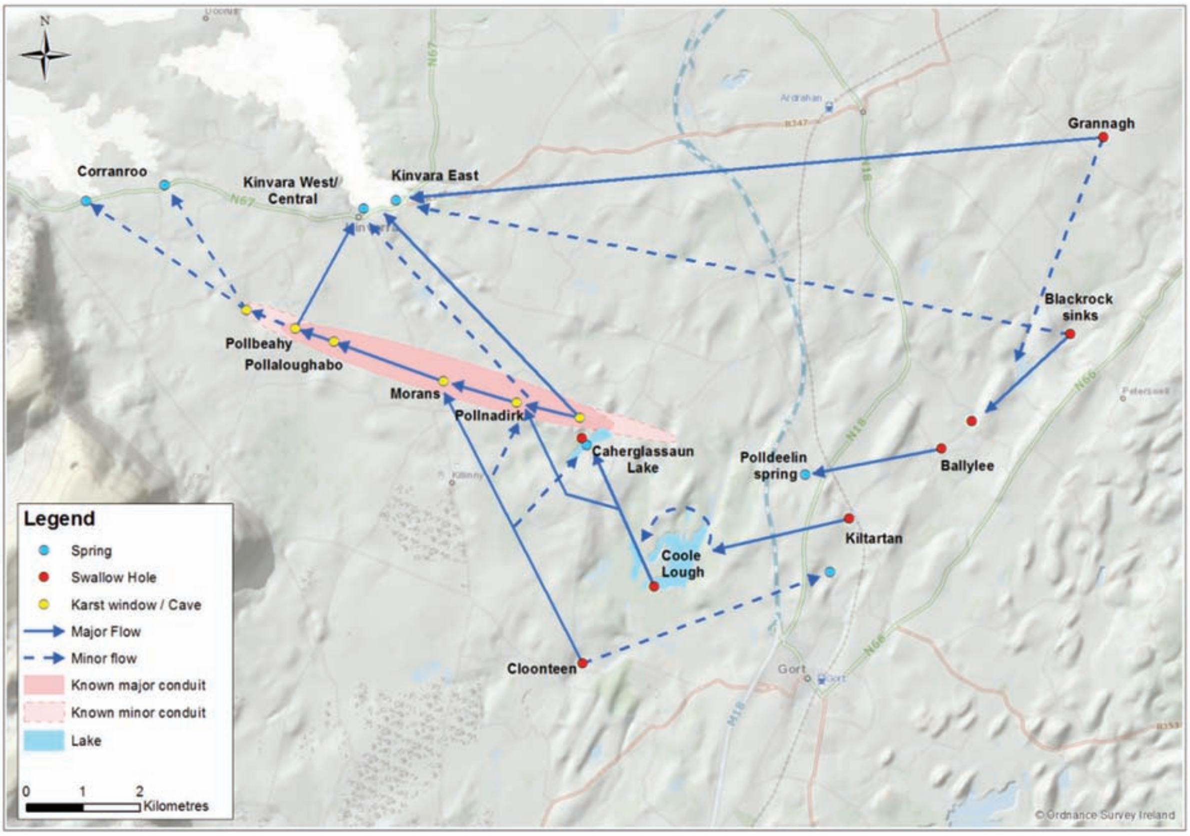


Figure 7.80 Schematic map showing groundwater flow routes in the Gort-Kinvara lowland. *(Adapted from Drew, 2003.)*

Figure 7.81 The three major groups of springs in the inter-tidal zone at Kinvara. (A) eastern springs (B) Dunguaire Castle springs (C) western springs. *(Photograph by Aerpas.)*

However, the main conduit continues, partly infilled with sediment, to Galway Bay at Corranroo to the west, at a depth of less than 12 m below present sea level, where significant groundwater discharge also occurs. It is likely that the springs at Kinvara represent a relatively recent capture of the main conduit flow that formerly discharged at an unknown location in Galway Bay.

The karst groundwater system of the Gort-Kinvara area may be representative of the character of karst aquifers over a much wider area of the western lowlands in pre-Quaternary times.

7.6 The Burren Plateau

The Burren upland, between the Atlantic Ocean and the Gort-Ennis corridor, has an area of approximately 400 km^2, roughly half that of the northwestern plateau limestones. It is also lower in altitude, ranging from 300 m O.D. at its northern scarp overlooking Galway Bay, to 30 m O.D. in the valley of the River Fergus at its southern extremity (Figure 7.82). Unlike the plateaux of Sligo, Leitrim and Fermanagh, karst landforms are abundant, bedrock exposures are widespread and the geological controls on groundwater occurrence and movement are apparent. These differences are due in part to the often impure character of the northwestern limestones in comparison to those of the Burren, which means that the bedrock in the northwestern areas is usually mantled with residual cherty debris, partly due to the altitude, which encourages the cover of blanket bog, and partly due to more extreme exposure to glacial and periglacial processes.

Namurian strata overlie the Carboniferous limestone of the Burren to the south and southwest, and the karstification of the Burren has taken place as this cover has been stripped

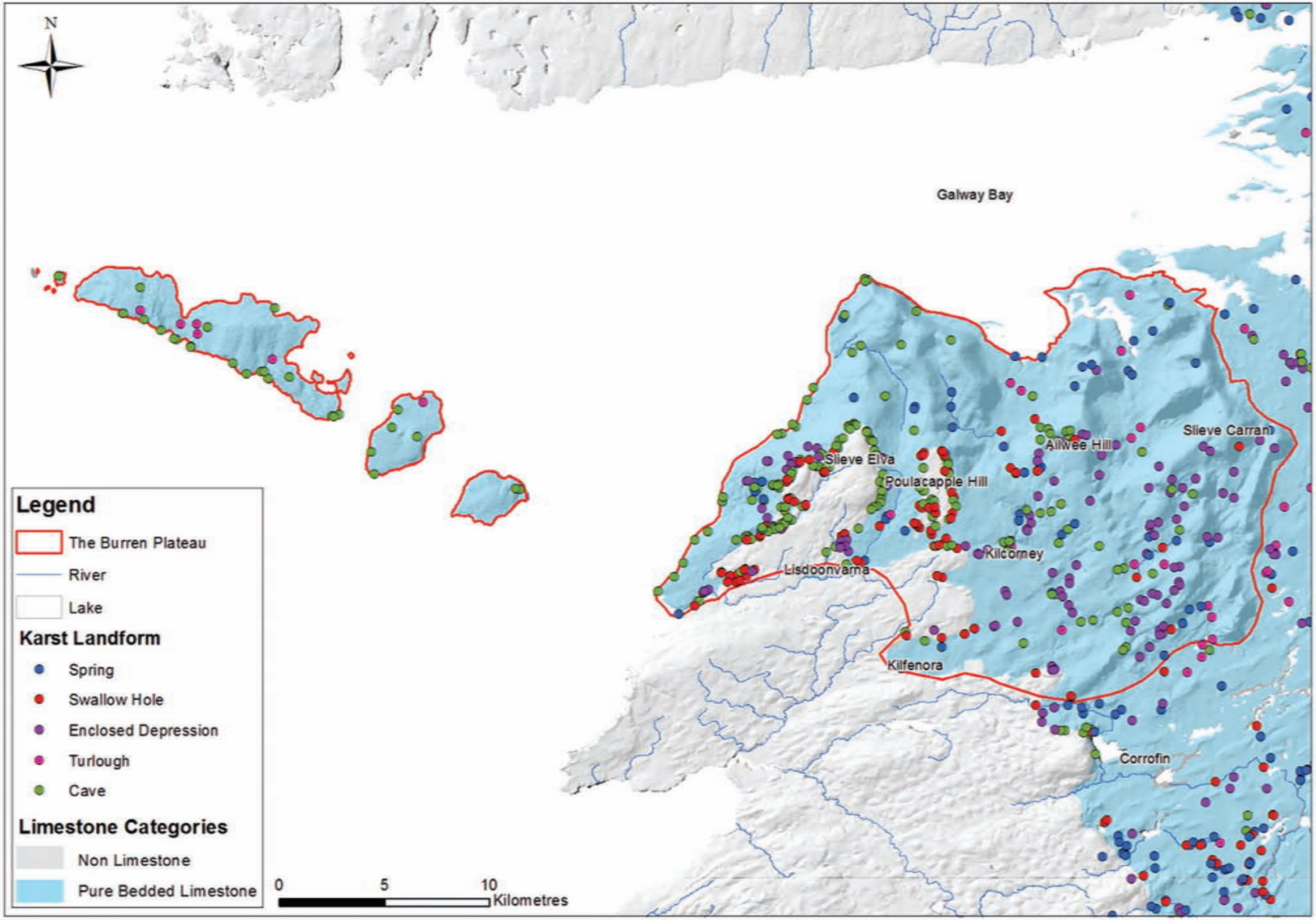


Figure 7.82 Geology, surface drainage and main karst landforms of the Burren. *(Data adapted from GSI.)*

Figure 7.83 The steep eastern scarp of the Burren plateau bordering the Gort-Ennis lowland. The coastal northern and western margins of the Burren are equally abrupt. *(Photograph by David Drew.)*

from east to west and exposed the limestone to weathering. Point recharge from sinking streams occurs along the junction between the shale and limestone, whilst diffuse recharge is the norm over the areas removed from the shale margin.

The geological contact is also the zone of most intense karstification on the Burren with, for example, the formation of collapse and suffosion dolines in karst windows within the shales and the leakage of water underground from the bed of streams which have cut down through the shale to reach the limestone beneath (Figure 7.84). The headwater of the Aille River, in the Lisdoonvarna area, is the most obvious example of such incipient karstification.

East and north of the shale contact, the landforms are wholly karstic on a small scale (dolines and karren for example) but they are often superimposed on fluvial or glacio-fluvial landforms such as the dry valley systems on Aillwee Hill (Figure 7.85).

The central Burren is characterised by a series of large enclosed depressions with internal drainage (Figure 7.86), one of which (Carron-Kilcorney) might be considered to be a polje (Figure 7.87). The only two upland turloughs in Ireland are both located in this area of the Burren.

The great range in the age of karst in the Burren is illustrated by the caves, some of which are simple trenches carrying a stream and are probably of Holocene age whilst others, such as Aillwee Cave, have a complex history and may date to early Pleistocene or even earlier times.

Groundwater flow in the Burren is strongly influenced by the gentle south-southwest dip of the strata, which provides extensive bedding controlled preferential flow paths for the water. East-west oriented joints and north-south veins are also significant controls on karstification (Figures 7.88 and 7.89).

Vertical infiltration of recharge is inhibited by the presence of chert bands in the uppermost limestones and by clay layers (wayboards) in the underlying Aillwee Formation and this is reflected by the presence of numerous small and usually ephemeral springs, the waters of which

Figure 7.84 'Recent' karst landforms developed at and near the contact between limestone and the overlying Namurian strata in the western Burren. (A) The boundary between the limestone (foreground) and Namurian shales (afforested) on Slieve Elva in the Burren. The collapse/ancient swallow hole feature in the foreground is the entrance to Pollnagollum Cave which may be located at an earlier shale/limestone contact. (B) A 'karst window' (green fields) in the shales near Lisdoonvarna. Aggressive waters draining into the hollow from surrounding shales will deepen and widen the hollow to form a major enclosed depression or uvala. (C) The sink of the River Fergus at the present-day contact between the shale (right) and limestone (left) east of Kilfenora. *(Photographs by Aerpas for David Drew.)*

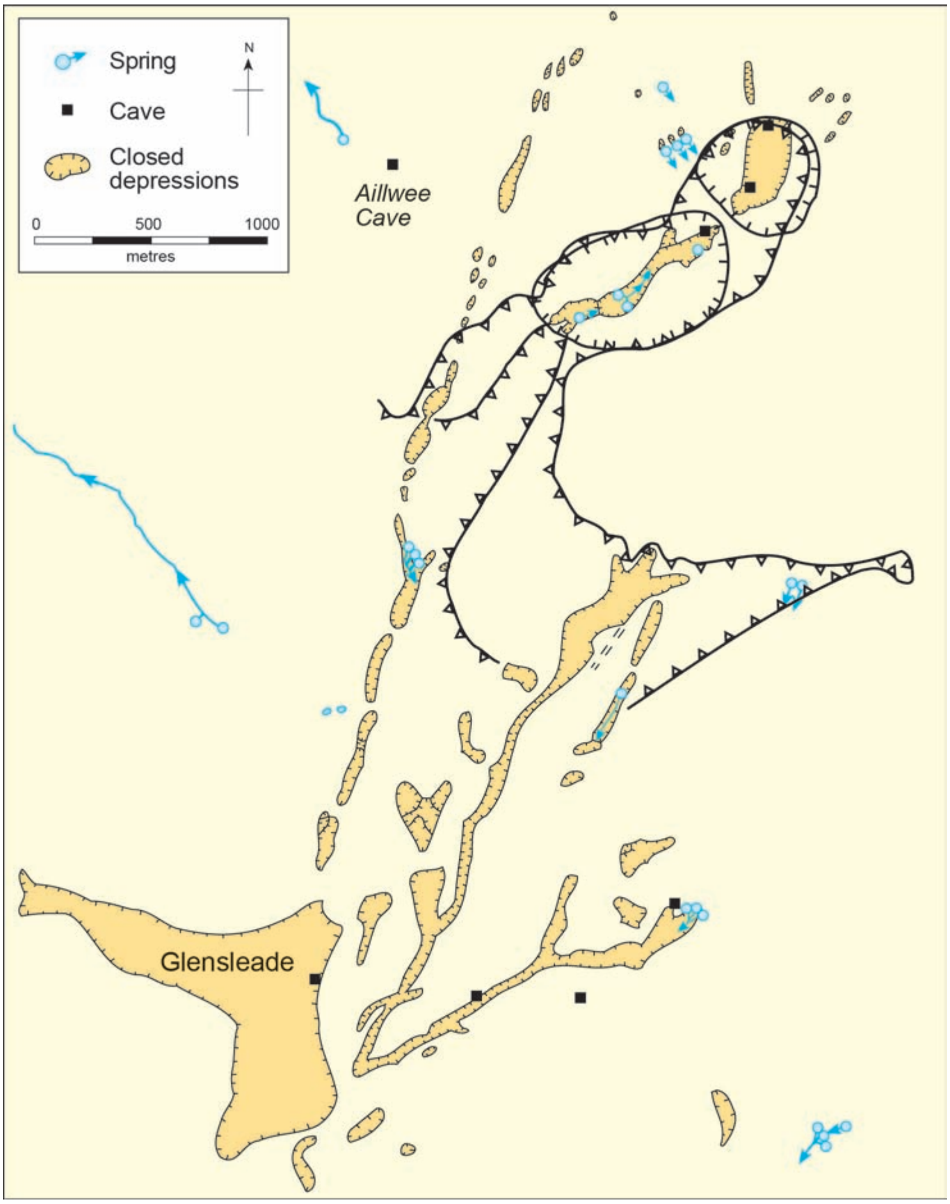


Figure 7.85 Enclosed depressions, fragmented dry valley systems and the hydrology of the southern flank of Aillwee Hill, north-central Burren. *(From Drew, 1973a.)*

sink underground after a surface course of a few metres (Figures 7.90 and 7.91). These 'internal' springs occur where shallow groundwater flow, perched on a chert or shale band, is forced to the surface at the point where the impeding layer intersects the land surface.

Some 60% of the Burren plateau drains directly to the sea. Drainage northwards (up-dip) to the intertidal springs on the south coast of Galway Bay is presumably via conduits developed along veins which extend through the full vertical extent of the limestone, as for example in Poll Gonzo cave near Carron (Figure 7.92).

Underground drainage westwards is mainly to submarine springs in the open Atlantic (Figure 7.93) which may relate to formally lower sea-levels. A series of caves, with and without flows of fresh water, has been explored near Doolin and further north at a depth of circa -10 m, extending inland from entrances in submarine cliffs (Mullan, 2003, Warny and Marek, 2014).

Figure 7.86 Some large enclosed depressions on the Burren: (A) Aillwee Hill uvala, (B) Slieve Carron doline, (C) The Glen of Clab dry valley-linear doline, (D) Kilcorney depression showing the channel leading to the Cave of the Wild Horses which can function as an estavelle. *(Photographs A and D by Aerpas for David Drew and Photographs B and C by David Drew.)*

Figure 7.87 A part of the polje, 9 km^2 in area, centred on Carron, in the central Burren, which contains several seasonal turloughs, shown under high (top) and low (below) water conditions. *(Photographs by Colin Bunce.)*

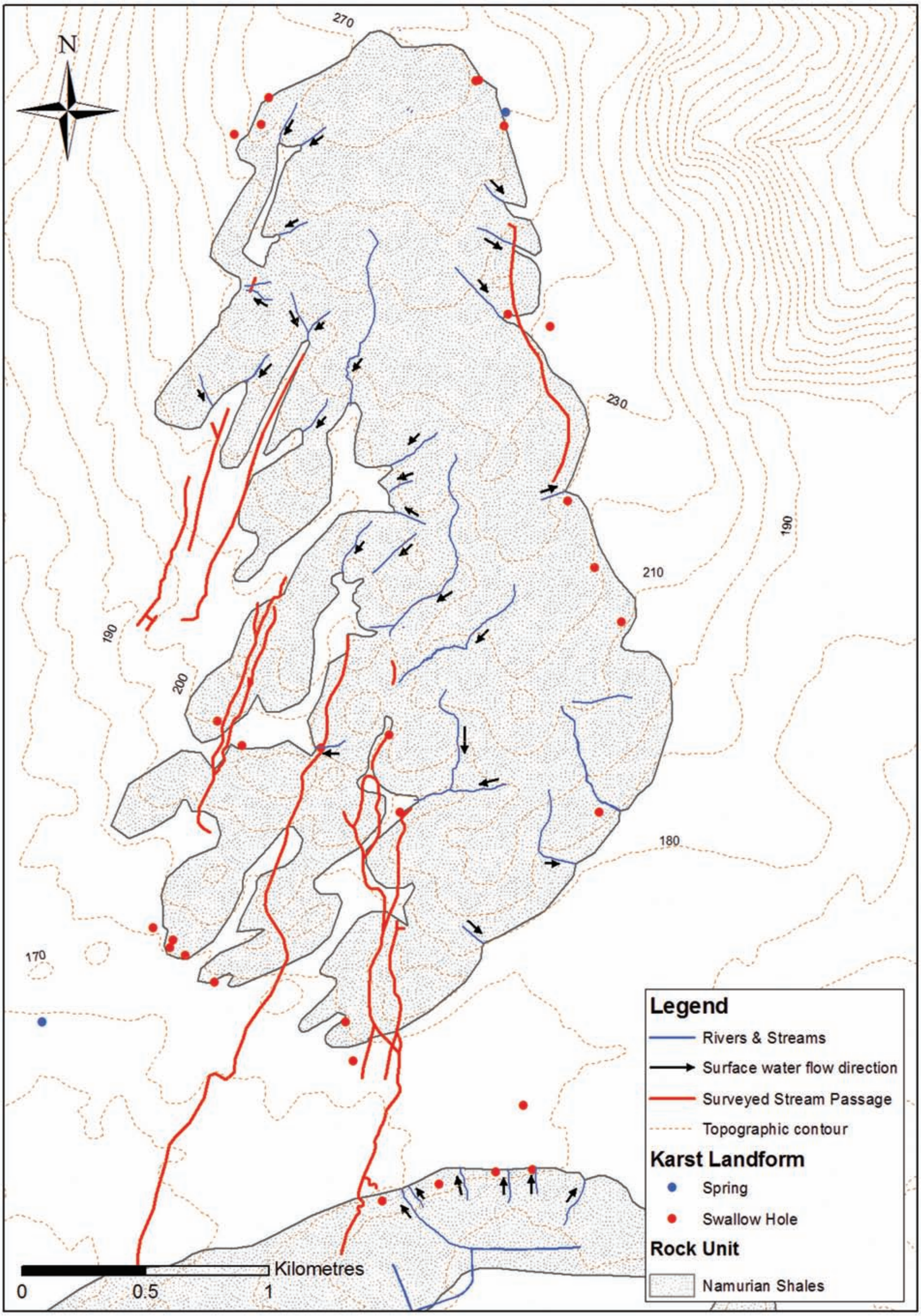


Figure 7.88 Surveyed stream cave passages (in red) draining the shale outlier of Poulacapple Hill in the western Burren. The conduits are developed in the NNE-SSW oriented veins and form an almost parallel series of caves (see also section 8.2). The drainage is southwards down the dip of the strata. Approximately 18,000 m of cave conduit are shown on the map. *(Modified after Tratman, 1969.)*

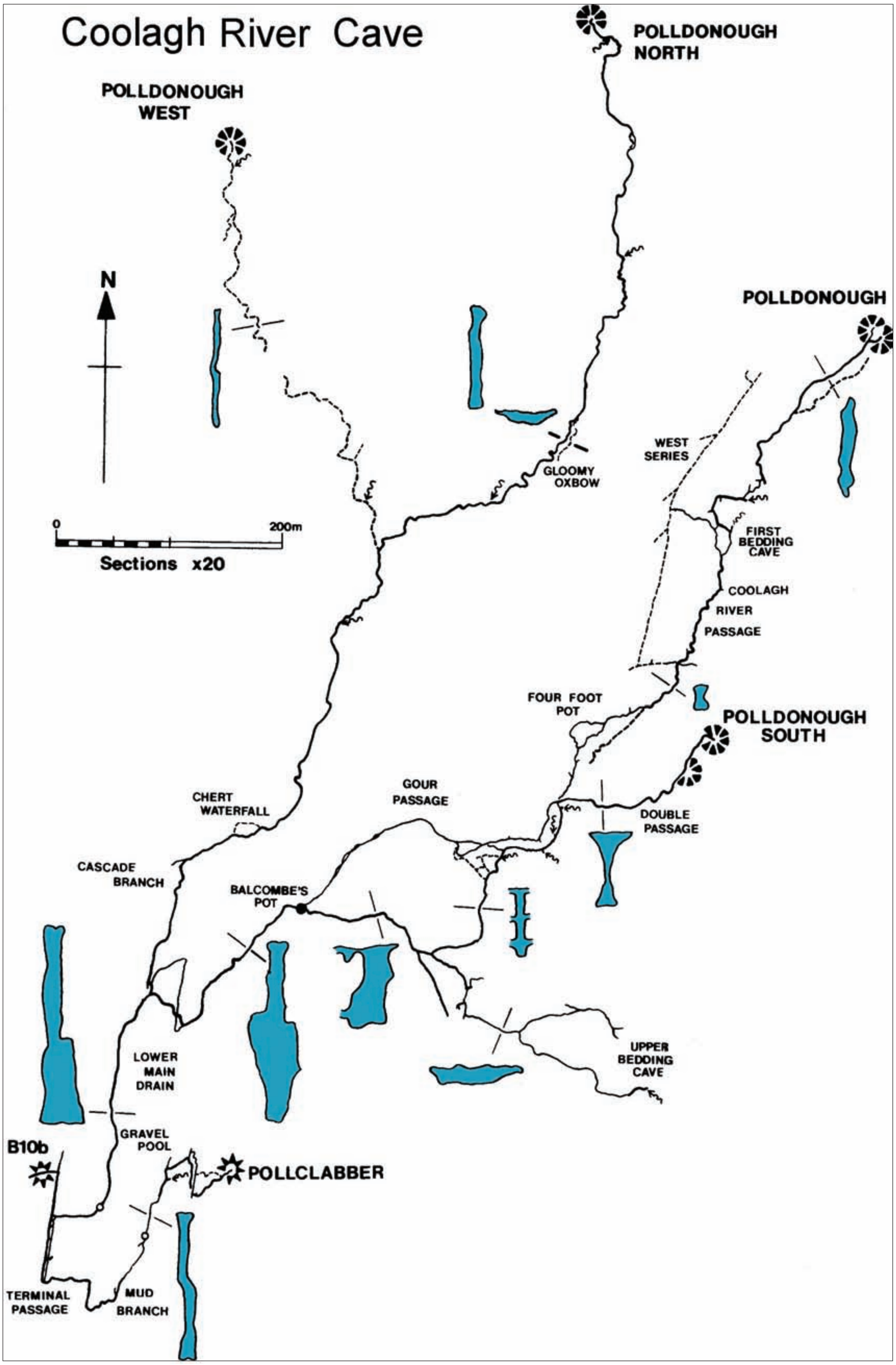


Figure 7.89 Plan survey of the Coolagh River cave system, Slieve Elva in the Burren. As with the cave conduits in Figure 7.88, the dominant controls on cave orientations are the veins and the dip of the strata, but east-west joints have also been enlarged by flowing water to create a partly dendritic drainage network, concentrating groundwater into a single, large conduit. *(From Mullan, 2003.)*

Figure 7.90 An example of an 'internal', ephemeral spring on the Burren, the waters of which sink underground within a short distance and which ceases to flow in periods of dry weather. *(Photograph by David Drew.)*

Figure 7.91 Epikarst flow emerging from the side of a cave shaft (Burren, County Clare). *(Photograph by David Drew.)*

As is apparent from Figure 7.94, the largest groundwater catchment on the Burren, draining 40% of the south-central plateau, feeds the springs that generate much of the flow in the upper reach of the River Fergus (6). The springs and the west-east course of the Fergus are located immediately north of where the limestone passes beneath the overlying Namurian shales. The River Fergus originates on the shale strata south of Kilfenora and flows east to sink underground at the contact with the limestone. Under normal conditions the river, augmented by water draining from the Burren to the north, rises at the spring of Poulnaboe, 1 km to the east, before continuing east into Lough Inchiquin and then turning south along the Gort-Ennis corridor, described previously.

However, under very low water conditions, the spring at Poulnaboe dries and the valley remains dry for some 2 km until all the flow emerges at the major spring at Elmvale (Figure 7.95).

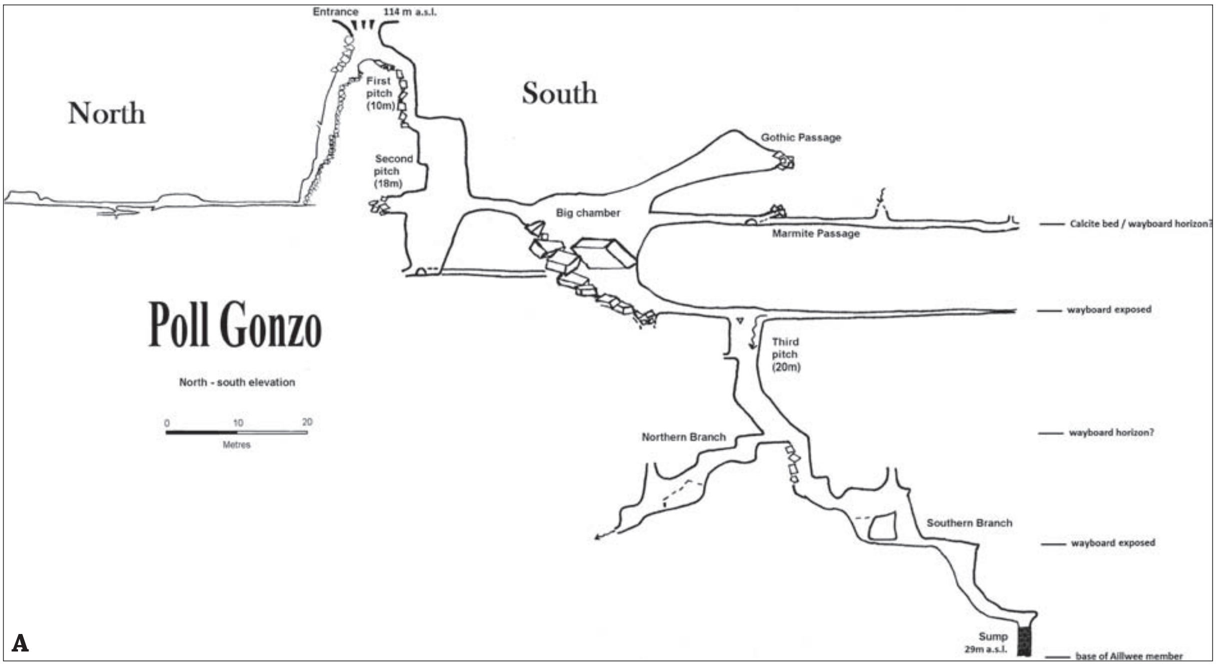


Figure 7.92 Poll Gonzo cave, Carron. (A) Longitudinal survey showing the horizontal (bedding controlled) passages and the vertical (vein controlled) rifts, which allow the water to progress vertically through the limestone sequence. *(From Bunce, 2010.)*. (B) The cave waters f owing from the near horizontal conduit developed above a clay wayboard down a vertical f ssure developed along a north-south mineral vein. *(Photograph by Colin Bunce.)*

Figure 7.93 A submarine spring located c.250 m of shore on the Atlantic coast of the Burren. The brown coloration is due to the peat staining of the water, presumably derived from swallow holes along the limestone-Namurian rock contact on Slieve Elva, to the east. *(Photograph by Dan Harries in Mullan, 2003).*

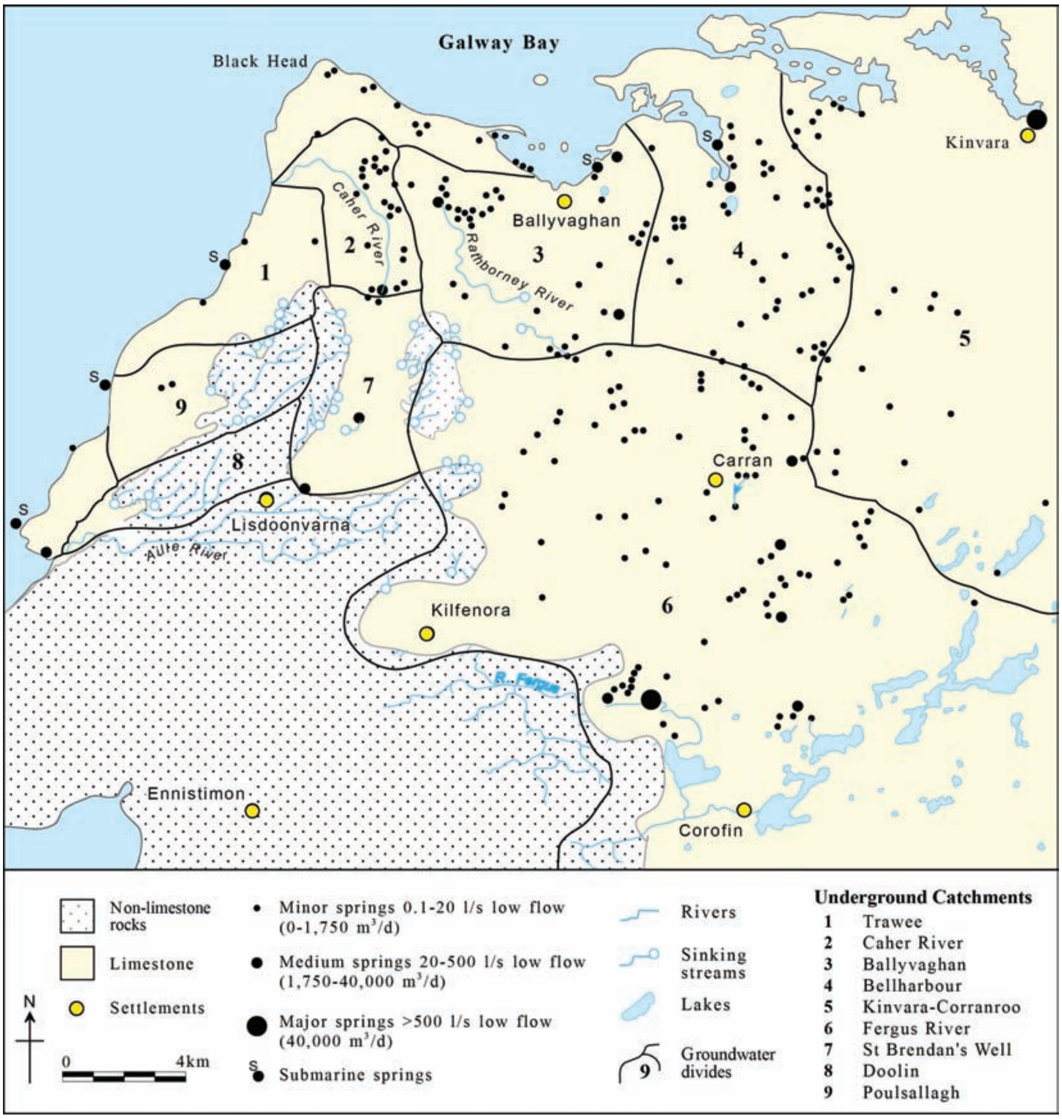


Figure 7.94 Groundwater (spring) catchments on the Burren. The locations of the major springs and the minor, internal springs, are also shown. *(From Drew, 1990.)*

Figure 7.95 The large springs at Elmvale (top centre), which drain 40% of the Burren plateau, joining the River Fergus upstream of Corofin. Flow in the River Fergus is from right to left. *(Photograph by Aerial Eye for David Drew.)*

The Elmvale spring with a mean discharge of c.450 l/s is the hydraulic control for the karst drainage of the southeast Burren and is also one of the largest springs in Ireland. Presumably the River Fergus is developing, as yet immature, karstic conduits at shallow depth beneath the present valley floor.

7.7 Outlying Karst Areas

In addition to the extensive areas of Carboniferous limestone described earlier in this chapter, there are also smaller locales, underlain by limestone, that are detached from the main outcrops (Figure 7.96). In some instances – for example around the shores of Donegal Bay and the Killala-Ballina area of northwest County Mayo – the limestone outcrops are simply extensions of the western lowlands, whilst the Aran Islands of County Galway may be regarded as westward outliers of the Burren.

All the areas mentioned above exhibit karstification to a greater or lesser degree. However, other limestone outcrops of significant extent are wholly detached from the main body of carbonate rocks. Three examples are described.

7.7.1 Northwestern County Kerry

V-shaped outcrops of karstified limestone extend from Fenit, via Tralee and Castleisland to Castlemaine Bay, an area of c.300 km^2 (Figure 7.96). The limestone is bounded by Namurian rocks to the east, north and south and by upper Devonian sandstone to the west (Figures 5.7 and 7.97), which comprises the eastern section of the Slieve Mish anticline. Accelerated karstification is taking place where streams sink at the contact between the Namurian shales and the Cloonagh limestone – Crag Cave with 3.8 km of surveyed passage, being the best example. However, Crag Cave dates from at least the last interglacial, and appears to have functioned hydrologically episodically throughout the last glacial (Fankhauser et al., 2016).

As elsewhere in Ireland, there are no obvious sinks at the contact between the Devonian inlier and the limestone. Waulsortian limestone forms the bedrock over most of the

Figure 7.96 The location and geology of the outlying karst regions. *(Data adapted from GSI.)*

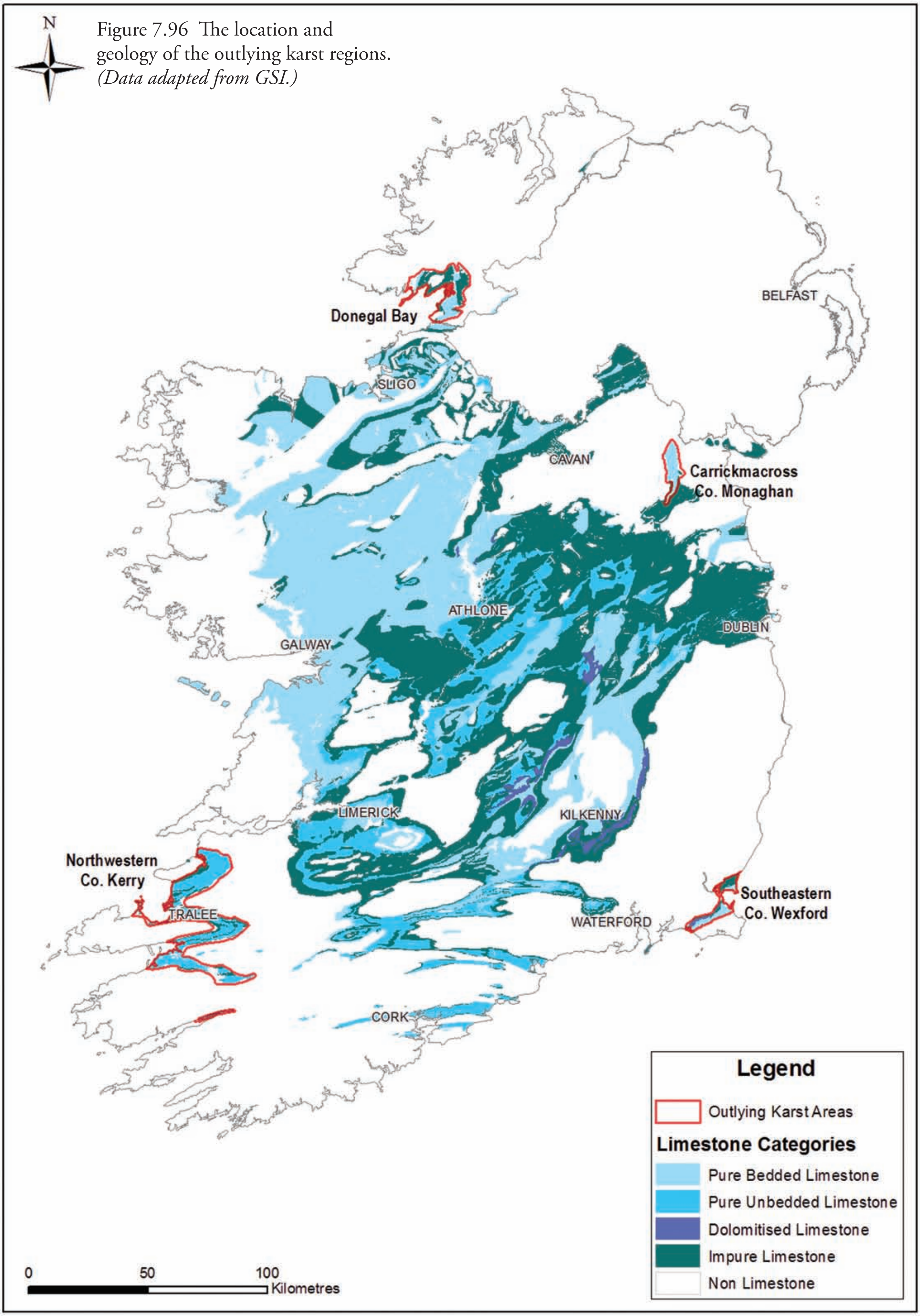


Figure 7.97 The karstified lowland near Castleisland, underlain by Waulsortian limestone with the Devonian rocks of the Dingle peninsula in the background. *(Photograph by David Drew.)*

low ground and most of the karst features, including both fossil and active caves, are developed in this area (Jones and Parkes, 1995). The major springs and largest-yielding groundwater sources are also located on the Waulsortian outcrop. The presence of fossil caves and 'karst towers' at Fenit (Figure 7.98), suggest that remnants of an ancient karst

Figure 7.98 Isolated 'karst towers' near the coast at Fenit (County Kerry). *(Photograph by Robert Meehan.)*

landscape are still present. Karst landforms persist as far as the extreme southwesterly outcrop of limestone at Killarney, in the form of lacustrine karren and caves on the shores of Lough Leane.

7.7.2 Carrickmacross County Monaghan

Stretching from Nobber in the south to Carrickmacross in the north, this limestone outlier has an area of approximately 150 km^2, of which the northern third around the town of Carrickmacross is demonstrably karstified. Glacial landforms, ribbed moraine and drumlins dominate the landscape (Figure 7.99) and the surface drainage system is poorly integrated (Meehan et al., 2013). However, karstification is widespread and the full range of karst landforms – swallow holes, cave systems, karst springs, dolines and even turloughs, are present (Figure 7.100).

The groundwater flow system appears to be shallow with short underground flow-paths. It commonly takes the form of (navigable) cave systems carrying a small stream and passing through small rock outcrops or rock-cored drumlins, thereby enhancing the efficiency of the surface drainage network (Kennedy, 2010). Figure 7.101 exemplifies this mix of surface and sub-surface drainage, showing the passages of Creevy Cave plotted onto an aerial photograph. The course taken by the underground drainage is similar to that taken by the surface stream, except that geological structural control of the cave conduits is much more apparent.

Figure 7.99 The Drumlin karst, north of south County Monaghan, looking south from the Creevy Cave towards Carrickmacross (Figure 7.101). *(Photograph by Aerial Eye for David Drew.)*

Figure 7.100 Moylan turlough near Carrickmacross, located amidst drumlins and one of the few turloughs in eastern Ireland. In the surrounding area are numerous inter-drumlin lakes which are not turloughs and inter-drumlin hollows at a similar altitude without lakes. *(Photograph by Aerial Eye for David Drew.)*

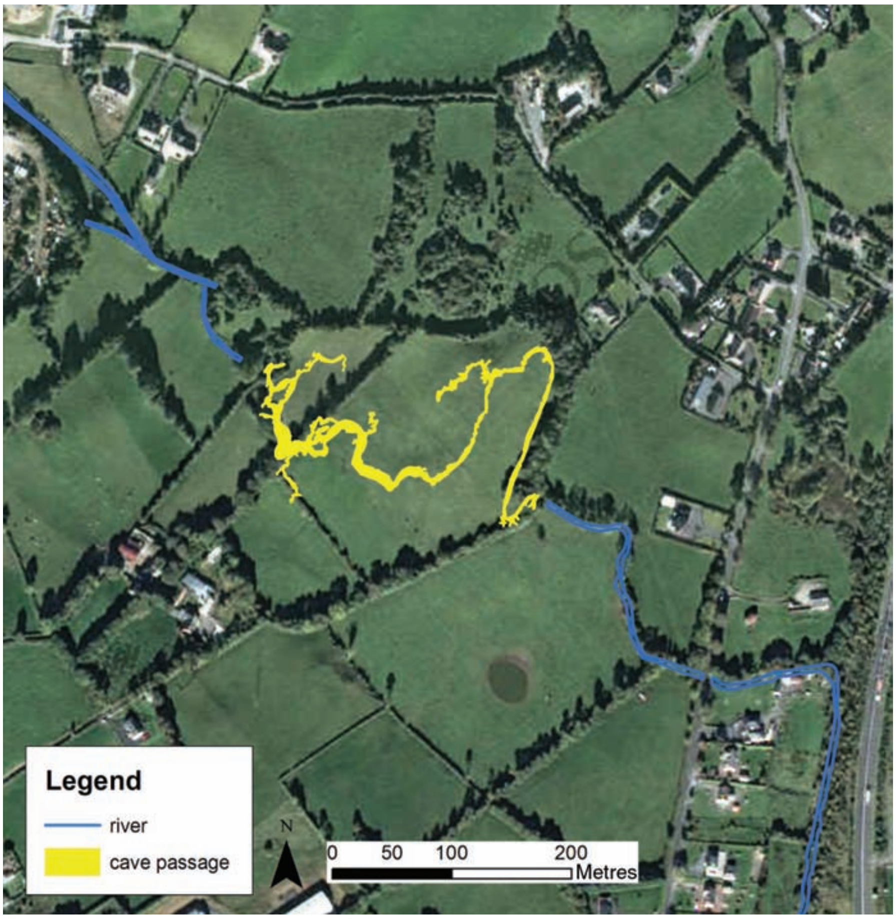


Figure 7.101 The underground route of the Creevy Cave stream (in yellow) in relation to surface topography and drainage. *(Cave survey by courtesy of Alasdair Kennedy and Artur Kozlowski, 2009.)*

7.7.3 Southeastern County Wexford

The only outcrop of Carboniferous limestone in County Wexford is the narrow strip extending from Ballyteige Bay in the southwest, to Wexford harbour in the northeast. This low-lying area is bordered by non-calcareous rocks of Devonian age to the north and Cambrian age to the south (Figure 5.7). The limestone includes the Wexford Formation of pure bedded limestone and the impure Ballysteen Formation, a part of which is significantly dolomitised. The aquifer extends beneath the sea at both ends. The limestone outcrop in County Wexford is comparable in extent (approximately 80 km^2) to that in the Carrickmacross area described above; the limestones are of comparable purity and the geological setting, surrounded by non-karstifiable strata, is similar. The County Monaghan aquifer is classified as Rkd, as is the Wexford aquifer, except for the undolomitised Ballysteen limestone, which is classified as Rf.

However, whereas the Carrickmacross area is clearly karstified, with more than 100 karst features recorded including 26 karst springs, no karst features have been reported from the County Wexford area. A complete drainage network is present in the Wexford area with a drainage density comparable with that on non-carbonate rocks. Annual groundwater level fluctuations are modest (less than 2 m) and the aquifer seems to be more akin to a diffuse fissure flow system, amenable to Darcian analysis to some degree, rather than a karstic system (Dillon and Kelly, 2015).

Chapter 8

HYDROGEOLOGY OF KARST IN IRELAND

8.1 Introduction

The hydrogeological characteristics of the Carboniferous limestones are primarily a function of the degree and type of karstification it has undergone. In turn, the karstification is determined by a variety of factors:

- the lithology of the limestone (primarily purity)
- fracturing – density, vertical extent, interconnectedness of fissures
- faulting – barriers or conductors (compartments or extensive aquifers)
- the presence of non-soluble rocks such as chert and shale as layers in the limestone
- bedding frequency
- diagenetic changes to the limestone e.g. secondary dolomitisation – enhanced permeability (often around faults)
- topographic and geological setting e.g. steep gradients, allogenic recharge
- impounded or free-flow conditions (confined/unconfined aquifers)
- subsoils – confining, semi-confining, buf ering and reservoir functions
- degree of infilling of fissure/conduit systems
- old sea levels and palaeo-topography
- intensified solution of the limestone, for example via sulphuric acid generated by adjacent sulphide rich rocks such as shale

The intensity and importance of each of the above factors varies areally, as do their combinations and, therefore, it is dif cult to predict with any certainty the water-bearing character of any particular limestone from any one factor, such as lithology.

Irish karst groundwater systems incorporate the full range of karst aquifer types, from wholly dif use recharge to almost 100% point recharge; from fracture flow through to wholly conduit dominated flow. In many areas the flow systems are a mixture of systems of various ages (the aquifer framework, not the water). For example, the Gort lowlands aquifer in County Galway includes extensive, large conduit systems, probably developed in pre-Quaternary times, which take most of the flow in some areas, take a part of the groundwater in other areas and are completely fossil in other locations. This conduit system interacts with an epikarst flow system of presumably Holocene age and a deeper, distributed groundwater flow system in enlarged fissures. The drainage outlets are similarly varied, ranging from partly blocked submarine conduit discharges to immature epikarst springs of limited capacity. For most karst aquifers in Ireland, little is known concerning the relative importance of these various types of karst flow.

The more conduit dominated the flow system (as on the upland karsts) the more localised and therefore unpredictable is the occurrence of water. However, it seems all Irish limestones can be both productive and unproductive locally. For example, on Aughinish Island in the Shannon Estuary, 18 wells were drilled to a depth of 40–45 m (35–45 m below the water table), in some instances spaced only a few metres apart. Seven of the wells were dry, with the remaining 11 productive to varying degrees. This is in a very restricted and apparently uniform low-lying outcrop of limestone (Hartwell et al., 1979).

The depth to which karstification, and hence groundwater circulation, occurs is uncertain. Daly (1995) suggests that 75%–80% of groundwater in the limestones of central Ireland is confined to the 20–30 m below the summer position of the water table, with 60% in the uppermost 10 m and only 4% below 100 m. The deepest water is considered to be mainly in faults. An epikarst (Chapter 4.2) is widely developed in Irish limestones and typically ranges from 0.5–3 m in thickness. It functions not only as a perched reservoir but also to concentrate and localise recharge to the main aquifer beneath.

A schematic conceptual model of the vertical distribution of permeability in Irish limestones as a function of depth and of lithology is shown in Figure 8.1. A productive zone of weathered rock with interconnected fissures extends to less than 30 m depth in pure limestones and typically less than 10–15 m in others (except where faulted). Below this weathered layer may be more isolated fissures, conduits and faults up to a depth of 150 m or to 200 m

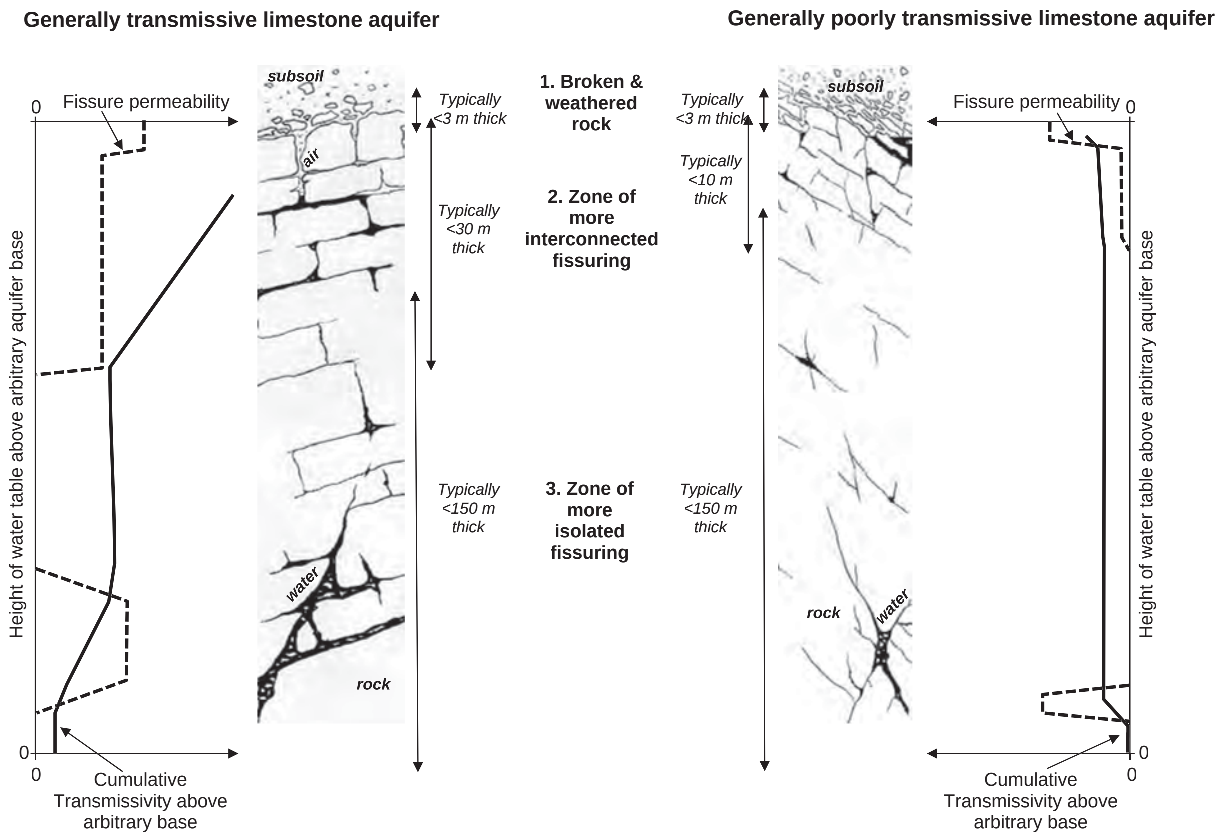


Figure 8.1 A schematic model of the vertical distribution of permeability in Irish limestone. *(From Fitzsimons et al., 2005.)*

in dolomite. However, the rock between the fissures may be dry. There is a non-linear relationship between depth and transmissivity. Permeability in the top layer is similar for all lithologies but there are large dif erences at depth between productive and unproductive aquifers. Permeability typically decreases by an order of magnitude or more, ranging from 1 m/d in the uppermost weathered zone (zone 1 in Figure 8.1), to 0.01 m/d in zone 2, to 0.001 m/d in zone 3 (Kelly et al., 2015). However, this is an idealised model and in practice local factors may greatly modify hydraulic characteristics.

It should be noted that many conceptual models such as this are based on information from water supply boreholes, which are generally quite shallow (less than 100–150 m deep) and there is limited information available about groundwater flow and karstification at depths greater than these.

Table 8.1 summarises currently known information on deep karstification (some evidenced and some inferred) in Ireland. The deep karst examples are almost always associated with

Table 8.1 Evidence of deep karst in Ireland.

Where	What	Metres below ground level	Metres below sea level	Data Source
Lisheen Mine, County Tipperary	Large groundwater inflows from regional fault (250–400 l/s)	120–140	0–15	Water Management Consultants Ltd, 2009
Cloyne and Ringaskiddy, County Cork	Boreholes encountered major zones of fissuring and water inflow	41	20–40	Wright, 1979
Cong Springs (Galway/Mayo)	Active large conduits	40	25–30	Divers' reports
Pollatoomary Spring, County Mayo	Active large conduits	110+	53	Kozłowski, 2009c Irish Times, 10/09/10
Gort-Kinvara, County Galway	Active karst conduits with cross-sectional areas of 20 m^2 encountered and dived	82	60	Kozłowski, 2010
Clondelara, County Offaly	Encountered large water bearing cavity when drilling and drill bit dropped >3 m	137	88	Tynan et al., 2017
Northwest Carboniferous Basin, Counties Sligo, Cavan and Fermanagh	Evidence of karst from oil and gas deep boreholes, such as losses of circulation, references to 'caving' and large freshwater influxes	277	150	Moe et al., 2016
Shannon Pot Spring, County Cavan	Chemical variability of spring suggests deep circulation	Estimated to be ~300	Estimated to be ~200	Brown, 2005
Enfield, County Meath	Dissolutional features in borehole records	250–300	170–220	Blake et al., 2016
Kilbrook Thermal Spring	Geophysical techniques and hydrochemical analysis indicate dissolutionally-enhanced fault	560–1000	480–920	Blake et al., 2016

the presence of large faults. As Table 8.1 shows, there is limited evidence from locations across Ireland of karstification extending to greater than 100 m below present sea level. The spatial extent of such karstification, its age and the extent to which it is presently active is uncertain.

In conduit dominated aquifers, consistency of hydraulic characteristics can only be realised with a Representative Elemental Volume (REV) (see Section 9.1 and Figure 9.2) of several cubic kilometres, but not locally and certainly not at the scale of boreholes, as the Aughinish data demonstrate. Thus most limestone aquifers in Ireland are not amenable to many standard investigative techniques of groundwater assessment. For example, there are problems in determining transmissivity values when the functional saturated thickness is uncertain, whilst permeability becomes a meaningless concept where flow systems are conduit dominated.

Fissure permeability is dominant in Irish aquifers due to the fractured nature of the bedrock and lack of primary porosity. Porosity is, therefore, almost entirely in secondary openings, with mean values of 1%–6% (Specific yield [Sy] 2.4%) for pure limestones and 1.3%–2.9% (Sy 0.9%) for impure limestones (ef ective porosity in fractured bedrock is generally taken to be similar to specific yield) (Kelly et al., 2015; Tedd et al., 2012). With increasing karstification, the relationship between surface river systems and groundwater becomes increasingly tenuous and, in extremis, surface drainage systems are replaced by wholly sub-surface drainage systems.

Irish limestones exhibit the full spectrum of such relationships. For example, Figures 8.2 and 8.3 show surface and groundwater flow systems in two contrasting areas. Figure 8.2 depicts the Nuenna catchment in County Kilkenny where, although a close relationship exists between rivers, valleys and groundwater flow systems, some degree of karstification is evident from the presence of swallow holes, springs and segments of dry valley.

The Dunkellin–Lavally catchments in eastern County Galway (Figure 8.3) show little relationship between surface and groundwater. For much of the time, the rivers sink underground leaving the middle and lower reaches of the channels dry. Groundwater flow systems are focussed on coastal springs in this highly karstified aquifer.

As mentioned in Chapter 5, the Republic of Ireland's land surface is divided into nine aquifer categories (also described as resource protection areas), based on the hydrogeological characteristics and on the value of the groundwater resource. They are as follows.

Regionally Important (R) Aquifers

- karstified bedrock (**Rk**)
- fissured bedrock (**Rf**)
- extensive sand and gravel (**Rg**)

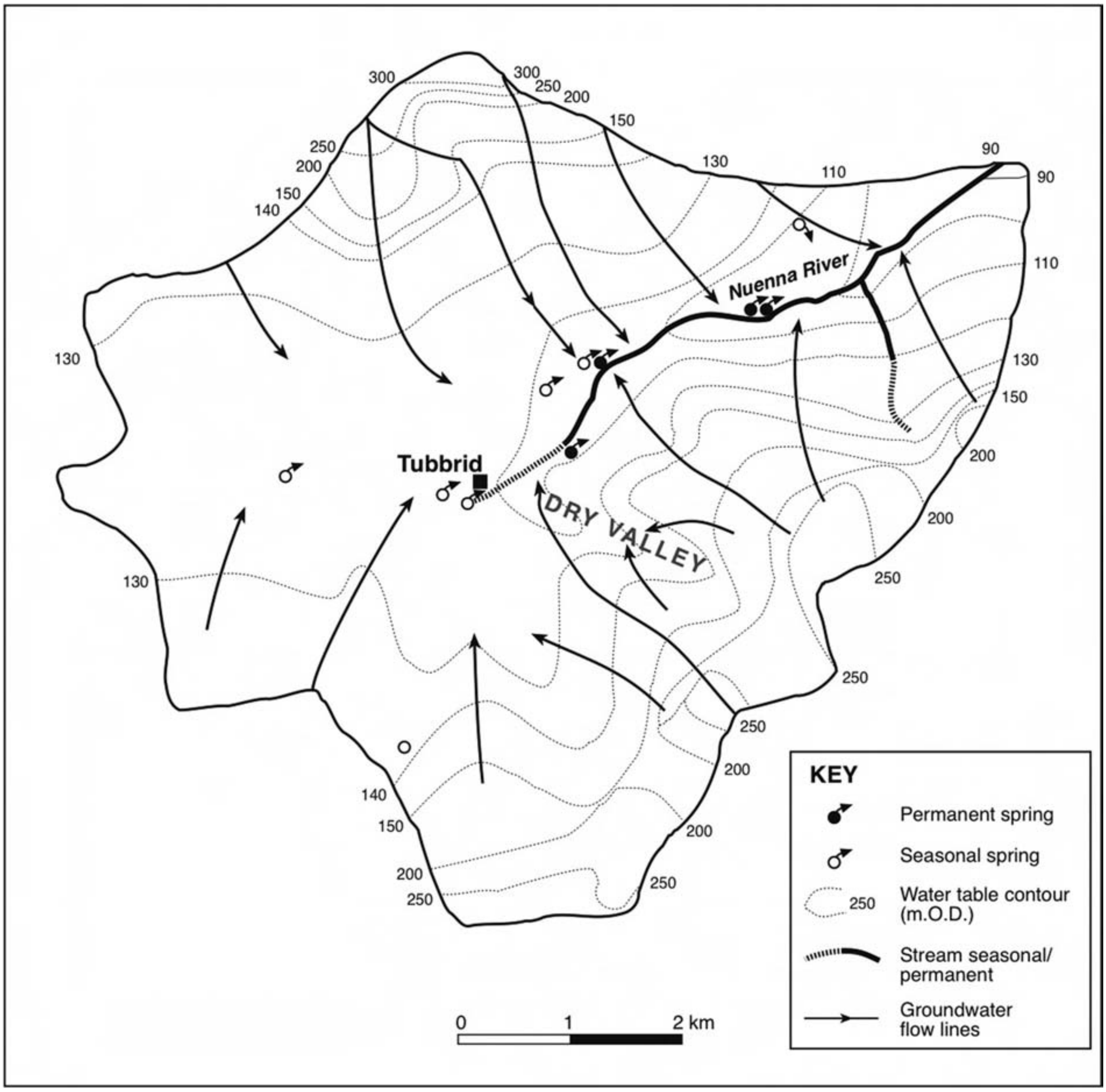


Figure 8.2 Potentiometric surface and groundwater flow lines in relation to surface drainage under low stage conditions: the Nuenna catchment (County Kilkenny). *(Adapted from Daly, 1994.)*

Locally Important (L) Aquifers

- karstified bedrock (**Lk**)
- sand and gravel (**Lg**)
- bedrock which is generally moderately productive (**Lm**)
- bedrock which is moderately productive only in local zones (**Ll**)

Poor (P) Aquifers

- bedrock which is generally unproductive except for local zones (**Pl**)
- bedrock which is generally unproductive (**Pu**)

Regionally important karstified bedrock aquifers (Rk) may, depending on the degree and nature of the karstification, be further characterised as either **Rkc** – dominated by conduit flow or **Rkd** – dominated by dif use flow. A summary of the main aquifer characteristics is given in Table 8.2.

Overviews of the carbonate aquifers in Ireland are given in Karst Working Group (2000), GSI and Drew (2008), while examples of detailed local hydrogeological studies such as the limestone aquifers of Roscommon are given in Hickey, 2008 and Lee and Daly, 2002 and in Chapter 10.

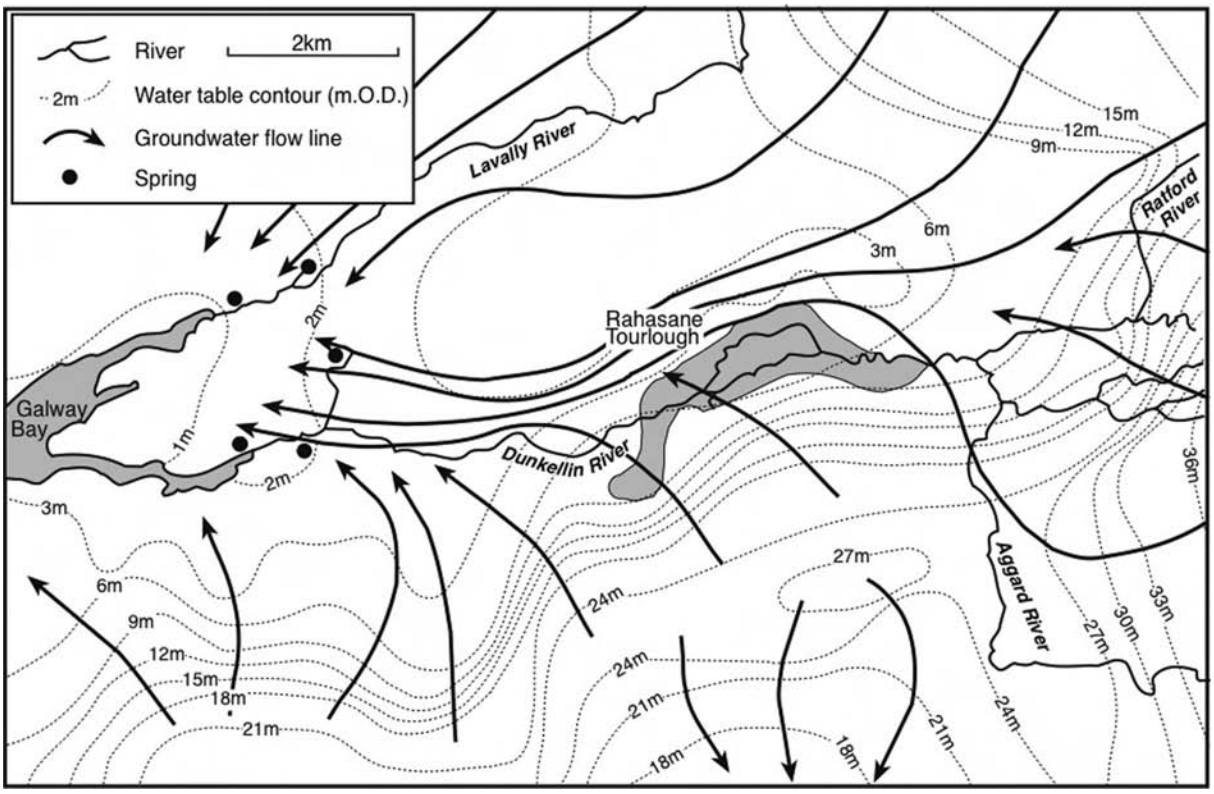


Figure 8.3 Potentiometric surface and groundwater flow lines in relation to surface drainage under low stage conditions: the Dunkellin–Lavally catchments County Galway. *(Adapted from Drew and Daly, 1993.)*

Table 8.2 Summary of the Main Bedrock Aquifer Classification Characteristics.

Class	T values (m^2/day)	Productivity	Borehole Yields	Potential extent of flow systems	Large springs	Lithology			Structure	Surface water discharge zones in areas of thin or free draining subsoil	Annual fluctuation in water levels
						Type	Dolomitic	Karst features			
Rf	Most >50. Several >500	Mostly I and II	Excellent yields very common	Regional	Potentially	Thin bedded sandstones, limestones volcanics	Potentially	Little or none	Volcanics and thick bedded limestones generally highly fractured	Lowland drainage density <0.5 km/km^2 Annual baseflow >60% annual river flow. Low flows >2 l/sec/km^2 and low flows >20% average flows (Rk_d may have lower low flows).	Generally <10 m
Rk_d	Variable. A few >500	Mostly I and II but fair proportion may be lower	Excellent yields very common	Regional	Potentially	Pure or dolomitic limestones	Potentially	Abundant	Thick bedded limestones generally highly fractured		Generally <15 m
Rk_c	Variable. A few >500	Probably all classes, average may be III	Extremely variable	Regional	Potentially	Pure limestones	Potentially	Abundant	Thick bedded limestones generally highly fractured		Often >15 m
Lm	Some >50. A few >500	Average III	Excellent yields very common	Regional to local	Potentially	Pure limestones, thin-bedded sandstones, volcanics	Potentially	Occasional	Volcanics and thick bedded limestones generally highly fractured		No criteria
Lk	As for Rk_c or Rk_d	As for Rk_c or Rk_d	As for Rk_c or Rk_d	Local	No	As for Rk_c or Rk_d	As for Rk_c or Rk_d	As for Rk_c or Rk_d	As for Rk_c or Rk_d	No criteria	As for Rk_c or Rk_d
Ll	Some >50. A few >500	Average III–IV, some II	Some excellent yields	Local (occasionally longer along fault zones)	Perhaps but unusual	Impure limestones, sandstones, shales, others	Perhaps, but not extensive	Occasional	No criteria	High drainage density, low baseflows	No criteria
Pl	Most <50. One or two >500	Mostly V and IV, some III	Excellent yields very rare if any	Local	No	Impure limestones, sandstones, shales, others	No	None	No criteria	Values will be complicated by upland climatic setting and steep slopes.	No criteria
Pu	<50	Mostly V and IV	No excellent yields. Good yields rare if any	Very localised	No	Impure limestones, sandstones, shales, others	No	None	No criteria		No criteria

8.2 Lithological and Structural Influences

8.2.1 Introduction

As remarked in the preceding section, there is rarely a consistent and unambiguous relationship between hydrogeological and geological conditions in the Carboniferous limestones. However, some degree of generalisation is possible, particularly with respect to the degree of purity of the limestone. Detailed analyses and interpretation of lithological and structural influences on Irish hydrogeology have been made for GSI's aquifer report (GSI in prep.) and the aquifer parameter database (Kelly et al., 2015), which are principal sources of data for this section.

Figure 8.4 presents histograms for borehole productivity (determined from 'QSC values', which are derived from relationships between Specific Capacity (SC) and abstraction values (Q), during a given pump test, divided into five categories, I to V, from highest to lowest) for a range of Carboniferous limestones compared to values for productive sand and gravel

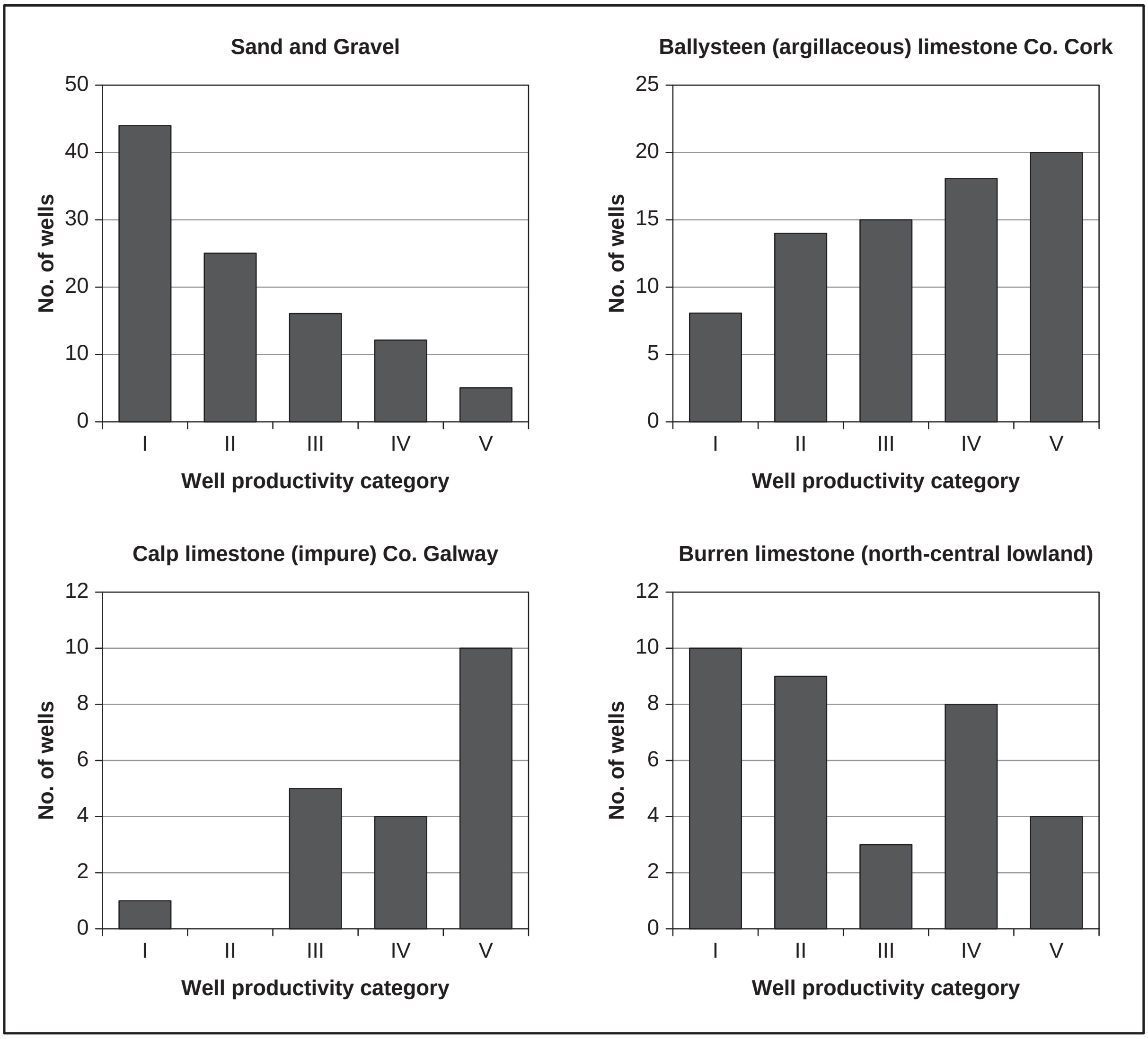


Figure 8.4 Borehole productivities for selected Irish aquifers in Ireland. *(Adapted from Wright, 2000.)*. I represents the highest productivity class, V the lowest.

aquifers (Wright, 2000). In sand and gravel aquifers, most wells are highly productive (category I) with progressively fewer wells with lower productivities. Impure limestones (Ballysteen and Calp) show a mirror-image distribution of productivity class, with fewest wells in categories I and II. The Burren pure bedded limestone has a bimodal distribution of yields, with significant numbers of both high and low productivity wells, suggesting that pure bedded limestone has better developed karstification but more variable yields because of the resulting high degree of heterogeneity of the aquifer.

This same pattern is reflected when looking at transmissivities (T). Figure 8.5 shows the best estimate (using the geometric mean) and distribution of T values for each aquifer type. Boreholes rarely intersect the main conduits of a karst aquifer flowing to springs; therefore, data from highly karstified aquifers may not be representative of the higher permeability conduits and may skew the results. For highly karstified aquifers, the arithmetic mean is more appropriate and is marked in Figure 8.5 with a red dot. However, there are a number of transmissivities with greater than 1,000 m^2/d where, presumably, a large conduit has been intersected.

As Figure 8.5 shows, there is a decrease in the "best estimate" T values of the R Aquifers through to the P Aquifers, with the apparent exception of the Rkc aquifers, which have a greater range but overall lower geometric mean (reflecting the more localised, less distributed permeability and higher number of poor yielding boreholes). The best estimate T values for limestones range from less than 10 m^2/d in impure limestones to greater than 500 m^2/d in Rkc aquifers (Kelly et al., 2015). The 95th percentile is far greater in the highly karstified aquifers than all the others. The 5th–95th percentile range for each aquifer group is outlined below.

- Poorly productive aquifers (Pu, Pl and Ll categories) range from 0.4–165 m^2/d.
- Productive fissured aquifers (Lm and Rf categories) range from 1–310 m^2/d.
- Karstic aquifers (Lk, Rk, Rkc and Rkd categories) range from 0.7–1110 m^2/d.

Although it seems that permeability and transmissivity decline sharply with depth below ground level (Figure 8.1), quantitative data are limited. In the dolomitic and undolomitised pure limestone of south Wexford, Cullen (1980) reports 20% of inflow occurring within

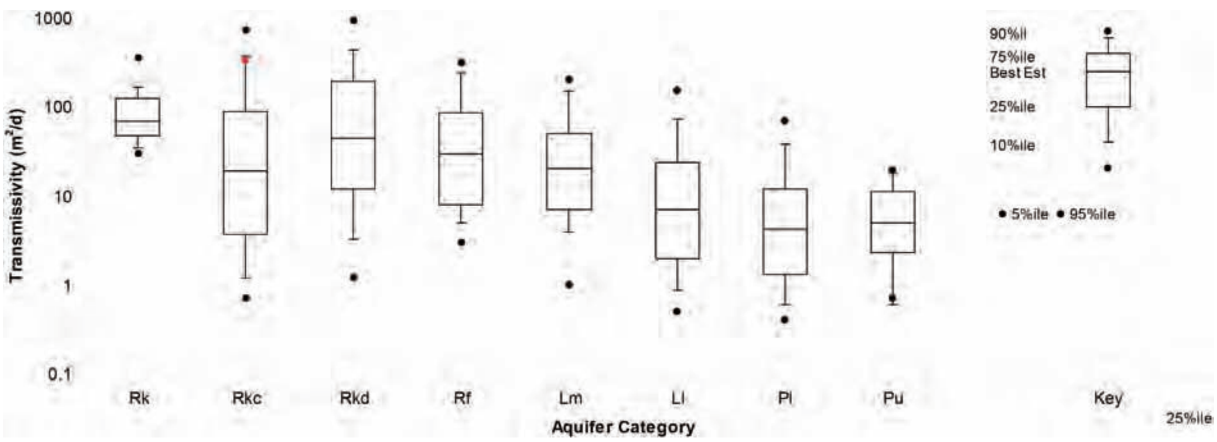


Figure 8.5 Distribution of transmissivity values (m^2/d) for dif erent bedrock aquifer categories shown on 'box and whisker' style graph, y-axis is logarithmic scale. The arithmetic mean for the Rkc aquifer is marked by a red dot. *(Modified after Kelly et al., 2015.)*

the uppermost 5 m, 64% in the top 30 m and no flows recorded below 94 m. Similarly, in Limerick, dolomitic limestone fissure density in the upper 45 m was ten times that between 45–155 bgl (Jones et al., 1999).

Evidence for deeper flows in the limestones is largely confined to isolated examples outlined at the beginning of this chapter (Table 8.1). Figure 8.6 shows the fissure frequency (derived from 637 boreholes) from the surface to −360 m in the vicinity of the Lisheen Mine. Fracture frequency is greatest in the 20–60 m bgl categories, with a steady fall-of below this depth and virtually no fissures present below −230 m. Some 20% of boreholes had no fissuring.

8.2.2 Stratigraphic and Structural Influence on Groundwater Flow

Even within pure limestones, impurities are common and may impact on the character of the aquifer. Shale/clay bands, even when only a few centimetres in thickness (Figure 8.7), may hinder vertical movement of groundwater and encourage lateral flow along bedding planes, especially where the strata are near-horizontal, for example in the Burren and on the Aran Islands. Thus, the shale bands may act as inception horizons (Chapter 3) and concentrate groundwater at that level, giving rise to increased karstification (Figure 8.8).

Chert lenses, even where they are discontinuous, have a similar barrier function to shales within the limestone aquifers. The plateau limestones of the northwest and the Derravarragh limestones of eastern County Westmeath exhibit strong groundwater flow influences due

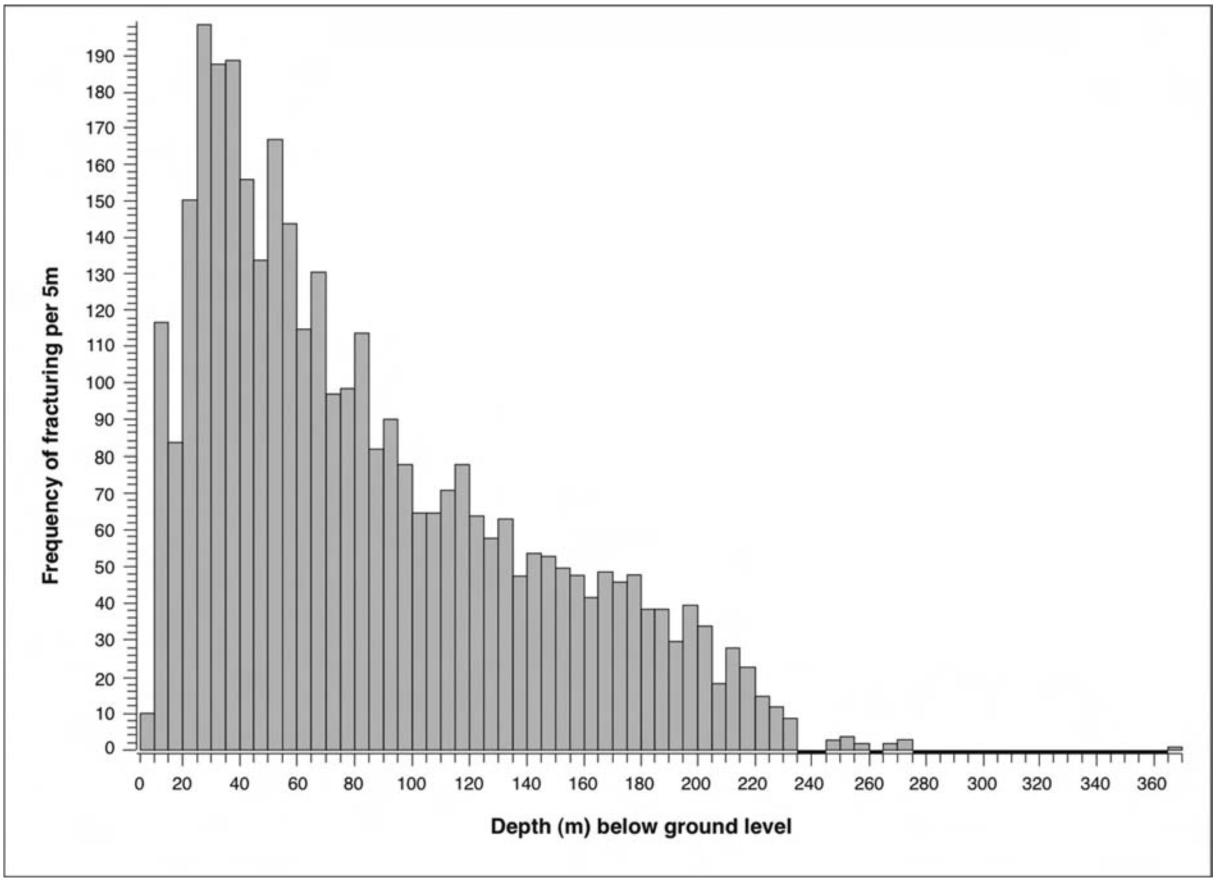


Figure 8.6 Fracture frequency in relation to depth below ground level (Lisheen Mine). *(Adapted from Jones et al., 1999.)*

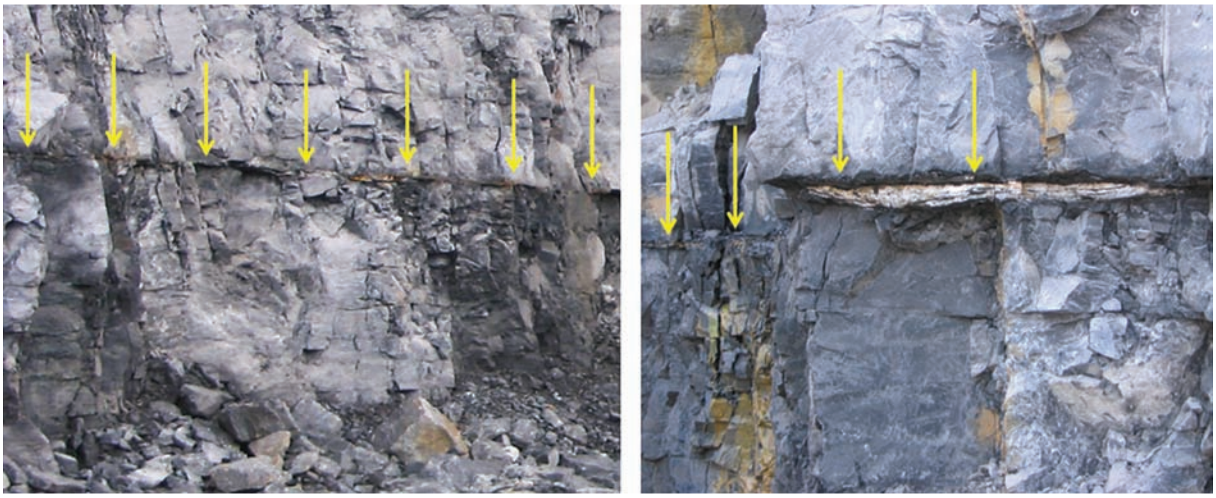


Figure 8.7 A shale band, (1 cm thick, marked by yellow arrows) in clean bedded limestones in a quarry in Kilkenny. *(Photographs by Caoimhe Hickey.)*

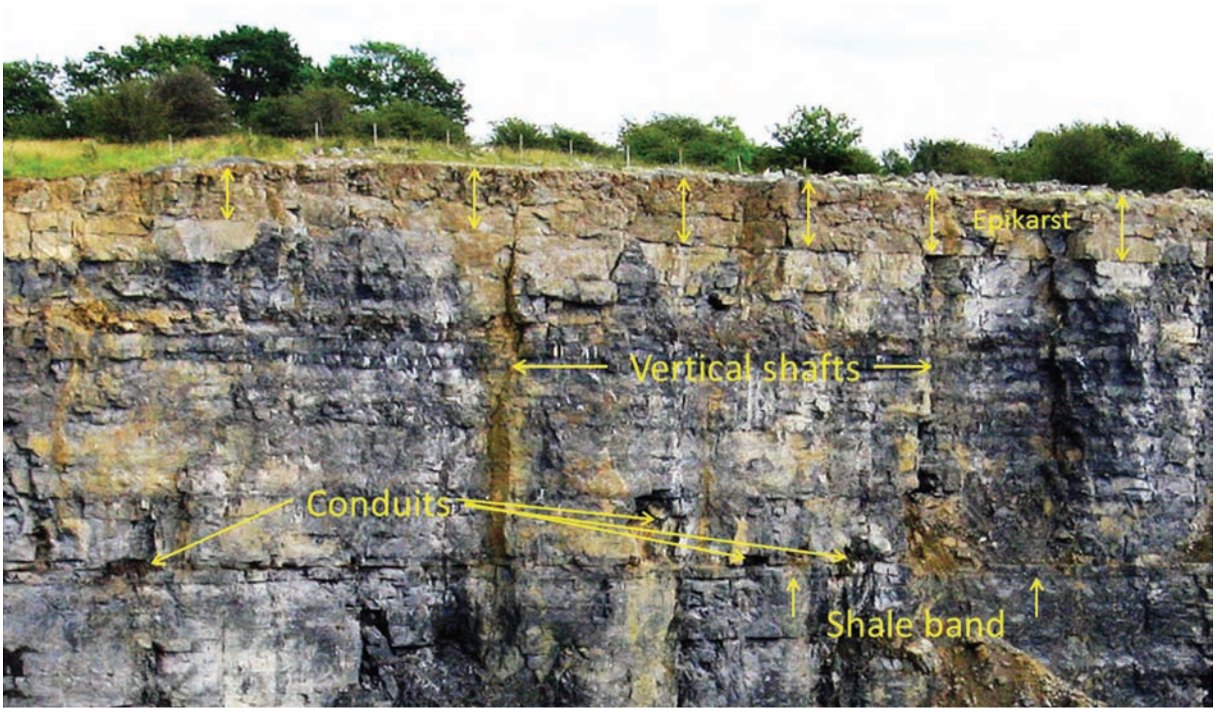


Figure 8.8 Bedded Burren limestones (County Galway), with karstification (conduits) concentrated in the vicinity of a shale band. Note also the well-developed epikarst layer which is linked to the conduit zone by solutionally enlarged joints which extend vertically across several beds of limestone. *(Photograph by John Kelly.)*

to the presence of extensive chert. Even though the Derravarragh limestones are impure, they have been classified as an Lk aquifer, as the chert has enabled karstification and conduit development.

Faults and fractures are a major influence on karst hydrogeology in Ireland. Some structures are baf es or barriers to groundwater flow, whilst others are conductive to groundwater flow. The Variscan Orogeny produced a variety of fracture types, of which vertically persistent and often highly clustered NNW to NNE striking veins are particularly significant. Although these fractures are sealed by calcite or clays, they often localise karstification in the adjacent limestones. The intersection of vein fractures (Figure 8.9) with stratigraphic barriers to flow is a common locus for karstification (e.g. Poll Gonzo in the Burren, Chapter 7.6). Intrinsically permeable structures include strike-slip faults of Cenozoic age (Figure 8.10) and joints. Joint spacing is inversely related to bed thickness but increases in intensity near the surface (the epikarst). A full description of the significance of faults and fracture systems on karst hydrogeology in Ireland is given in Moore and Walsh (2013a).

Folded limestones, in addition to having well-developed fracture sets, form semi-impounded aquifers where they comprise synclinal valley-floor outcrops in the south of Ireland and these are often high yielding aquifers, possibly because of the distributed nature of karstification. In the flat-lying, pure limestones that stretch from south Clare into south Mayo and County Roscommon groundwater is abundant but highly anisotropic.

In the limestones of the midlands, compartmentalisation of the limestone into hydrogeological blocks is widespread. Tectonic stretching, which occurred in the Carboniferous, resulted in the formation of a 'block and basin' topography. The blocks, bounded by faults, moved up relative to the basins. These blocks became areas of mainly shallow-water pure limestone sedimentation,

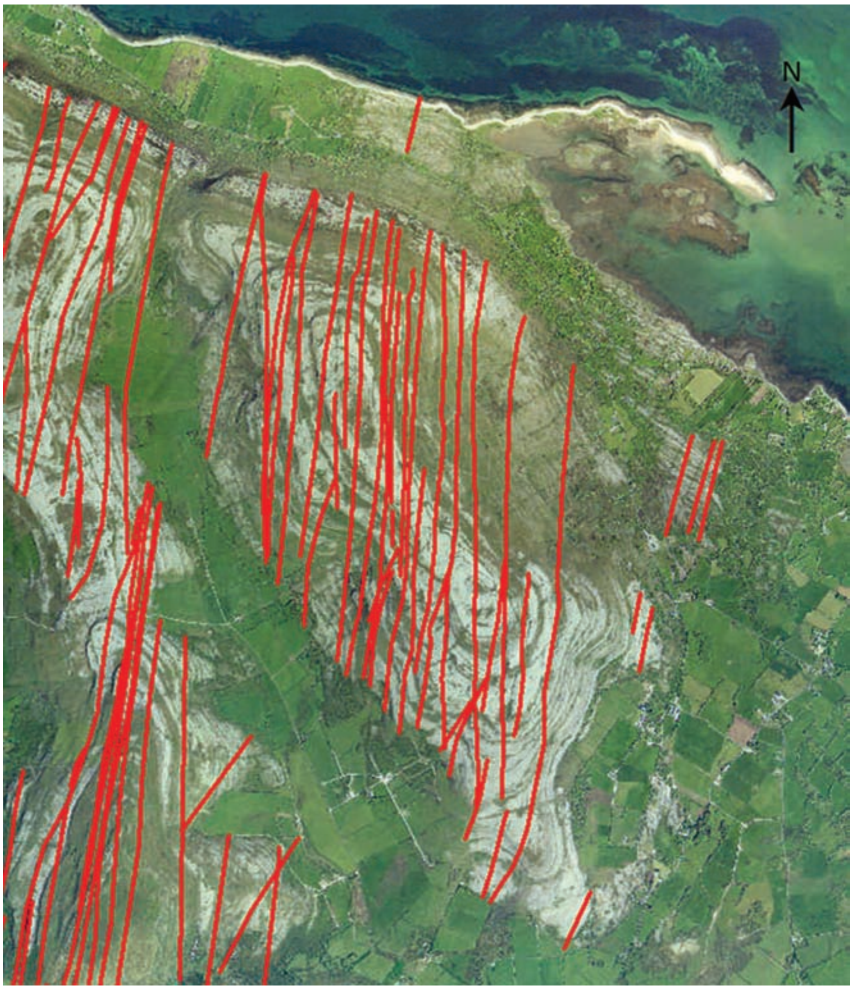


Figure 8.9 Variscan veins oriented almost north-south on Cappanawalla Hill in the northwest Burren. Such veins are major controls on groundwater flow in the Burren (Chapter 7.6). *(From Moore and Walsh, 2013b.)*

Figure 8.10 Significant groundwater discharge (7,000 m^3/d) from a cavity located above a Tertiary strike slip fault Huntstown Quarry (Dublin). *(Photograph by Sarah Blake.)*

while the basins accumulated fine-grained deep-water impure limestone plus debris from the uplifted platforms. The basin rocks are much less permeable and karstifiable than the shelf rocks and may be a reason why lakes and rivers are common east of the Shannon and less common to the west (Morris et al., 2003). Adjacent blocks with volumes of several cubic kilometres, may have dif erent transmissivities and groundwater levels and so have stepped hydrogeological boundaries, precluding the occurrence of extensive aquifers. The blocks are often bounded by faults and individual faults/lineaments may be barriers or transmitting zones or may change character along their length. The termination of a dolomitised zone of limestone may also function as a hydrogeological barrier. There is also some evidence of vertical compartmentalisation of the midland limestones due to the occurrence of less permeable strata.

8.2.3 Pure Bedded Limestones

The pure bedded limestones directly underlie 17% of Ireland and account for 39% of all Irish Carboniferous limestones (Figure 5.8). In the south and midlands, these rocks generally occur as tilted strata around the edges of non-limestone upland regions such as the Galtee Mountains and Slieveardagh Hills, and in elongate strips in the cores of synclines. In contrast, the pure bedded limestones in the west of Ireland, from north Clare to Mayo form an extensive uninterrupted lowland terrain.

Productivity graphs for all the pure bedded limestones (Figure 8.11 A) show an almost even distribution across all productivity classes, except for somewhat greater values in the highest

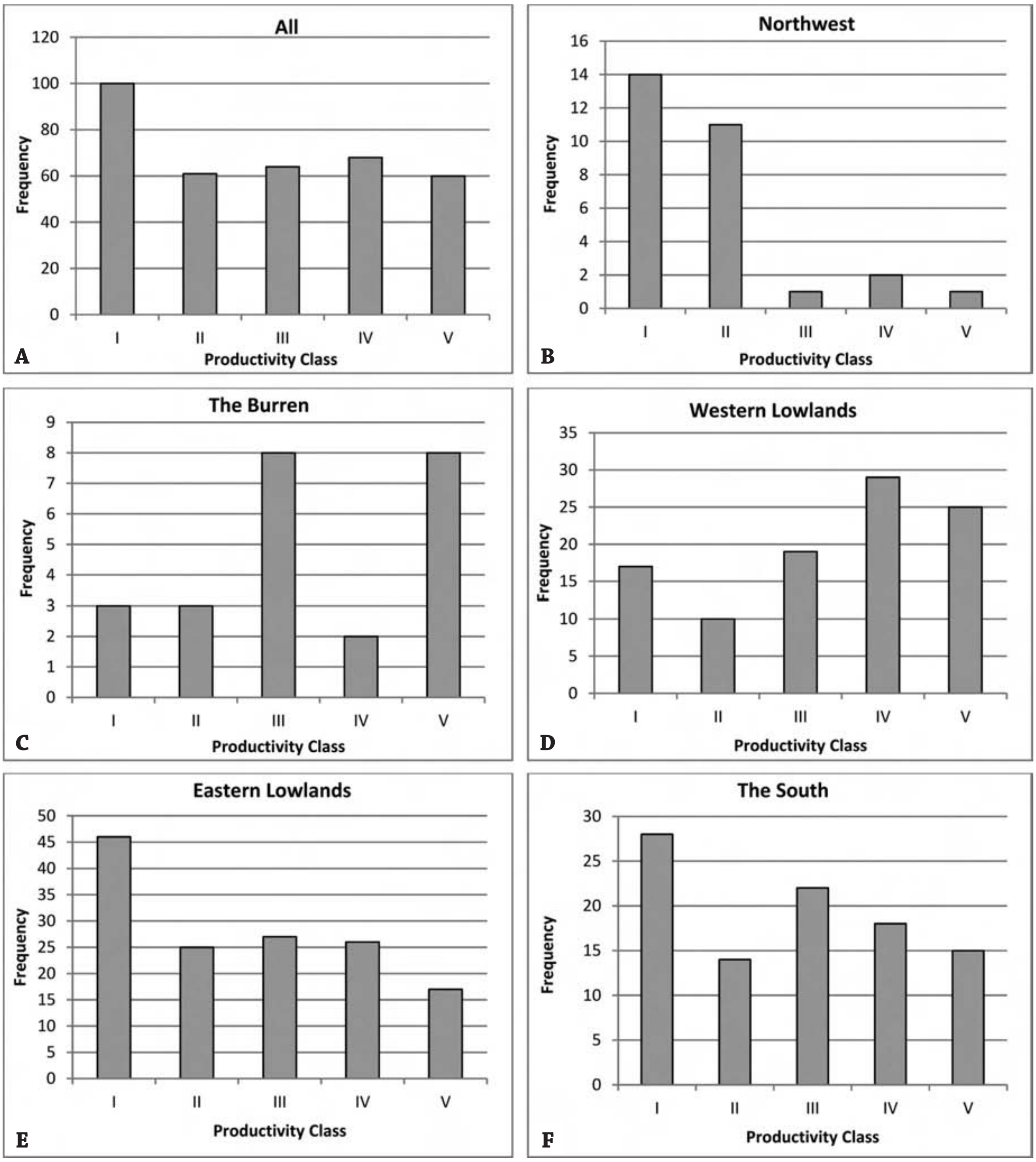


Figure 8.11 Productivity values from wells located in the pure bedded limestones, (A) Total productivity values, (B–F) by limestone region. *(Data adapted from GSI.)*

productivity class. This reflects the highly karstified nature of these rocks in general, with the full range of well yields and productivities occurring, even within a small areal extent.

Productivity graphs for the pure bedded limestones within the dif erent limestone regions also show no obvious pattern (Figure 8.11 B–F). However, it does appear that the more highly karstified areas (such as the western lowlands and the Burren) are slightly skewed towards lower productivity wells, whilst the north-western region shows the opposite pattern. This is thought to be due to a large number of values taken from wells located in the Carrickmacross area of County Monaghan, which have unusually high productivity values. Productivity values are thought to be higher in the southern region due to the increased structural deformation, from the Variscan Orogeny, giving rise to a more distributed flow

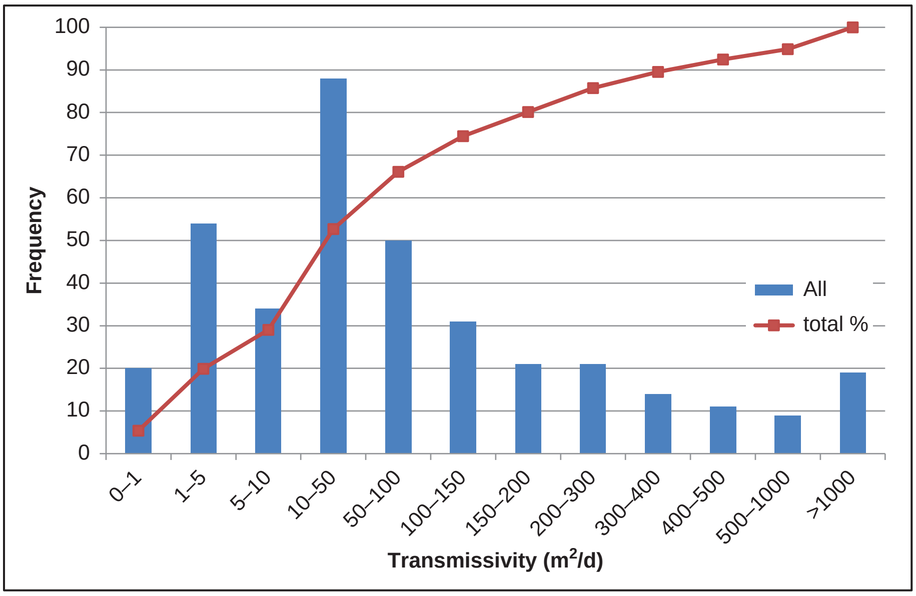


Figure 8.12 Transmissivity histogram and cumulative frequency for pure bedded limestones (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

system. Some areas in the eastern lowlands are significantly dolomitised, giving rise to appreciable numbers of highly productive wells in this region.

The distribution of transmissivities in pure bedded limestones is shown in Figure 8.12 and shows a wide spread of transmissivities. Twenty percent of wells had transmissivities greater than 200 m^2/d and 8% had values greater than 500 m^2/d. However, almost half of the wells have transmissivities less than 50 m^2/d. The modal value is around 100 m^2/d and the arithmetic mean is 420 m^2/d; the high mean transmissivity relative to the mode reflects the overall negative skew of the T values, as well as significant numbers of higher transmissivities, and highlights the large spread of values.

The varying nature of karstification within the pure bedded limestones is shown in Figures 8.13–8.15 from dif erent localities.

Figure 8.13 Pure bedded limestones with karstification largely limited to the 2–4 m thick epikarst (County Clare). *(Photograph by John Kelly.)*

Figure 8.14 Highly karstified pure bedded limestone with well-developed conduits (County Fermanagh). *(Photograph by John Kelly.)*

Figure 8.15 Pure bedded limestones with large water bearing conduits at two dif erent depths (LeCarrow, County Roscommon). *(Photograph by Caoimhe Hickey.)*

8.2.4 Impure Limestones

Impure limestones account for 44% of Irish limestones and mainly underlie the eastern limestone lowlands (Figure 5.8). The impure limestones encompass a range of limestones that comprise impure, dark grey to black, well-bedded, fine-to-coarse-grained limestones. The limestones can have considerable variations in grain size and in the occurrence of chert and shale bands. The majority of rock units within the group are known as 'Calp' limestones and Ballysteen limestones. Although the impure limestones are ubiquitous throughout most of Ireland, they can vary in character between certain regions.

The impure limestones productivities are generally skewed towards the lower categories (Figure 8.16 A). This skew is even more pronounced when only the values from the eastern midlands are considered (Figure 8.16 B). This demonstrates the greater variability in areas outside the eastern midlands.

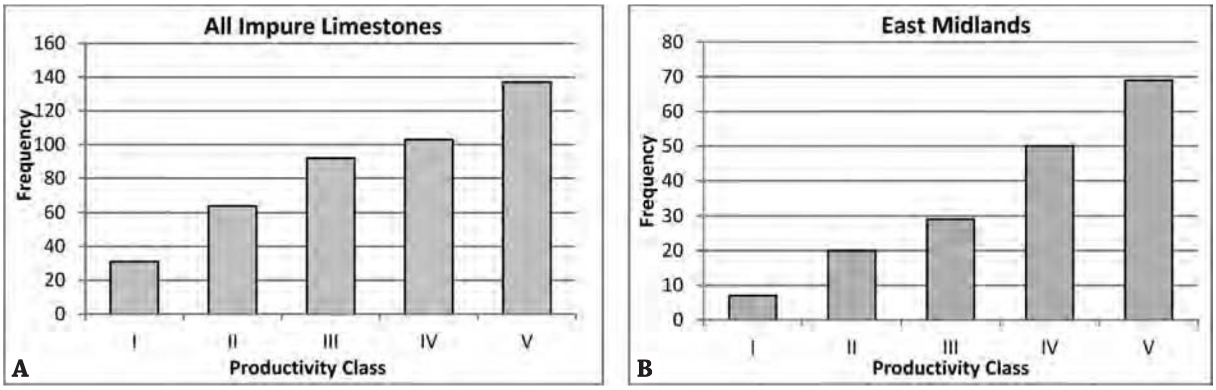


Figure 8.16 (A) Well productivity values for all the impure limestones. *(Data adapted from GSI.)* (B) Productivity values for wells located in the impure limestones in the East Midlands. *(Data adapted from GSI.)*

However, if constituent lithologies within the 'impure limestones' are considered, the picture becomes more complex. The impure limestones are widely considered too argillaceous to develop significant karstification, yet stream sinks occur in south Cork and karst springs are known (for example at Fore, County Westmeath), though spring discharges rarely exceed 30 l/s and many are less than 1 l/s. Karstification seems to be confined to the uppermost 10 m of bedrock.

Figure 8.17 illustrates the considerable degree of hydrogeological variation within a single lithology, the Calp, from locations in eastern and central Ireland. Well-productivity histograms at three locations (D, E and C) are skewed towards lower productivity categories; the distribution for the Kilkenny–Laois–Tipperary region (B) is almost a normal distribution, whilst the Meath–north Dublin region (A) has more wells with higher productivities. This may to be due to some purer beds within the limestone in places and greater structural deformation. The more distributed productivity values in the Kilkenny–Laois–Tipperary example may also be a function of more fissuring and fracturing related to the greater structural deformation of that area and increased dolomitisation of the limestone. Thus, 'impure' limestones can be locally productive, possibly due to a function of purer beds, fracturing, faulting and dolomitisation (Figure 8.10).

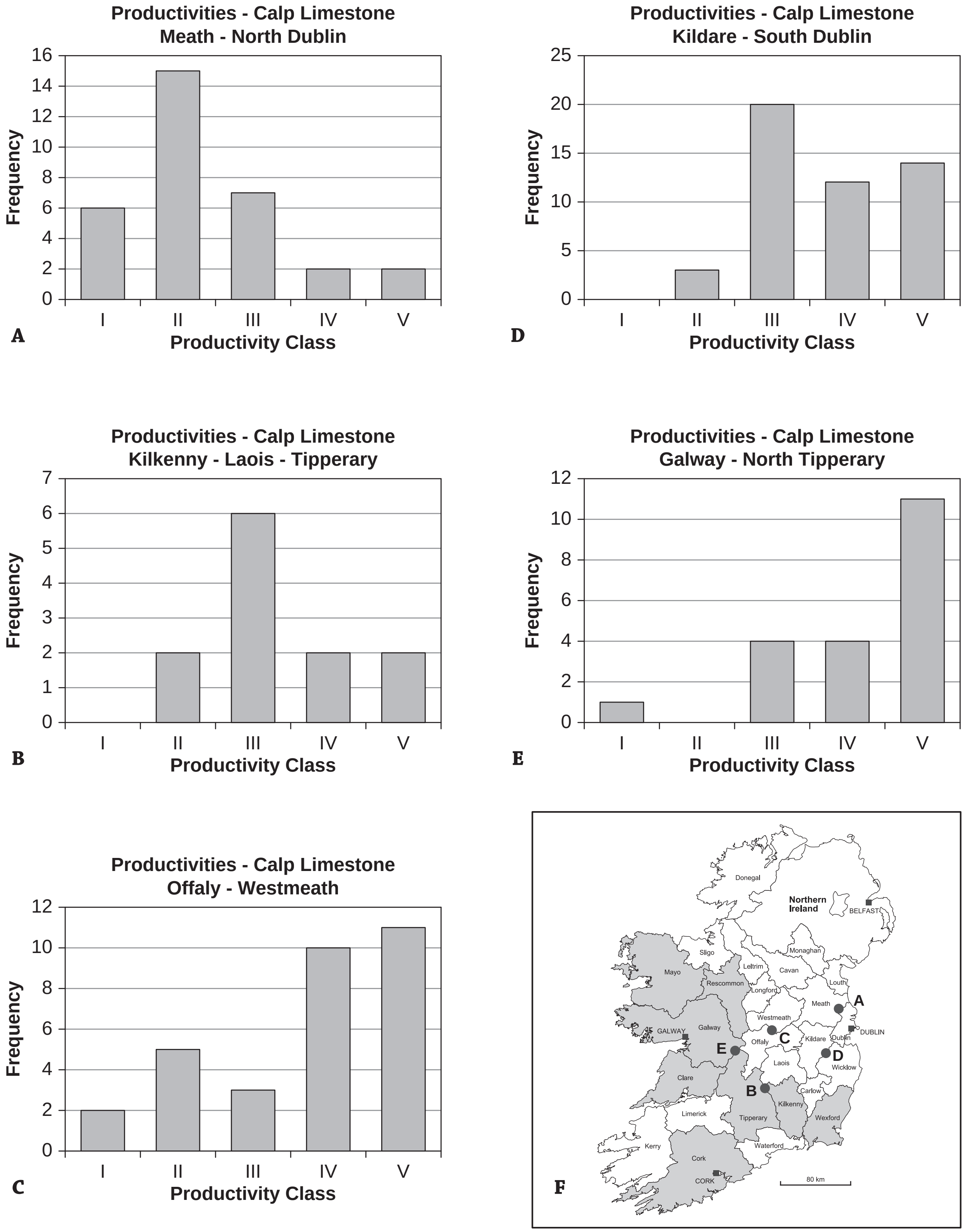


Figure 8.17 Well productivities in the Calp (Lucan Formation) in various localities in Ireland. *(Geological Survey Ireland, in prep.)*

Conroy (2007) compares yields from 42 boreholes located in both impure limestones (Loughshinny and Lucan Formations) and pure bedded limestones (Platin and Mornington Formations) in east County Meath, north County Dublin and south County Louth. Little systematic dif erences are apparent between lithologies in terms of absolute yields and range of yields. For example, specific capacity for the impure limestone averages 104 $m^3/m/d$ and

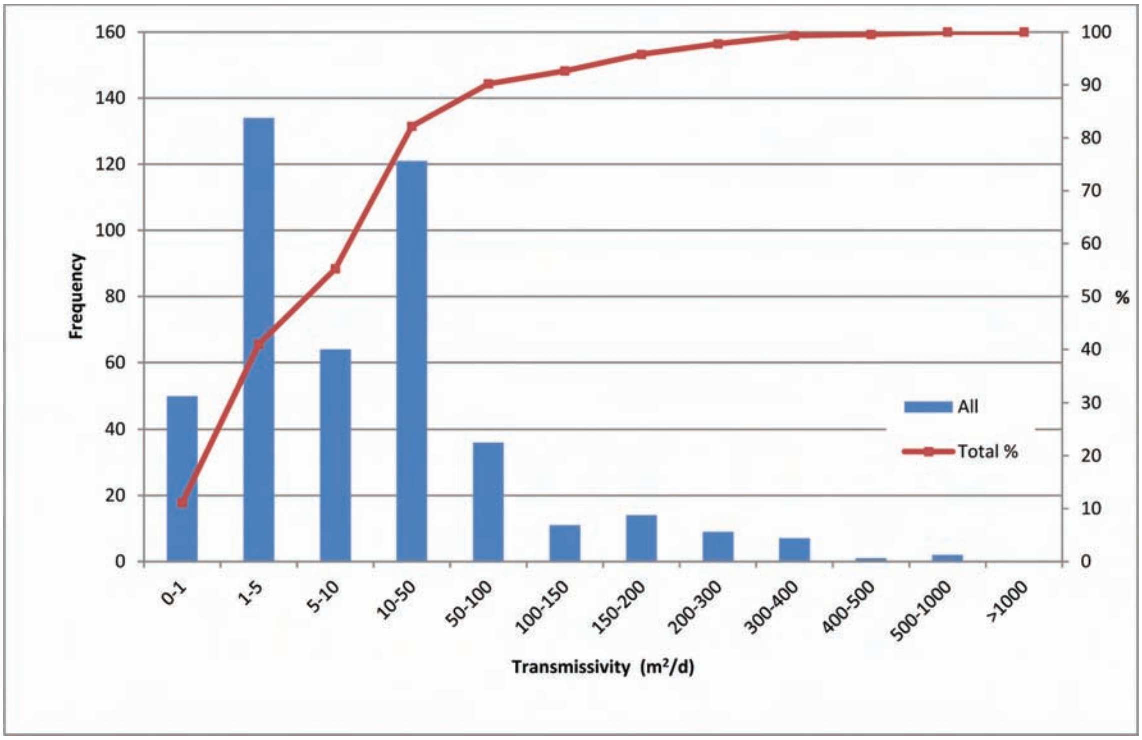


Figure 8.18 Transmissivity histogram and cumulative frequency for impure limestones (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

for the pure bedded limestones is 75 $m^3/m/d$. Overall, 30% of the boreholes were classified as failures whilst 36% gave yields of category I.

T values in the impure limestones are shown in Figure 8.18. The distribution is much less spread than the transmissivity graph for the pure bedded limestones, with a marked skew towards the lower T values. Fifty five percent of all wells have T values of less than 10 m^2/d and 90% of wells have values of less than 100 m^2/d. The mean (37 m^2/d), mode (13 m^2/d) and median (8 m^2/d) values all reflect the dominance of the low T values. Figures 8.19, 8.20 and 8.10 show examples of impure limestones in Ireland.

8.2.5 Pure Unbedded Limestones

Pure unbedded limestones (mostly made up of Waulsortian limestones but also including Dartry mudbank limestones) usually have a high degree of purity and are commonly fine-grained, massive and unbedded, with well-developed jointing or fissuring only if they are located close to faults or folds. Outcrop of these limestones is most widespread in the midlands and in the valleys of counties Cork, Tipperary and Waterford (Figure 5.8) and they account for 15% of Irish limestones. Yield data and field observations indicate that the degree and density of fracturing decreases northwards. The southern outcrop with folded limestones is more productive and is thought to be due to increased karstification in the fractured rock. The north–south dif erences in the water-bearing character of the Waulsortian limestones are summarised in Figure 8.21. This regional dif erence is also reflected in the aquifer category, as the Waulsortian limestones in the south are classified as Rkd, and in the midlands as Ll.

Figure 8.19 Impure (Calp type) limestone showing minimal karstification and little water-bearing capacity (County Dublin). *(Photograph by John Kelly.)*

Figure 8.20 Ballysteen limestone overlain by calcareous till with little karstification of the limestone (County Of aly). *(Photograph by John Kelly.)*

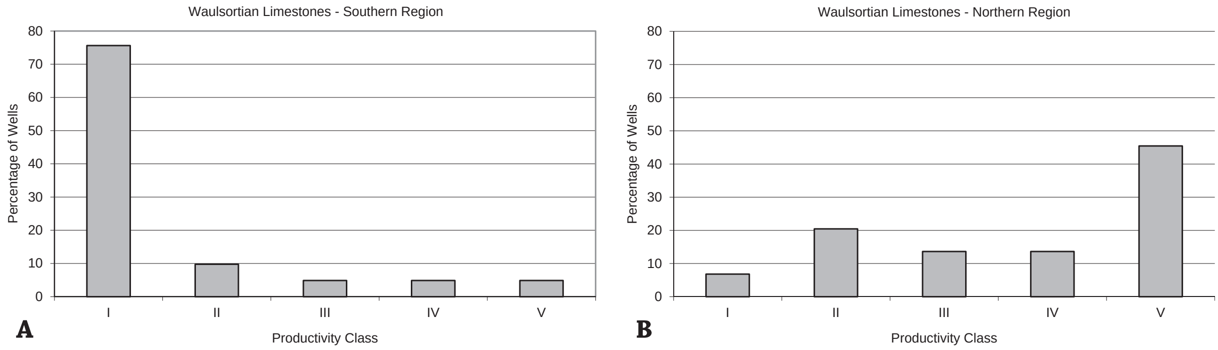


Figure 8.21 Well productivities in the Waulsortian in northern and southern areas of Ireland. *(After Geological Survey Ireland, in press.)*

Figure 8.22 shows the T values for the all pure unbedded limestones. Seventy four percent of all wells have transmissivities of less than 50 m^2/d. However, 15% of wells have transmissivities of greater than 150 m^2/d. The higher mean value of 220 m^2/d compared to the low mode (1 m^2/d) and median (11 m^2/d) values reflect this divergence.

Figure 8.23 shows the T values for each aquifer category within the pure unbedded limestone. The higher values are generally found in the Rkd aquifers from the south. For example, near Dungarvan in County Waterford T values reach 3,000 m^2/d, with permeabilities of 0.5–200 m/d. Large springs are associated with fractured Waulsortian limestone, for example the Kedrah spring near Clonmel (baseflow 250 l/), whilst the River Suir between Thurles and Ardfinnan receives large inflows from a series of springs issuing from Waulsortian limestone. Thus the hydrogeological character of a specific pure limestone lithology may be significantly af ected by the occurrence or otherwise of potentially karstifiable secondary openings. Examples of pure unbedded limestones with varying degrees of karstification are shown in Figures 8.24–8.26.

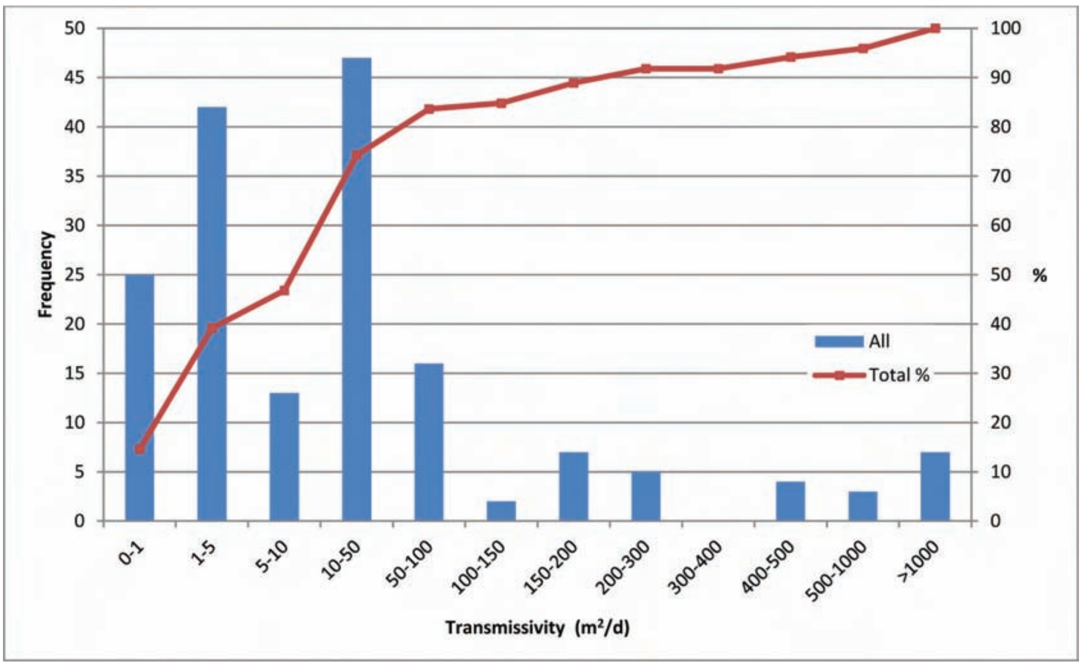


Figure 8.22 Transmissivity histogram and cumulative frequency for wells in the pure unbedded limestones (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

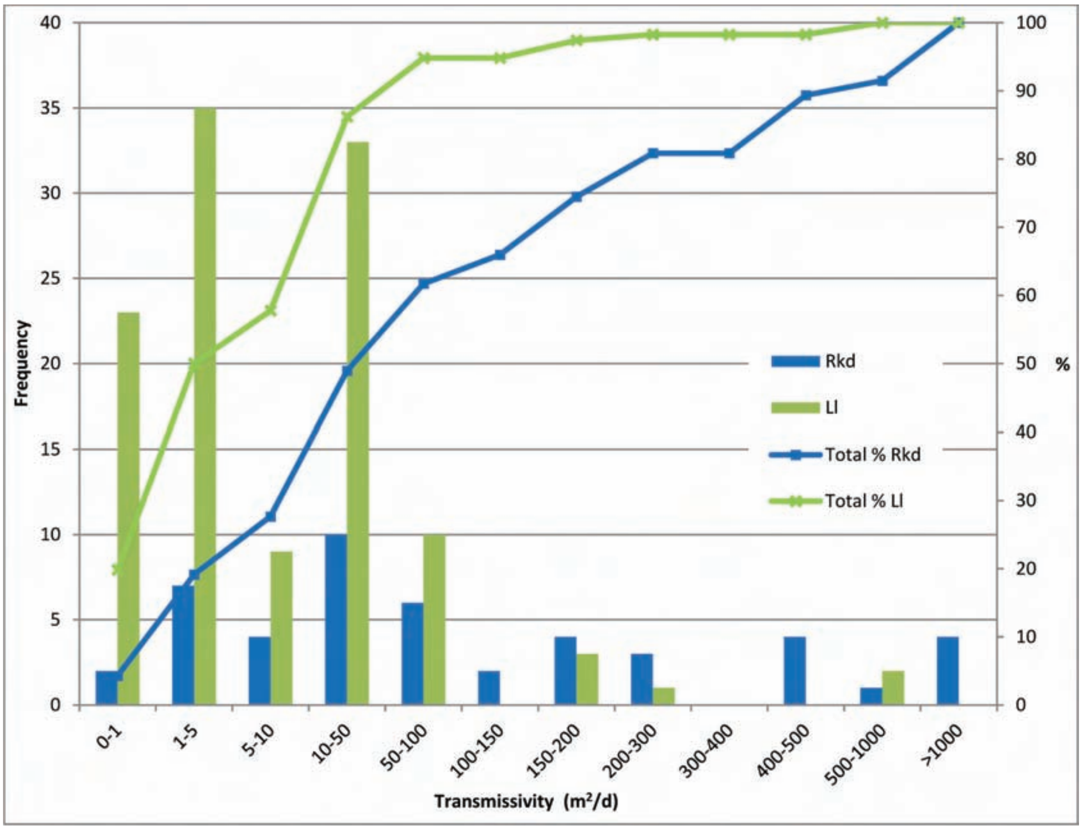


Figure 8.23 Transmissivity values and cumulative frequencies in the pure unbedded limestones, subdivided into Rkd — regional important karstified aquifer with dif use flow (southern synclines) and Ll — locally important aquifer which is moderately productive only in local zones (midlands and northern) aquifers (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

Figure 8.24 Massive mudbank Dartry limestone, County Leitrim, showing little evidence of karstification. *(Photograph by John Kelly.)*

Figure 8.25 Massive Waulsortian limestone, County Limerick, showing limited evidence of karstification. The most significant karst conduits (at lower right) are filled with sediment and are probably hydrologically inactive at present. *(Photograph by John Kelly.)*

Figure 8.26 Significant karstification of Waulsortian limestone (classified as Rkd), in Ardfert (County Kerry). *(Photograph by John Paul Moore.)*

8.2.6 Dolomitised Limestones

Dolomitised limestones outcrop primarily in the central and eastern midlands and in south County Wexford (Figure 5.8). Dolomitisation appears to significantly af ect the water bearing character of limestones in Ireland. Particularly in pure limestones, increasing degrees of dolomitisation are associated with increasing permeability and well yields. Table 8.3 shows the occurrences per metre of average fractures and flowing fractures for various lithologies in County Limerick. The increase in both overall fracturing and productive fractures with increased dolomitisation is apparent.

Figure 8.27 presents the transmissivity histogram for the dolomitised limestones, showing a dominance of highly productive wells, though this may relate as much to increased porosity as to increased karstification. Figure 8.28 shows the increased well productivity due to dolomitisation of the Waulsortian limestones from wells in southern Ireland.

The dolomitised limestones are classed as regionally important karst aquifers (Rkd). Transmissivities range from 1–1000 m^2/d and there appears to be a bimodal distribution

Table 8.3 Fracture occurrence relative to lithology (County Limerick). (*Adapted from Jones et al., 1999.*). Granular limestone is very heavily dolomitised limestone, with a granular consistency.

Fractures per metre	Limestone	Dolomite	Dolomitised limestone	Granular limestone
Overall fractures	0.67	0.95	7.03	1.94
Flowing fractures	0.13	0.02	2.1	1.7

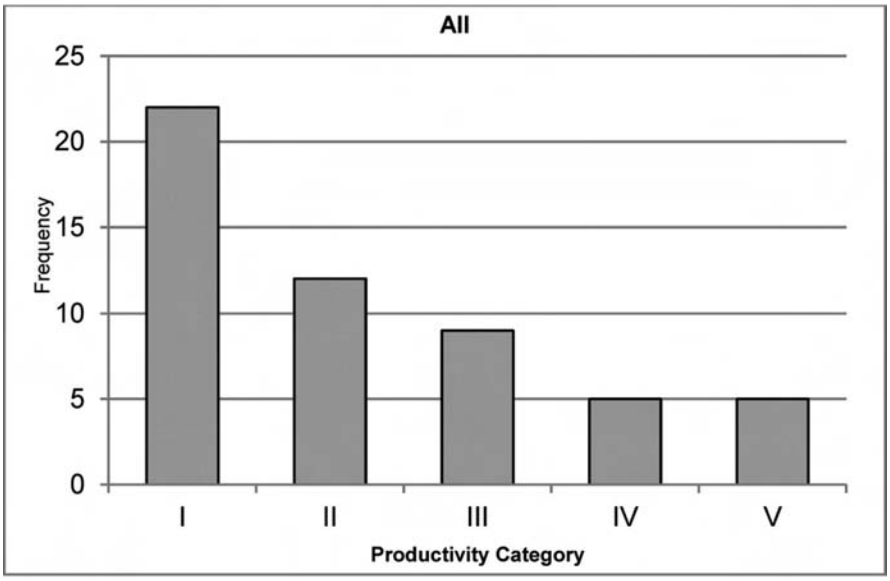


Figure 8.27 Borehole productivities in the dolomitised limestones. *(From Caoimhe Hickey; data adapted from GSI.)*

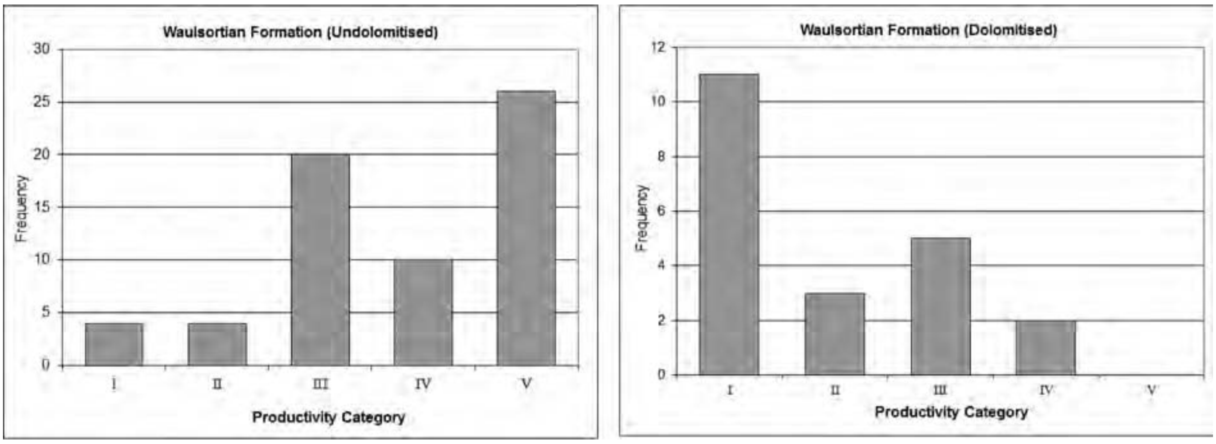


Figure 8.28 Dif erences in productivity between the dolomitised and undolomitised Waulsortian in north Tipperary and surrounding counties. *(Hunter Williams et al., 2002c; data from GSI.)*

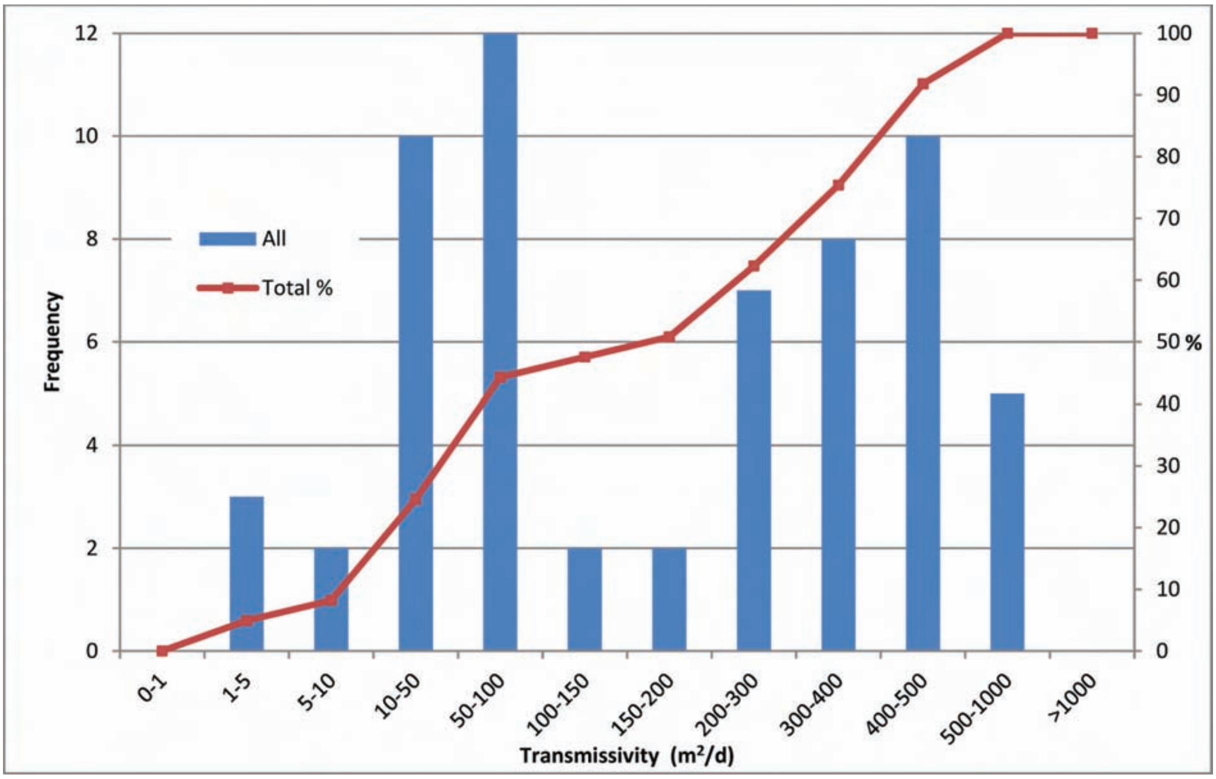


Figure 8.29 Transmissivity histogram and cumulative frequency for wells in dolomitised limestones (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

(Figure 8.29). This is mostly due to data from Lisheen mine. The geometric mean excluding the Lisheen data is 52 m^2/d and with the Lisheen mine data is 230 m^2/d. The median value is 180 m^2/d, for the total dataset. Figure 8.30 shows the transmissivity histogram with the Lisheen data separated out, and shows the dominance of the Lisheen data in the higher T values. The presence of cavities, infilled paleokarst features, and a transmissive

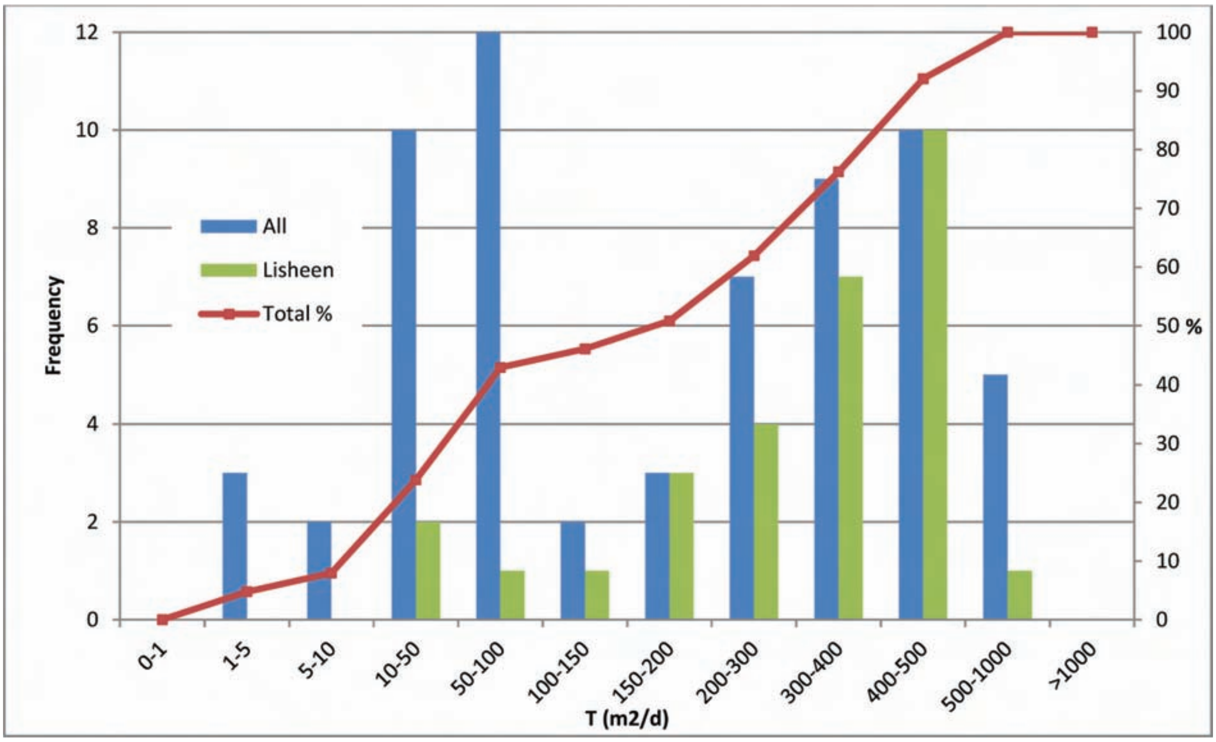


Figure 8.30 Lisheen mine transmissivities compared to total transmissivities for wells in dolomitised limestones (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

north-south fracture network are the likely reasons for the higher transmissivities at Lisheen.

In south County Wexford, Cullen (1980) reports that yields from wells in dolomitised limestone are up to 2,125 m^3/d (SC 23–330 m^3/m/d), in adjacent limestones are up to 1,200 m^3/d (SC 28–103 m^3/m/d) and, for comparison, in a contiguous sand and gravel aquifer up to 2,500 m^3/d (SC up to 650 m^3/m/d).

Overall, well yields from dolomitised rock are markedly skewed to high yields with relatively high transmissivities, indicating a more distributed permeability and possibly bimodal permeability in some locations as compared with pure limestones. Figure 8.31 shows highly dolomitised limestones in County Laois.

A summary of the main dif erences in groundwater flow properties between the dif erent limestone lithologies is shown in Figure 8.32, which compares the cumulative frequency curves of T values for each lithological unit. For example, wells with transmissivities of less than 10 m^2/d account for only 8% of the wells in the dolomitised limestones and 55% of the wells in the impure limestones. The steepest slope is found in the impure limestones in the lower T values, indicating the dominance of the lower T values. The next steepest curve is for the pure unbedded limestones, followed by the pure bedded limestones and then the dolomitised limestones. The bimodal distribution is apparent in the stepped nature of the dolomitised limestones curve. More information on aquifer properties can be found in GSI's aquifer report (GSI, in press) and the aquifer parameter database (Kelly et al., 2015).

Figure 8.31 Dolomitised Waulsortian limestone with high porosity overlying undolomitised limestone (grey rock) (County Laois). *(Photograph by John Kelly.)*

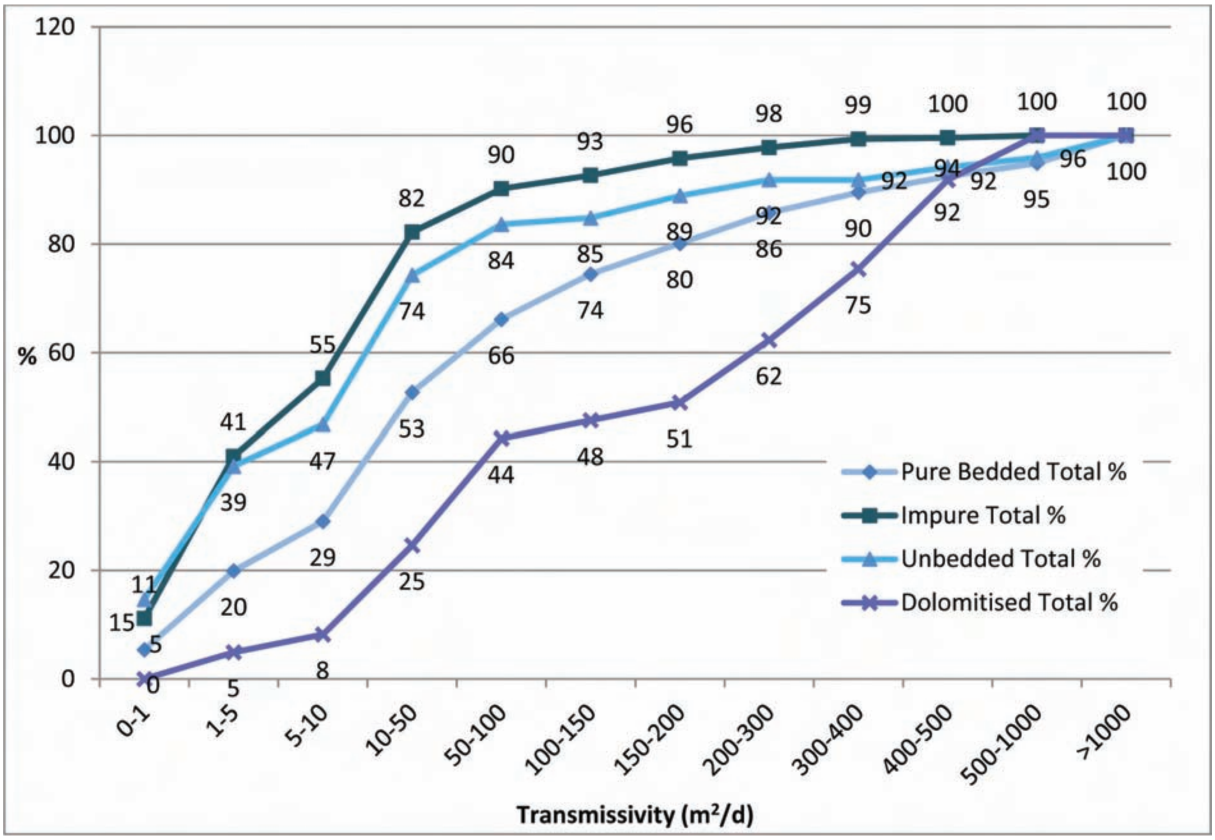


Figure 8.32 Cumulative frequency curves of transmissivity values for the dif erent limestones lithologies (note that the category sizes are not equal). *(Based on data from the aquifer parameters database.)*

Figure 8.33 shows the number of high yielding springs in relation to lithology and bedding. The occurrence of large springs is presumed to be related to the degree of integration of the karst groundwater system. This is a distinction of the basis of ef ect rather than cause, and the data are not normalised with respect to outcrop percentage. More on spring discharges can be found in Section 8.5.

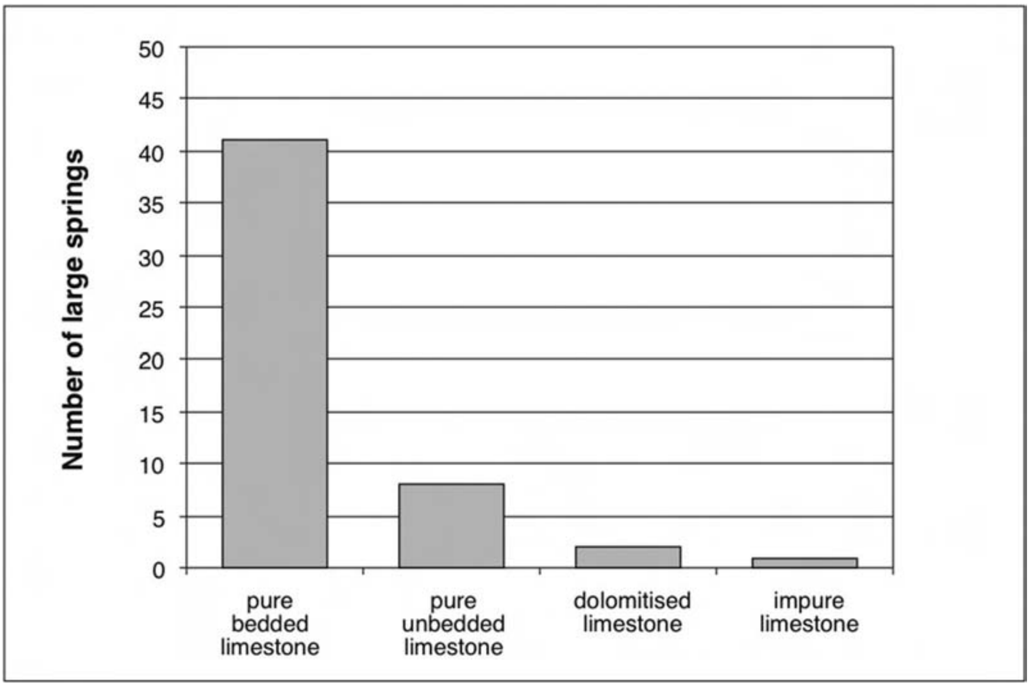


Figure 8.33 Spring yields in relation to lithology. *(After Fitzsimons et al., 2005; data from GSI.)*

8.3 Recharge

The great majority of recharge to the Carboniferous limestone aquifers is dif use in character, though sub-surface concentration of flow in the epikarst and in deeper parts of the unsaturated zone is probably the norm. Pre-concentrated (indirect) recharge is important in some areas and may take the form of autogenic (Figure 8.34) or allogenic sinking streams, inflowing

Figure 8.34 A small sink (inflow c.<5 l/s) typical of the lowland karst, near Tuam (County Galway). The runof is generated on the till-covered limestone. *(Photograph by David Drew.)*

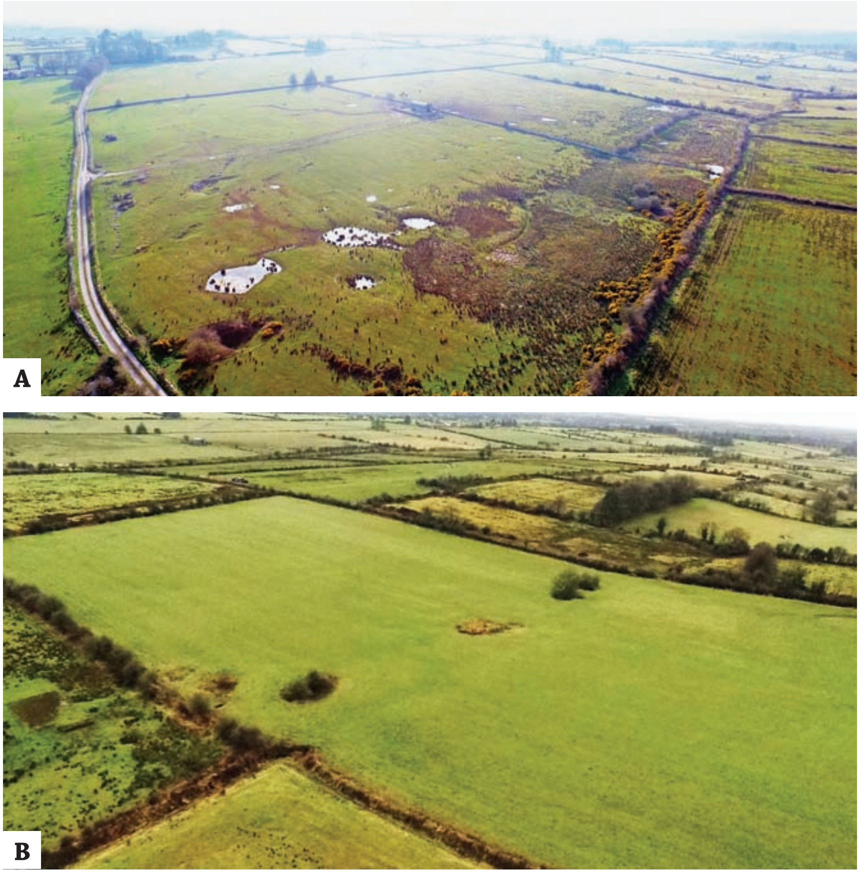


Figure 8.35 Linear alignment of dolines near Castlerea (County Roscommon): (A) under wet conditions. *(Photograph by Aerial Eye for David Drew.)*, (B) under dry conditions. *(Photograph Aerpas for Caoimhe Hickey.)*

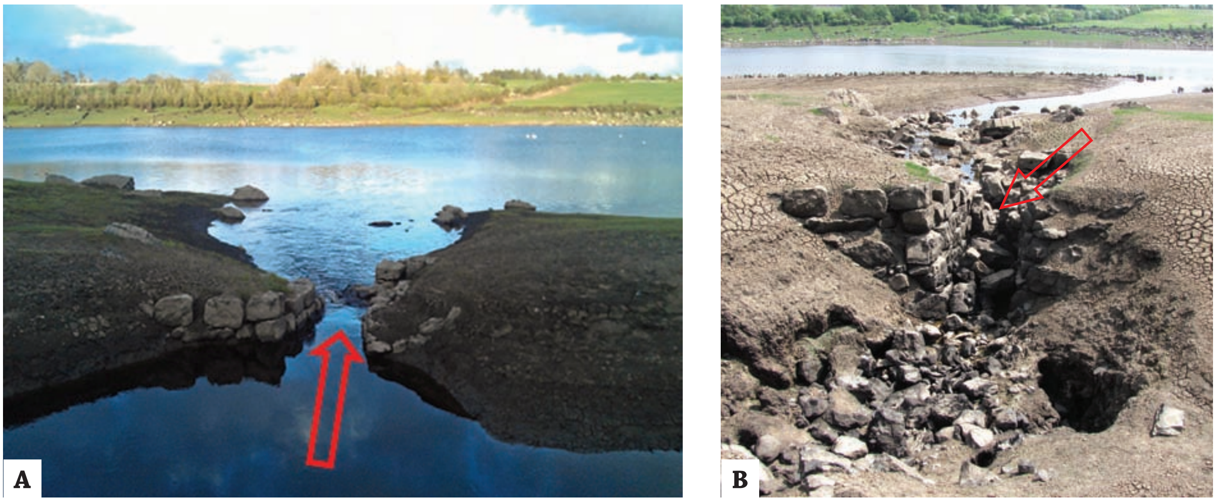


Figure 8.36 Estavelle on the edge of Lough Coy (County Galway). Flow direction is marked by red arrow: (A) Outflowing from ground to turlough (B) Inflowing from turlough to ground. *(Photograph A by Ted McCormack, Photograph B by Pat Veale.)*

reaches of surface rivers, hydrologically active dolines (Figure 8.35) or turlough sinks. The latter are sometimes estavelles, functioning alternately as sinks and springs depending on local hydraulic head relationships (Figure 8.36).

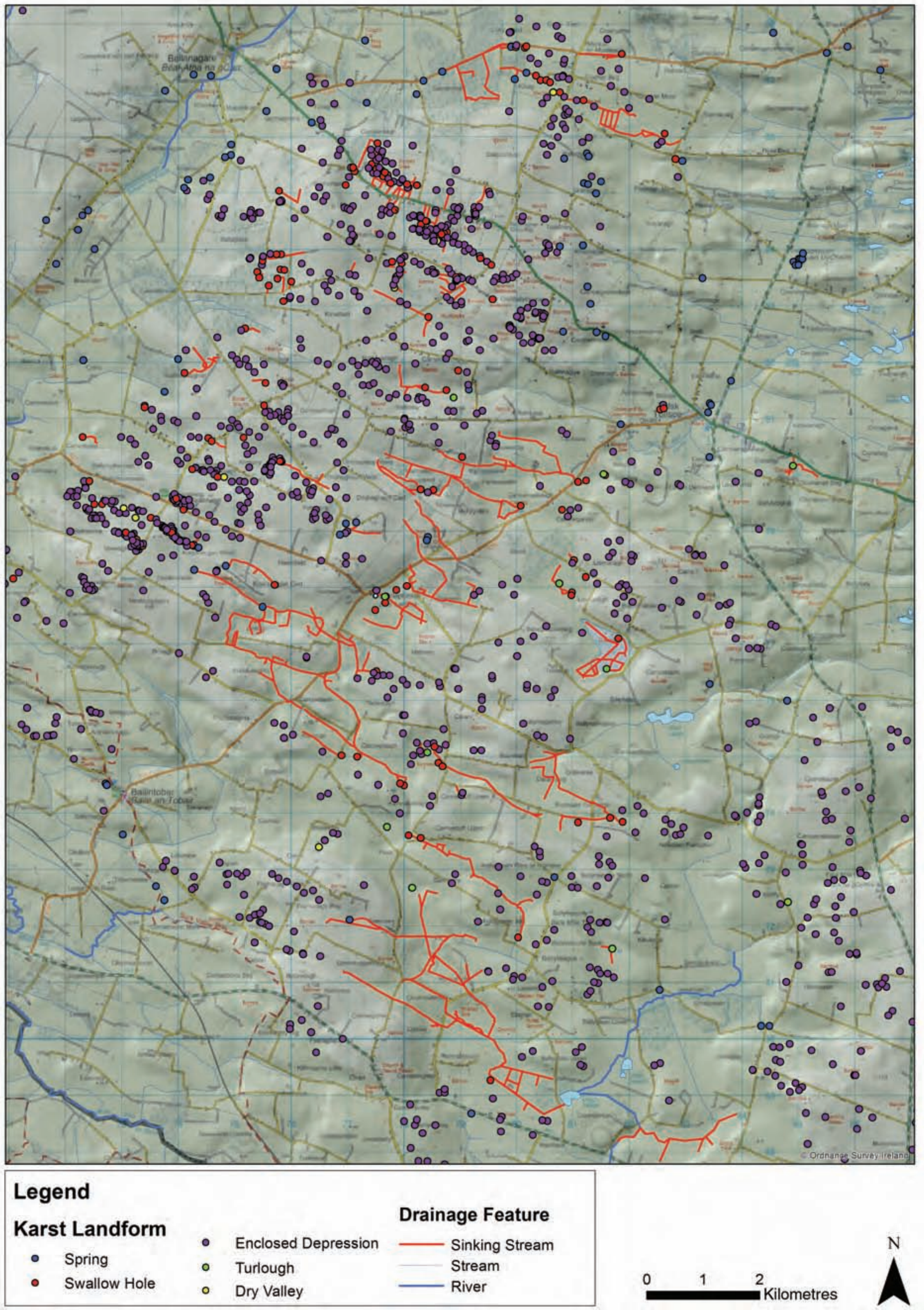


Figure 8.37 Surface drainage and karst landforms in north Roscommon. *(Based on GSI data.)*

Lowland aquifers that have a significant thickness of subsoil exhibit little obvious indirect recharge, but where subsoils are thinner, for example over large areas of County Roscommon, east Mayo, east Galway and south Clare, small autogenic streams generated on low permeability subsoils occur in considerable numbers (Figure 8.34 and 8.37). For example, in County Roscommon such point recharge sites occur at a mean density of 0.6/km^2 with 75% being dolines and the remainder discrete stream sinks (Hickey, 2008). Locally, however, doline fields with densities of up to 25/km^2 are known, sometimes with clear patterns of distribution, such as linear alignments (possibly indicating a geological control on karstification) or at the periphery of areas of acid peat (Figures 8.35 and 8.37). The mean inflow at these sites rarely exceeds 5 l/s. The stream catchments are commonly less than 1 km^2 and the catchment for individual dolines probably only amounts to some hundreds of square metres or less (Hickey, 2008). Such autogenic indirect recharge amounts to 5%–10% of total recharge over much of the western lowlands.

Plateau limestones with adjacent non-carbonate rocks that generate surface drainage may experience considerable indirect allogenic recharge where streams sink at the contact with the limestone. For example, the catchment for Killeany spring in the Burren, County Clare (Figure 4.14), includes areas of shale and sandstone on its margins and a series of sinking streams contribute c.40% of the total recharge. Although predominantly lowland, the catchment for the nearby coastal springs at Kinvara, County Galway includes large sinking streams generated on the Slieve Aughty Mountains and allogenic recharge may be as high as 85% of total discharge at Kinvara. Elsewhere, values of 5%–10% are more typical. Allogenic recharge was calculated to account for only 0.6% of total recharge in County Roscommon (Hickey, 2008).

In effect, recharge to most of the limestone aquifers occurs in varying proportions along a continuum of mechanisms from direct diffuse, to epikarst – concentrated subsurface, to doline to autogenic and allogenic stream recharge. Extreme examples of point recharge exist where a sinking stream provides 100% of the outflow at a spring. This occurs where water from the sink of the Aille River (the waters of which are generated on the impermeable rocks of the Partry Mountains near Westport, County Mayo) provides virtually all of the discharge from the spring at Pollatoomary, some 3 km distant (Figure 8.38). The largest of all sinking streams, however, are those entering the swallow holes in the southeast part of Lough Mask in south County Mayo which engulf all of the lake outflow (Figure 7.64).

Some surface streams have stretches of channel which are inflowing to groundwater at least under low groundwater conditions. Reaches of the River Clare and River Robe exhibit this behaviour. In extreme instances, stretches of the rivers may dry completely for a part of the year, such as the Dunkellin River in County Galway. Such influent streams are most common in the lowlands of Counties Clare, Galway, Mayo and Roscommon but are also found in Counties Cork (River Bregoge) (Figure 8.39) and Louth (Dry Bridge stream). Perhaps the most spectacular example is the River Deel, upstream of Crossmolina, where up to 1.2 m^3/s of water sinks in the river bed leaving the channel dry on occasions (Figure 8.40) with the water re-appearing from a large spring some 2–3 km to the east.

Figure 8.38 (A) The sink of the Aille River near Westport County Mayo where the river originating on the Partry Mountains crosses on to the limestone. To the right of the sink is a collapse doline into the underground conduit. A series of such dolines exists between the sink and the rising at Polltoomary some 3 km distant. *(Photograph by Aerial Eye for David Drew.).* (B) The resurgence for the Aille River sink at Pollatoomary spring. Groundwater flows between sink and rising at depths exceeding −110 m (70 m below sea level) before emerging via a vertical conduit at the spring. *(Photograph by David Drew.)*

Figure 8.39 The seasonally dry channel of the River Bregoge, County Cork, downstream of the main swallow holes. *(Photograph by David Drew.)*

Figure 8.40 (A) River Deel at Crossmolina at mean flow conditions (April 2016). *(Photograph by David Drew.)*. (B) Dry channel of the River Deel at Crossmolina (June 2016). *(Photograph by David Drew.)*

8.4 Flow Systems

8.4.1 Introduction

The parameters used in the previous sections of this chapter (such as productivity, transmissivity and yields) are derived from information acquired from boreholes. In a non-karst (Darcian) aquifer, most information about groundwater velocities, flow directions and aquifer storage can be obtained from borehole test data, though for highly fractured aquifers this can be stretched to the limit. As stated previously, these parameters are extremely dif cult to determine by borehole analysis in karstified aquifers. Wells rarely penetrate the main conduits of a karst groundwater basin and conduits usually account for only a very small percentage of the aquifer but often contain most of the flow. Transmissivity and hydraulic conductivity, estimated from boreholes are not considered to represent most of flow in highly karstified aquifers. In these heterogeneous, anisotropic conditions, flow velocities from tracer tests are more appropriate.

In Ireland to date, water tracings have been the primary source of data from which the character of karstic aquifers has been inferred. In some karsts in Ireland, extensive, hydrologically active cave systems have been explored and mapped, providing an understanding of the distribution, flows and other characteristics of at least that part of the conduit system that is accessible to speleologists. Unfortunately almost all of these mapped cave systems are located in karst uplands such as the Burren where demand for water supplies is relatively small. On the other hand, lowland karst aquifers, where water demand is much greater, lack explorable cave systems, and knowledge of the karst flow systems is largely derived from input–output water tracings, with no direct information available on the intervening aquifer characteristics.

As is outlined in Chapter 4, karst groundwater systems range from being conduit dominated (as in the Gort area of County Galway) to relatively un-integrated flow systems with distributed groundwater flow in fractures that are only slightly enlarged by solution of the rock (as in parts of the eastern lowlands, but also in some uplands such as the Bricklieve Mountains in County Sligo).

This spectrum of flow systems is reflected in the classification of limestone aquifer types in Ireland recognised by the Geological Survey (Chapter 5). However, water tracings undertaken in Ireland have been overwhelmingly dominated by tracer inputs into stream sinks (point recharge), which are the upstream end of some type of conduit system. Tracings from dif use recharge locations are few as are inter-aquifer tracings, for example using boreholes. For Irish karsts as a whole, dif use recharge is the norm and the degree to which integration of drainage into a hierarchical drainage system takes place within the aquifer is largely unknown. Analysis of spring flow hydrographs (Chapters 4 and 10) are an indirect means of gaining such information.

Analysis of groundwater flow in Irish karsts, given below, is based on data from 465 water traces carried out in Ireland (up to 2017), and recorded in GSI's National Tracing Database. It should be noted that there is uncertainty as to how representative these largely conduit-flow derived data are of total flow regimes in karst aquifers in Ireland. Figure 8.41

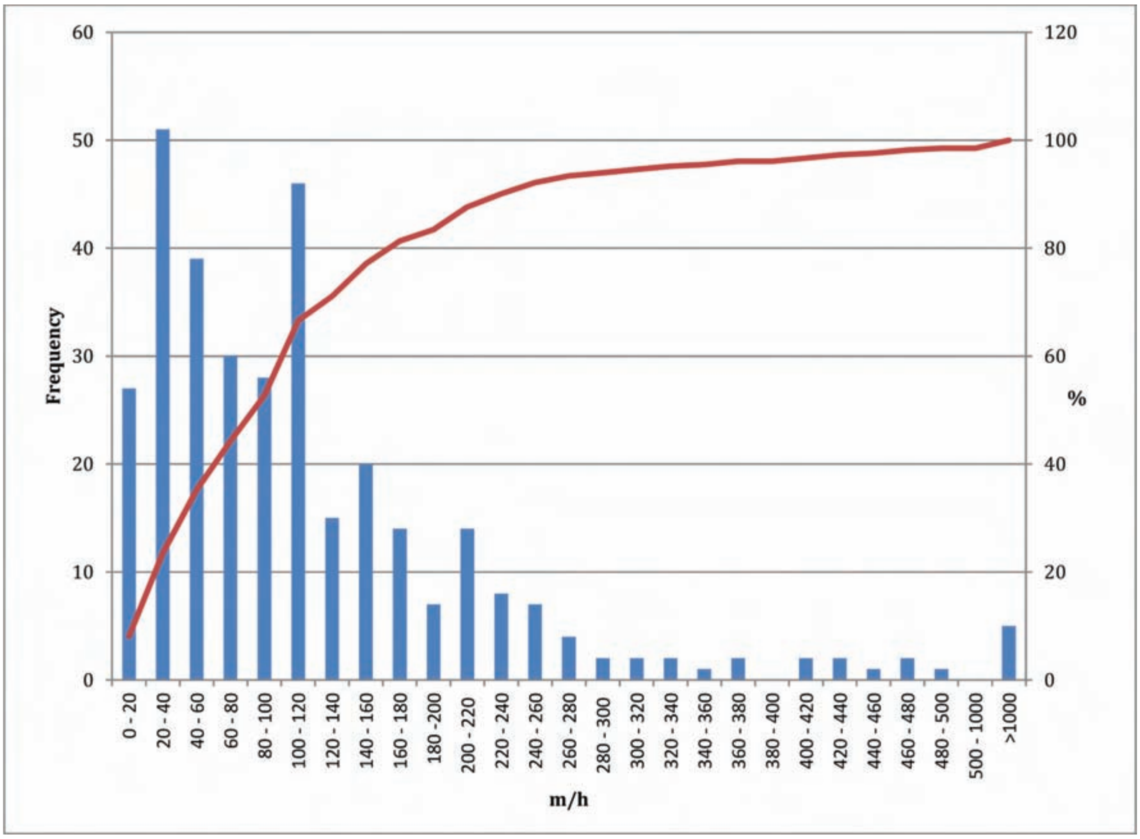


Figure 8.41 Frequency distribution histogram and cumulative frequency of groundwater flow rates in Irish limestones from water tracing experiments. *(From GSI's water tracing database.)*

shows the frequency distribution histogram of minimum groundwater velocities derived from the water tracing database. They are minimum values for two reasons; firstly a straight line is used to calculate velocities, which is often significantly shorter than actual pathway the water takes and secondly, most values have been calculated from discrete water sampling, which is usually not more frequent than once every 24 hours.

Figure 8.41 uses velocity data from 332 water tracing experiments, as not all the 465 entries in the database contain velocity information. The minimum groundwater velocities recorded in Irish karsts (assuming a straight line flow path) derived from tracing experiments, range from 2–1,200 m/h with an arithmetic mean flow rate of 122 m/h. However, two-thirds of all traces have minimum groundwater velocities of less than 120 m/h, showing that the arithmetic mean value is not a suitable variable. In this case, the median value of 92 m/h is considered to be more representative. This is comparable to the global value of 80 m/h for more than 3,000 tracings world-wide presented by Ford and Williams (2007). As shown in Figure 8.41, only 5% of traces had velocities greater than 300 m/h.

The great majority are tracings from sinking streams and are therefore not representative of overall groundwater recharge in general; conduit flow velocities are recorded, and not total aquifer residence time, in some situations. In contrast, dye entering the aquifer via small sinking streams in low stage conditions may sit in the unsaturated zone for some time before making its way into conduit system and may give rise to much slower velocities than exist in the conduits.

Lengths of underground flow path from water traces range from 64 m to more than 15.5 km. The mean straight-line distance is 3.9 km and the median is 3 km.

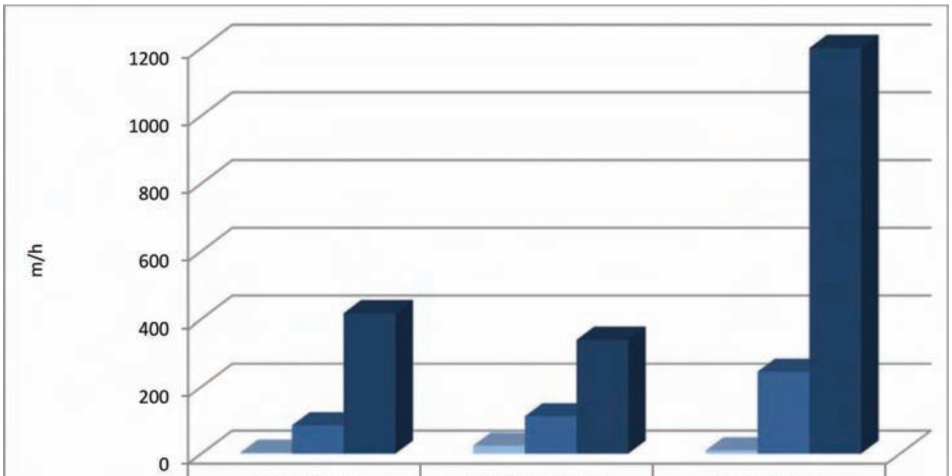
8.4.2 Effects of Stage Conditions on Flow

As mentioned above, recharge may be perched in the epikarst or unsaturated zone of the aquifer, giving rise to comparatively slower groundwater velocities. This ponding of recharge is often related to the nature of recharge and the antecedent stage conditions. Groundwater velocities, acquired from water tracing experiments vary depending on stage conditions as well. This may be due to ponding of recharge in low stage conditions or changes in groundwater head. It can be seen that average groundwater velocities are almost three times higher for traces undertaken during high stage conditions than those undertaken during low stage conditions (Figure 8.42).

To exclude any other variables, repeat traces (traces that were repeated in the same injection and output sites) are presented in Figure 8.43. It was found that stage conditions can increase flow velocities by more than 50 times, with the average being a 12-fold increase in flow velocities between low and high stage conditions (Figure 8.43).

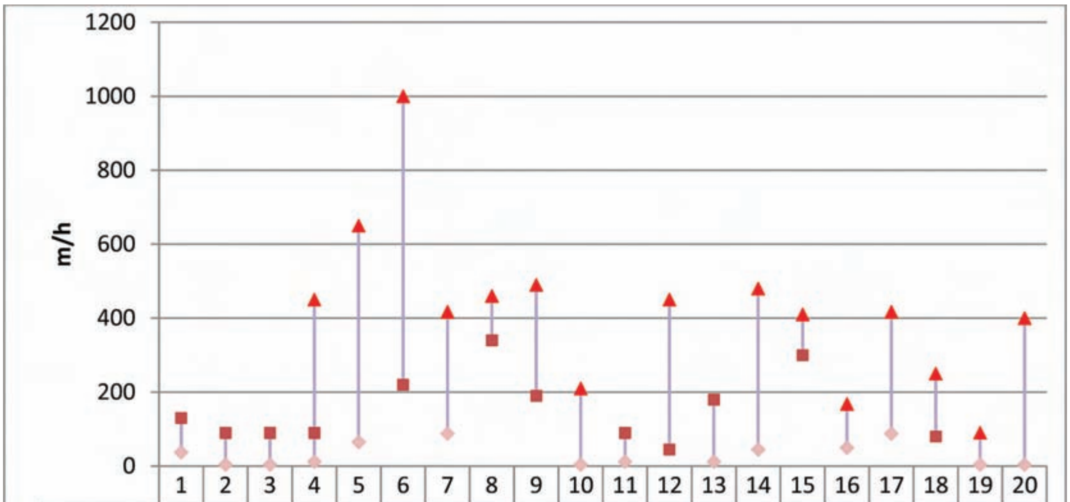
8.4.3 Regional Variations in Flow

Hydraulic gradients in the upland limestones are often steep (>0.1) if the – often deep – unsaturated zone is taken into account. However, gradients within the saturated zone are similar in upland and lowland limestones, typically ranging between 0.001–0.01 and averaging 0.03. Minimum conduit flow velocities in the uplands ranges from 3–330 m/h, with an average of 89 m/h, and in the lowlands ranges from 2–1200 m/h, with an average of 136 m/h (Figure 8.44). Median values are closer with minimum flow velocities of 86 m/h for upland karsts and 95 m/h for lowland karsts. The minimum flowpath lengths for upland and



	Low stage	Medium stage	High stage
Minimum	3	24	10
Mean	85	112	245
Maximum	417	340	1200

Figure 8.42 Groundwater flow velocities and stage conditions. *(From GSI's water tracing database.)*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
◆ Low	37	4	4	12	65		88			4	12		12	45		50	88		4	4
■ Medium	130	90	90	90		220		340	190		90	45	180		300			80		
▲ High				450	650	100	417	460	490	210		450		480	410	168	417	250	90	400

Figure 8.43 Groundwater flow velocities and stage conditions in repeat traces. *(From GSI's water tracing database.)*

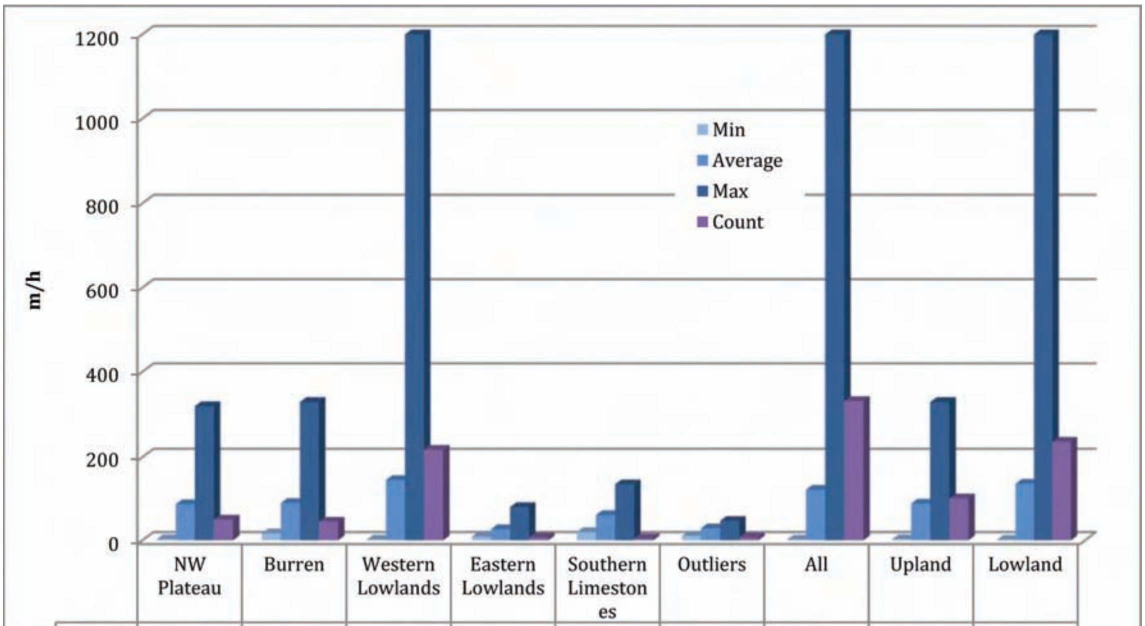
lowland karsts are similar with flowpath lengths in upland karst ranging from 94 m–14 km, averaging 3.3 km and the range for lowland karst is 64 m–15.7 km, averaging 4.2 km.

Differences also exist between the main karst regions, described in Chapter 7 and shown in Figure 7.7. Figure 8.44 shows summary statistics for groundwater velocities in these main karst regions. Minimum and average groundwater velocities for the two upland karst areas (The northwest plateau karst and the Burren) are very similar, with similar average flow velocities. However, there is considerable variation between the four lowland karst regions. The eastern limestones, the southern limestones, and the outliers have few data, but it appears that the flow rates are slightly higher, on average, in the southern limestones than the eastern lowlands or outliers. There is a considerable contrast between these three lowland categories and the western lowlands. The low-lying limestones west of the Shannon have a large range of flow velocities and higher average flow rates than any other region.

Flow rates vary five-fold between karst areas in Ireland, with the highest velocities recorded in the lowland Gort-Kinvara aquifer, where flow is dominantly in large conduits with a uniform gradient and where a large proportion of recharge is from allogenic sinking streams. The fastest measured groundwater velocity (1,200 m/h) was recorded in this region, from a tracer injected into a borehole straight into a main conduit.

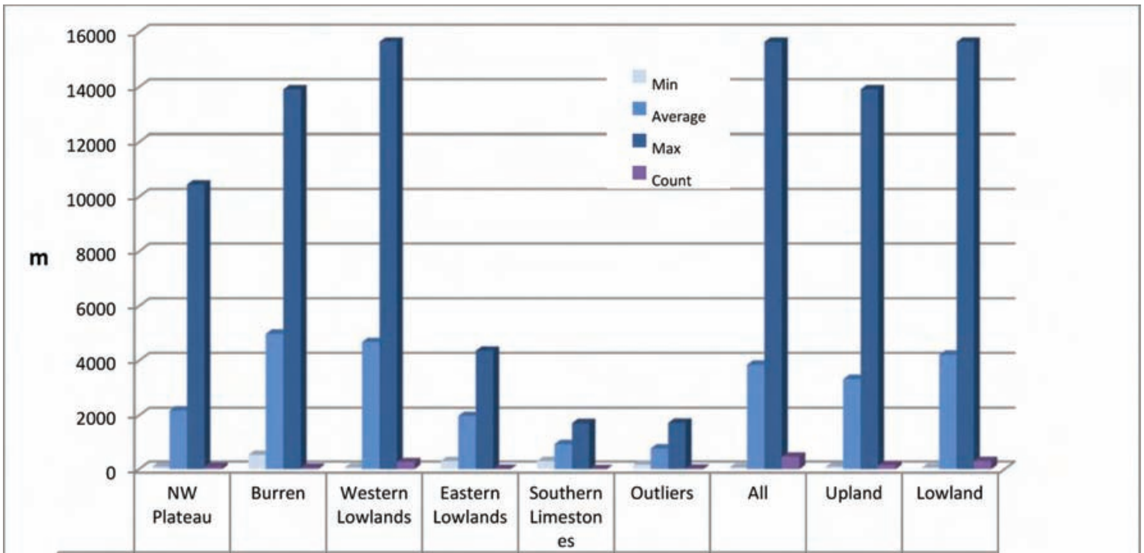
Perhaps not surprisingly, the average minimum flowpath length recorded from water tracing is greater in the extensive limestone lowlands in the west than other regions, but long flow path lengths are common in upland karst also (Figure 8.45). The longest straight-line distance recorded is over 15.5 km, and is in the Gort/Kinvara area.

Figure 8.46 shows frequency distribution graphs of flow velocities in the different limestone regions in Ireland. However, the values are not necessarily fully representative of flow rates



	NW Plateau	Burren	Western Lowlands	Eastern Lowlands	Southern Limestones	Outliers	All	Upland	Lowland
Min	3	17	2	9	20	11	2	3	2
Average	87	90	145	27	61	29	122	89	136
Max	320	330	1200	80	135	47	1200	330	1200
Count	50	45	218	7	5	7	332	101	237

Figure 8.44 Minimum groundwater velocities recorded from water tracing experiments in Irish karsts. *(From GSI's water tracing database.)*



	NW Plateau	Burren	Western Lowlands	Eastern Lowlands	Southern Limestones	Outliers	All	Upland	Lowland
Min	94	535	64	306	307	175	64	94	64
Average	2184	4990	4683	1985	934	774	3850	3350	4216
Max	10451	13916	15659	4365	1715	1727	15659	13916	15659
Count	83	59	267	13	5	23	467	142	308

Figure 8.45 Minimum groundwater flow path lengths from water tracing experiments in Irish karsts. *(From GSI's water tracing database.)*

in all limestone regions because the information is areally unbalanced with many data from Counties Galway, Roscommon, Clare and Cavan-Fermanagh but relatively few data from elsewhere (see Figure 8.44 for counts).

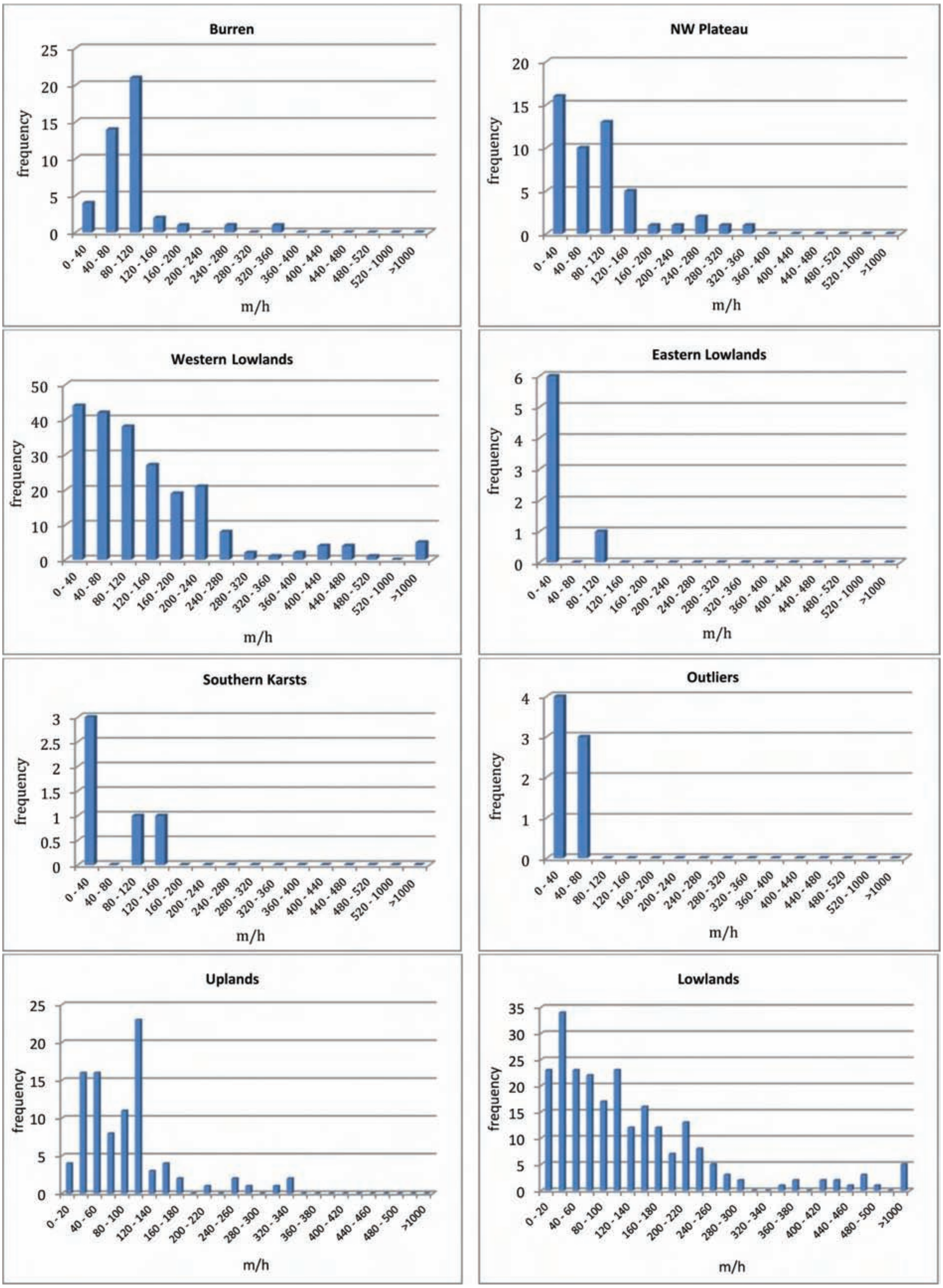


Figure 8.46 Frequency distribution of minimum groundwater velocities for the dif erent limestone regions in Ireland derived from water tracing experiments. *(From GSI's water tracing database.)*. The two graphs at the bottom summarise flow velocities in upland and lowland karsts.

It is unwise to draw any concrete conclusions, as the sample sizes are small in some regions, but it may be that the eastern lowlands and the outliers have the lowest groundwater velocities. In the eastern lowlands 85% of flow velocities are less than 40 m/h with only one higher value of 80 m/h. The maximum velocity recorded from the outliers is 47 m/h, with most values being less than 20 m/h (Figure 8.46). Minimum flow velocities in the southern synclines are also low, with the majority having minimum velocities of 30 m/h or less, although two traces recorded flow rates of more than 100 m/h.

The upland areas (the Burren and the northwest plateau) have flow velocities in the 320–360 m/h range, though the majority of velocities recorded are less than 120 m/h. The western lowlands have the most widely distributed flow velocities with some velocities of greater than 1,000 m/h.

8.5 Discharge

Because Irish Carboniferous limestones are karstified, groundwater flow is mainly focused on springs as discharge points, though dif use discharge into rivers does occur. More than 80% of the springs emerging from limestone bedrock aquifers are small, with a mean discharge of a few litres per second and with correspondingly small catchments. Mean flow at approximately 770 springs exceeds 10 l/s (Figure 8.47). Most springs have a contributing area (catchment) in the range 1.5–10 km^2 corresponding in size to first or second order surface drainage basins in Ireland. The great majority of springs are located on the pure limestones or at the contact with impure limestones, or non-limestones and are, therefore, most abundant in the west and the south.

Table 8.4 lists springs with 'large' discharges – in terms of Ireland a large discharge is regarded as having a baseflow of greater than 200 l/s. There are few karst springs in Ireland for which suf cient data are available to generate a robust mean or representative discharge and the sites included in Table 8.4 are only those for which there is reasonable evidence that their mean discharge/representative discharge/baseflow exceeds 200 l/s. Almost certainly, other springs exceed this flow threshold but to date the evidence is only anecdotal or visual. Re-emergences of single sinking streams (the rivers in the Gort area of County Galway and the resurgence of the Aille River in County Mayo for example) are not regarded as being true springs. The highest and lowest discharges recorded at each site are also included, though given the low number of readings at many of the springs these values are indicative at best. The aggregate discharge from multiple springs in an area is included only where there is evidence that they comprise water from the same source(s).

Some 18 springs probably have baseflow discharges above the 200 l/s threshold, of which County Galway has seven, Mayo four, Roscommon three, Clare two, Tipperary and Cork one each (Table 8.4). Two groups of springs are large in international terms. The intertidal zone springs at Kinvara, County Galway, have an estimated mean discharge of 12,000 l/s whilst the springs at Cong, County Mayo, that discharge both the sinking waters of Lough Mask and sinking streams generated on an area of non-limestone rocks to the west, have a mean outflow of c.17,000 l/s (Chapter 7.5). The high flow value for the Cong springs (and

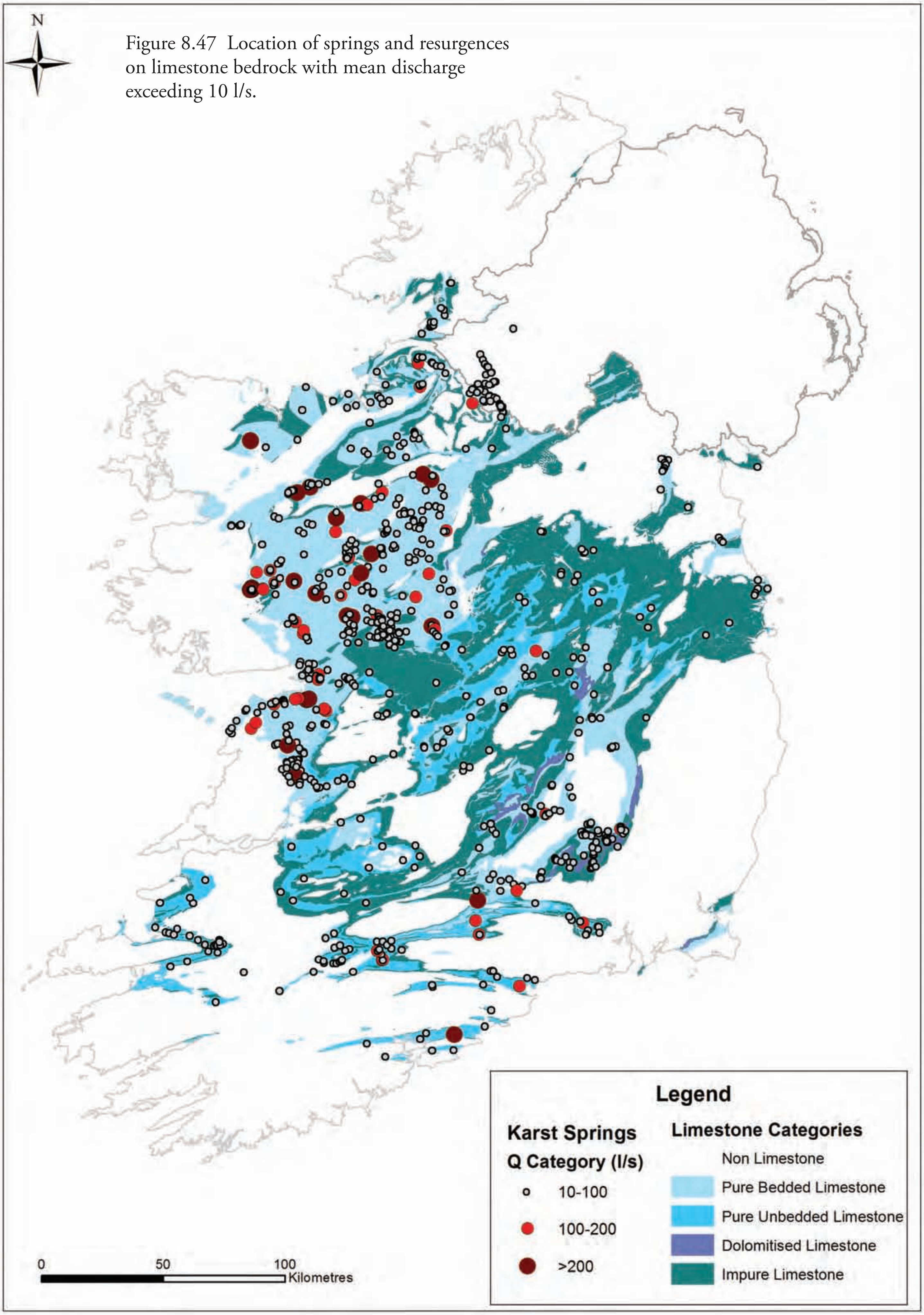


Figure 8.47 Location of springs and resurgences on limestone bedrock with mean discharge exceeding 10 l/s.

Table 8.4 Springs in Ireland considered to have a representative discharge/baseflow in excess of 200 l/s.

Spring Name	County	Grid Reference (ITM)	Q Mean (l/s)	Q Low (l/s)	Q High (l/s)	Q Ratio (l/s)	Source of Q data
Cong*	Galway	514729 755488, 514161 755444, 514832 765232	17,000	5,000	50,000	10	Drew, pers. comm.
Kinvara*	Galway	537931 710506, 537321 710384	12,000	4000	19,500	5	McCormack, Gill, et al., 2014; McCormack pers. comm.
Mullenmore*	Mayo	514259 816445, 514208 816609	960	790	1,130	1.4	OPW, 6 readings
Rockingham	Roscommon	584949 802892	780	320	5,020	16	EPA (2009–2017) continuous readings
Killeglan/ Tobermore	Roscommon	588651 740551	520	100	2,320	23	EPA (2008–2017) continuous readings
Lettera	Galway	559549 762071	400	80	860	10	Drew, pers. comm., 7 readings by Drew in Daly 1995
Elmvale	Clare	525682 691823	450	450	8000	18	Drew, 1990
Pollifrin*/ Brierfield GWS	Galway	555986 744191	410	30	2,630	87	Moe and Smietanka, 2012 6 readings
Dower	Cork	597930 572996	430	50	1,200	24	Cork C.C. (weekly readings 1979 and 1980)
Tobermore	Galway	532036 759053	300	300	1,000	3	Chance, 2005, 3 readings
Tobernalour/ Kilbenan/ Tonlegee	Galway	541104 754023	310	50	1,470	27	EPA, 40 readings (2007–2017)
Mid-Galway and Barnaderg*	Galway	553902 744810, 554509 745153	310	20	3,620	165	Moe & Smeitanka, 2012 and EPA (2009–2011) continuous readings
Aughmore (Pollacorry Well)	Mayo	549406 784786	290	30	870	26	EPA, 36 readings (2007–2017)
Kedrah	Tipperary	607398 628001	280	140	840	6	EPA, 26 readings (1976–2000)
Swinford	Mayo	538749 797526	240	60	910	15	EPA, 50 readings (2007–2017)
Pollmore	Roscommon	559599 790854	230	140	750	6	Hickey, 2008, 3 readings
Bohola	Mayo	533443 795191	230	70	780	11	EPA, 36 readings (2007–2017)
Drumcliff/ Whitegate	Clare	532859 678961	200	170	270	2	Deakin, 2000, >6 measurements

*Denotes a location with a cluster of springs hence the ratio between high and flow flow) is based on pre-Cong Canal conditions when the entire outflow from Lough Mask sank underground. Three springs have discharges between 500–1000 l/s.

All of the large springs apart from one (Elmvale which drains the south-central Burren), drain lowland karst areas, with more than 80% of the total being located in the western lowlands. There are also 36 springs with known representative discharges of between 100–200 l/s. Again, the majority (64%) are located in the western lowlands and, again, springs draining upland karsts make up only a small proportion of the total (14%). However, the southern and midland karsts have proportionately more springs of this magnitude than of springs with a discharge above 200 l/s (30% as against 10%).

Of the 18 largest springs, those with a discharge exceeding 200 l/s, all but two (89%) are located on Rkc aquifers (conduit dominated flow). Both of the springs located on Rkd aquifers (dif use flow, karstified) are in the south of Ireland at Kedrah in County Tipperary and at Dower in County Cork. For springs with a discharge in the range 100–200 l/s, some 75% are located on Rkc aquifers. All the springs of this magnitude that are located on Rkd aquifers are located in the midlands and southern counties (Cork, Tipperary, Kilkenny, Waterford and Of aly). These distributions are to be expected given that increased karstification of an aquifer implies the evolution of an integrated conduit system focussing underground drainage on a limited number of large spring outlets.

The range of discharge values (ratio between highest and lowest recorded discharge values) at springs is considerable with some springs having less than a five-fold variation in flow, whilst others, in apparently similar environments, show one-hundredfold variations. For the majority of springs, the discharge ratio is greater than ten. A number of springs (including some with large flows) cease to flow altogether in response to a few weeks of dry weather.

Of 43 springs with average discharges of greater than 10 l/s, in County Roscommon, Hickey (2008) found that 70% had discharge ratios of less than 10, 28% had discharge ratios of between 10–30, and only one (2%) had a discharge ratio over 50, the highest being a discharge ratio of 55 (Figure 8.48).

Even within a limited area and with a uniform lithology, groundwater flow systems can vary markedly, as evidenced by spring behaviour. For example, Figure 8.49 shows variations in electrical conductivity at four springs that discharge into the Clashawley River over a 4-km reach of a channel south of Fethard, County Tipperary. Two spring catchments lie to the east of the river and two to the west. During a 50-day period the Mullenbaun spring exhibits flashiness, with a conductivity range of 90 µS/cm, the Kiltartan springs vary by only 20 µS/cm units, whilst the Toberatudar spring shows intermediate characteristics.

In upland areas of limestone and in some lowland areas of limestone, groundwater catchments can be determined with some degree of confidence. For example, in County Roscommon most of the springs with a mean discharge of greater than 10 l/s are located on the periphery of areas (10–150 km^2 in extent) that are elevated some 10–30 m above their surroundings. Such springs have clearly defined catchment areas (see Chapter 10 for more detail).

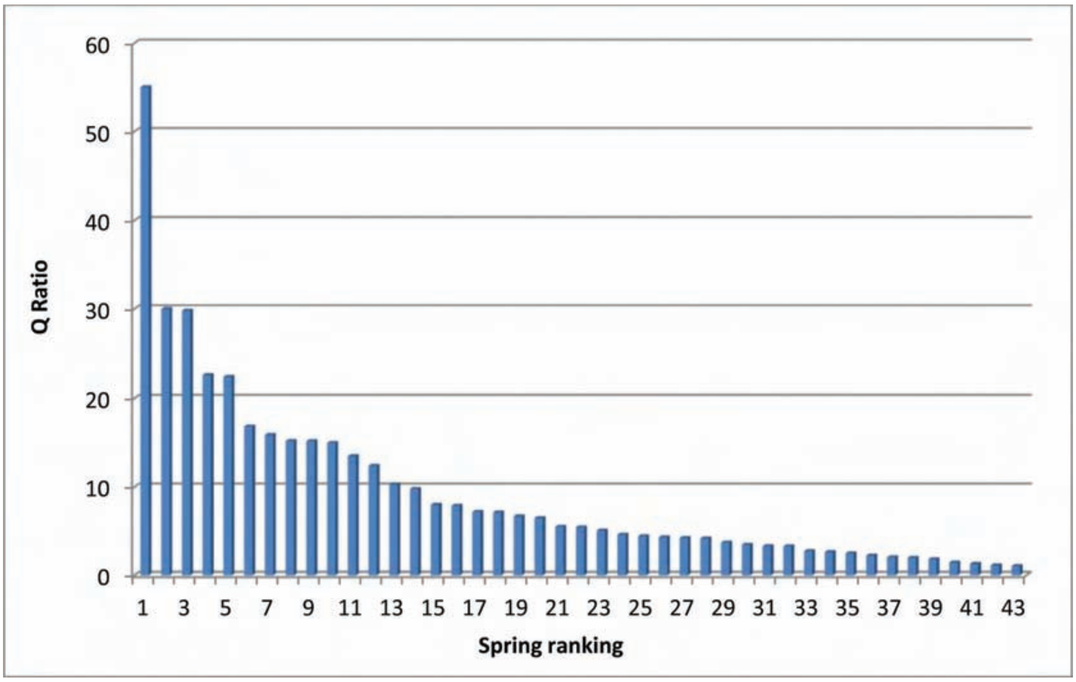


Figure 8.48 Discharge ratios for 43 karst springs in County Roscommon with mean Q >10 l/s. *(After Hickey, 2008.)*

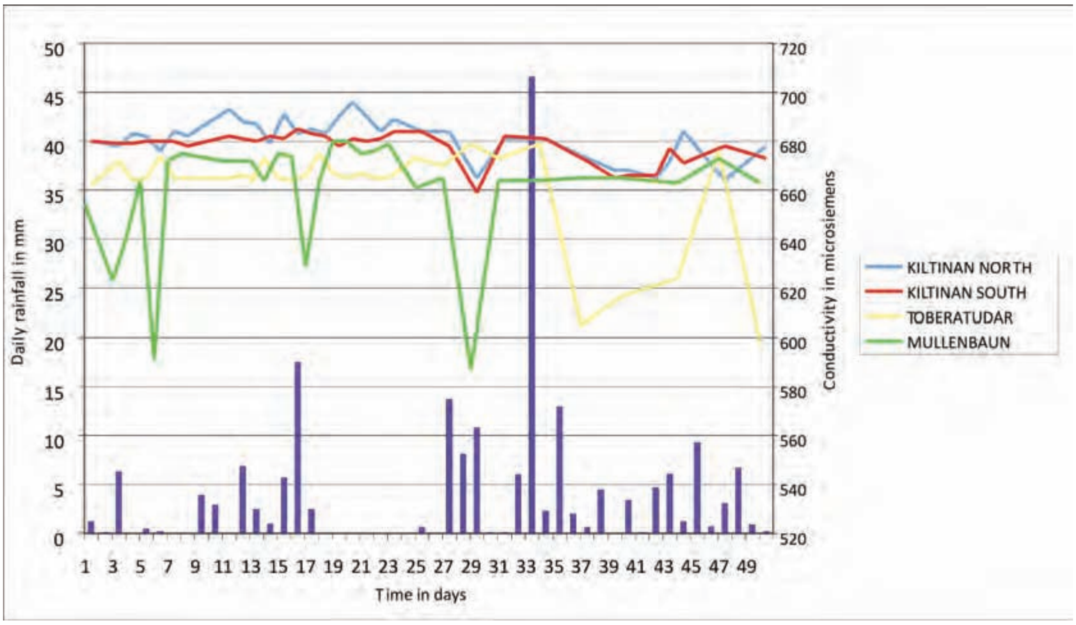


Figure 8.49 Variations in the electrical conductivity at four adjacent springs in the Clashawley valley, County Tipperary over a seven-week period, April–June 2007. Rainfall is shown in purple.

In limestone lowlands with virtually no relief, spring catchments are more dif cult to define. For example, in east Galway a catchment for Caltra Spring (Figure 7.60 and Chapter 9.3.2) could not be delineated with any confidence despite an in-depth study and dye tracing experiments being conducted. All of the dye injected, at eight separate injection sites, was recovered at locations other than Caltra Spring (Moe and Smietanka, 2013).

Figure 8.50 shows possible catchment areas for three adjacent springs near Tuam in northeast County Galway. Although the area required to feed each spring is known, from water balance calculations, the location of that area is less certain as topographic watersheds cannot be defined and piezometric surface maps do not provide the resolution necessary to allow groundwater flow lines to be drawn. Thus, the positions of the catchments shown are somewhat arbitrary. For the Aughclogeen spring, the situation is further complicated by the fact that some water from a river sinks well outside the designated catchment area and feeds the spring. Thus the whole surface catchment of the river upstream of the sink must be regarded as a part of the spring catchment.

A larger-scale version of this scenario occurs in northwest County Mayo where part of the flow of the River Deel sinks over a 2 km reach of channel. The water resurges at a large spring to the east and, therefore, the catchment of the Deel upstream of the sinks, more than

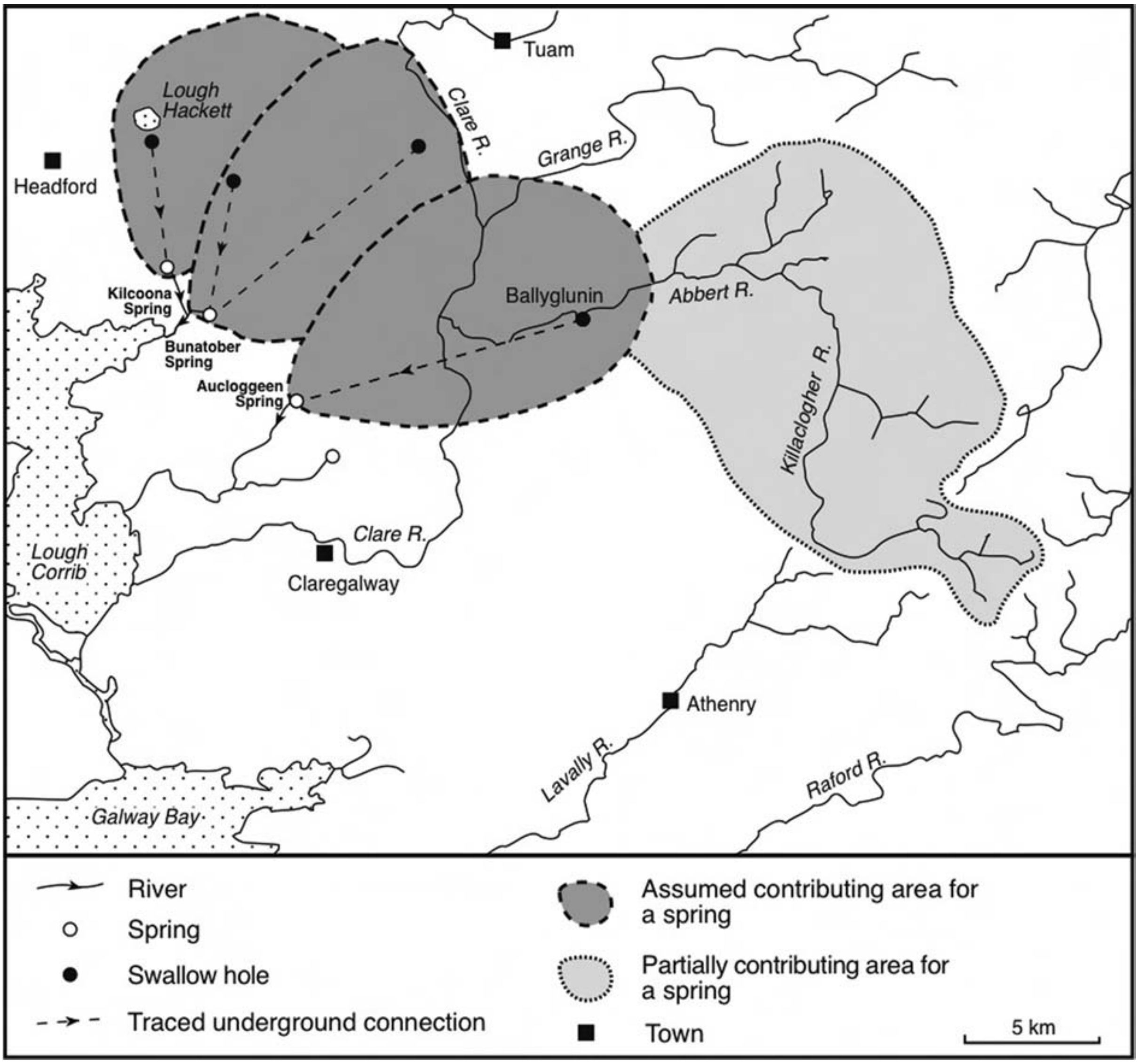


Figure 8.50 Assumed zones of contribution to three adjacent springs in east County Galway. *(Adapted from Drew and Daly, 1993.)*

150 km², is a partial contributing area to the spring whereas the 'conventional' groundwater catchment is probably only 25% or less of this area.

Groundwater discharge direct to intertidal or submarine springs is known to be important along the coast of the Burren and the eastern and southern shores of Galway Bay (Sections 7.5 and 7.6) and probably takes place wherever karstified limestone aquifers outcrop along the coastline.

The location of known major springs in the littoral zone of south and east Galway Bay is shown in Figure 8.51. The springs are located at the inland end of funnel shaped bays that have been formed by spring recession inland. This is accentuated by enhanced solution of the limestone bedrock where the freshwater and seawater meet, a phenomenon known from other coastal karst areas such as Mallorca and the Yucatan peninsula.

Such discharges also occur into lake waters and have been identified by temperature, conductivity and radon anomalies in the lakes. Figures 8.52 and 8.53 show such anomalies in Lough Mask, County Mayo and in Lough Owel, County Westmeath respectively. In the case of Lough Owel, the groundwater inflow seems to be related to a known surface (overflow?) spring. The actual discharges are uncertain but, in the case of Lough Mask at least, are likely to be considerable.

Figure 8.51 Major springs (blue circles) in the littoral zone around the southern and eastern shores of Galway Bay. (A) Ballyvaughan; (B) Bell Harbour; (C) Corranroo; (D) Kinvara; (E) Clarinbridge; (F) Kilcolgan.

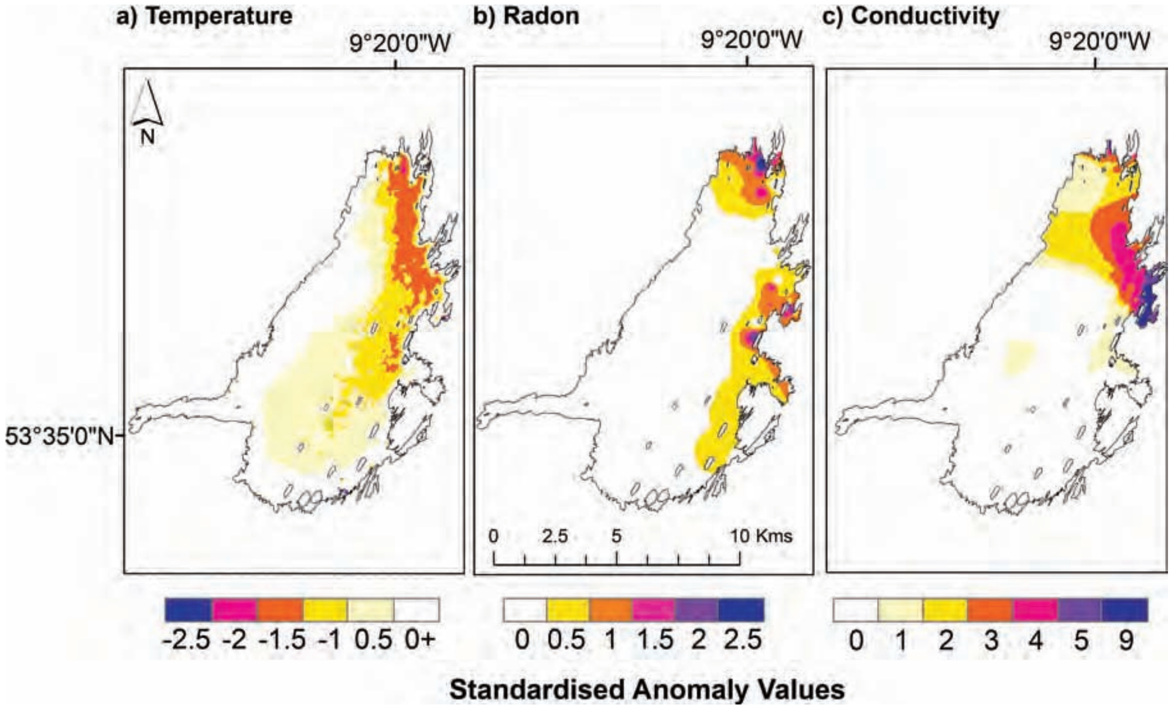


Figure 8.52 Temperature, radon and conductivity concentrations in Lough Mask, County Mayo, July 2012. *(From Wilson and Rocha, 2016.)*. High values of radon and conductivity and low temperatures correspond to areas of groundwater inflows.

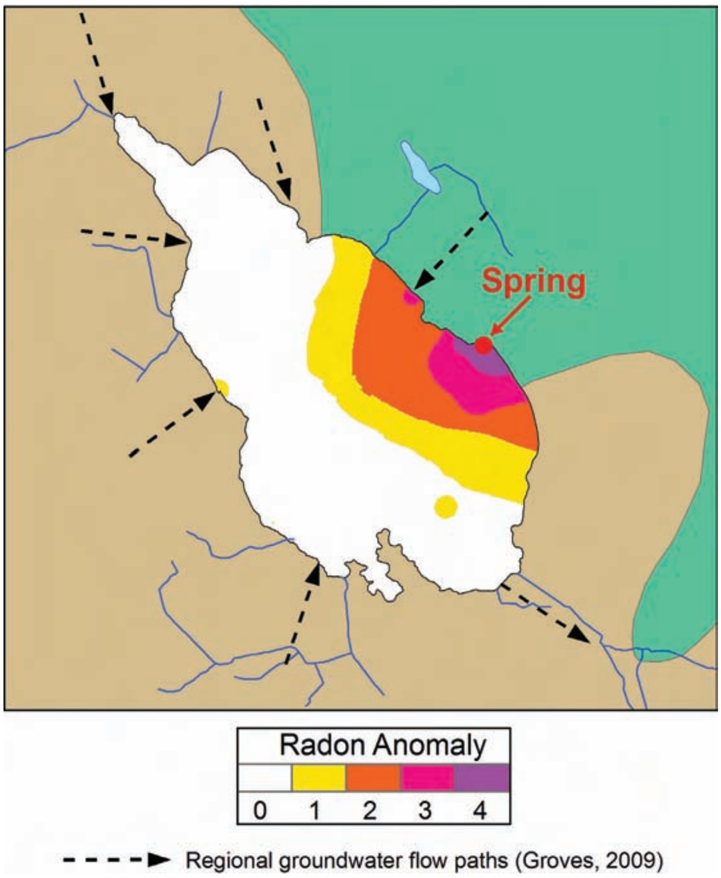


Figure 8.53 Radon anomaly values, springs and groundwater flow paths Lough Owel, County Westmeath. *(From Wilson 2016.)*. The bedrock is limestone; green shading indicates limestones presumed to be significantly karstified.

8.6 Groundwater Level Changes

Groundwater level fluctuations are a function of rainfall and recharge patterns, subsoils and the nature of the aquifer. However, the peculiarities of the limestone aquifers (low storage and high but spatially extremely variable permeability) are reflected in well hydrographs. The water table in the unconfined lowland aquifers is usually less than 10 m bgl with annual fluctuations of less than 5 m. In the plateau limestones with relief of up to 600 m, the saturated zone may be several hundred metres below ground level and seasonal variations in the water table can exceed 30 m. Figure 8.54 shows the response of groundwater to precipitation in three aquifers over a 6-year period. The muted response of the moderate porosity Kiltorcan sandstone aquifer (2 m fluctuation) contrasts with the karstified Waulsortian and Ballyadams limestones that have water level changes of 6 m and 11 m respectively over the same period. However, all three show multiple annual peaks and are all fissure-flow aquifers, though with solutionally opened fissures in the case of the

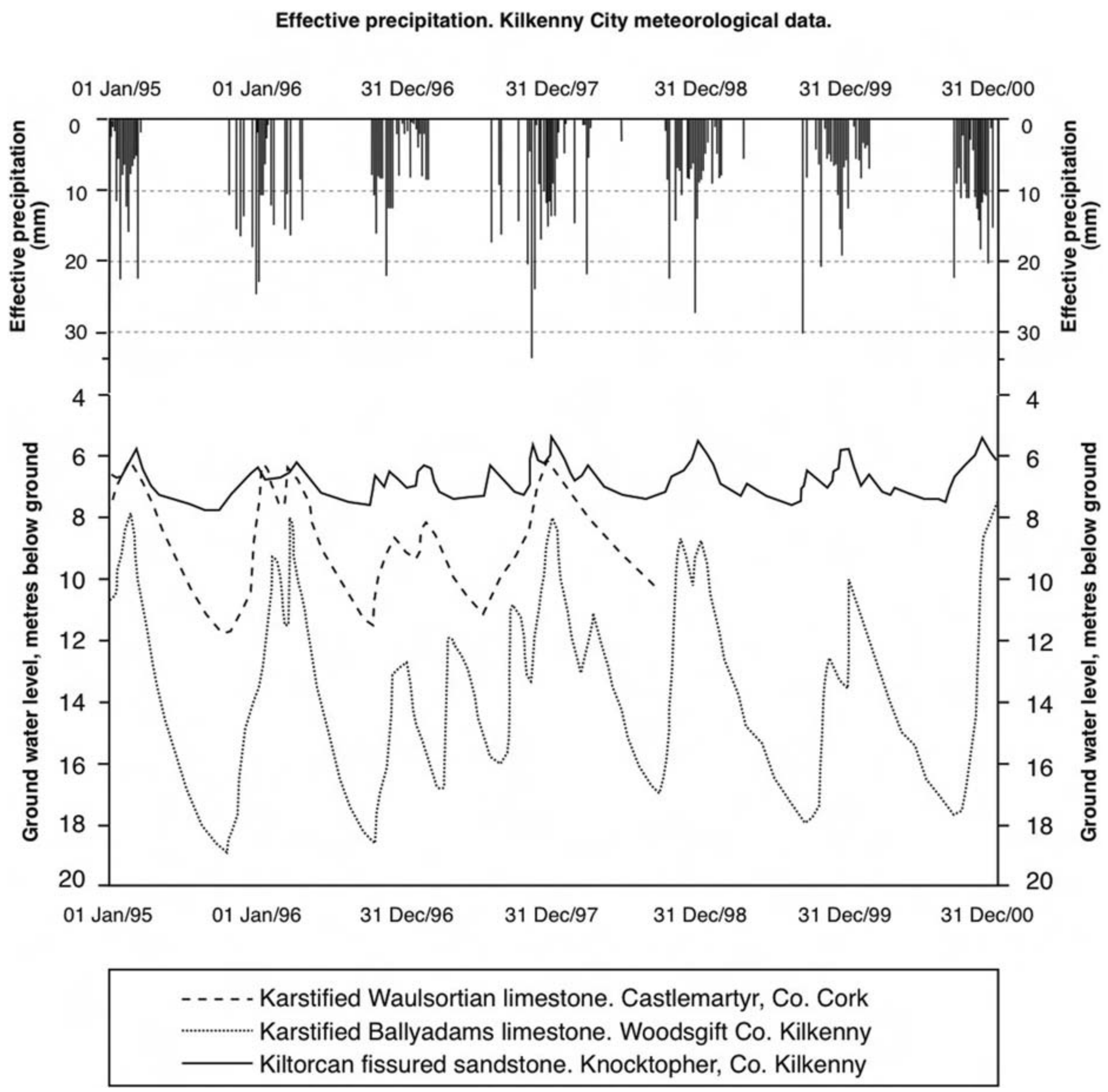


Figure 8.54 Well hydrographs in karstified Waulsortian limestone, karstified Ballyadams limestone and Kiltorcan fissured sandstone. *(From Fitzsimons and Misstear, 2006.)*

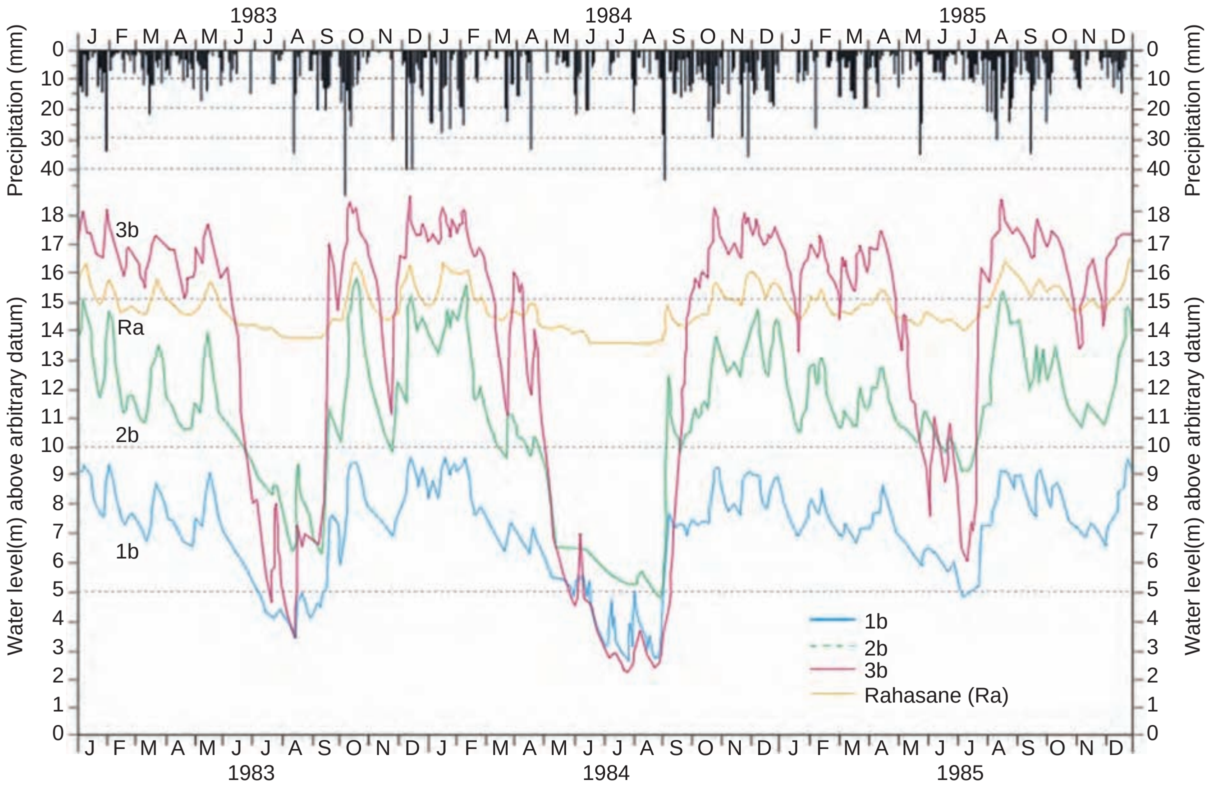


Figure 8.55 Water level variations and rainfall over a three-year period in 3 boreholes (1b, 2b, 3b) and Rahasane Turlough, Dunkellin–Lavally catchments, located in a 2 km^2 area on pure Carboniferous limestone (County Galway). *(After Drew and Daly, 1993.)*

limestones. There are variations in the overlying subsoils in these locations and this may have an ef ect on the pattern of groundwater level fluctuation.

Figure 8.55 shows water level variations for three boreholes and a turlough, all located within a 2 km^2 area with similar subsoil and recharge characteristics. Although the water level in all three boreholes responds rapidly to rainfall events, there are large dif erences in their recession response and therefore, specific yields (or storage). There are also considerable dif erences in the magnitude of groundwater level variation, with borehole 3b having the greatest fluctuation (17 m) and borehole 1b having the least (approximately 6 m). This variability is thought to be due to dif erences in proximity to the nearby surface river channel and some more local subsoil dif erences.

Figure 8.56 shows annual groundwater regimes in a limestone aquifer within the River Barrow catchment. The three boreholes in the upper catchment (A) show very dif erent responses, with 5–17 m of annual oscillation, with two or three annual peaks in some years, suggesting a rapid response to recharge events. In the lower Barrow catchment (B) water levels are controlled by the river and annual change in water levels are only 0.1 m and 0.8 m in the two boreholes.

Tedd et al. (2011) looked at groundwater levels in the southeast of Ireland and the significance of their location within a catchment. For example, three hydrographs located in the Rkd karstified Ballyadams Formation of the Nuenna catchment were examined. Even though the three boreholes were located within 1.5 km of each other, their annual fluctuations and

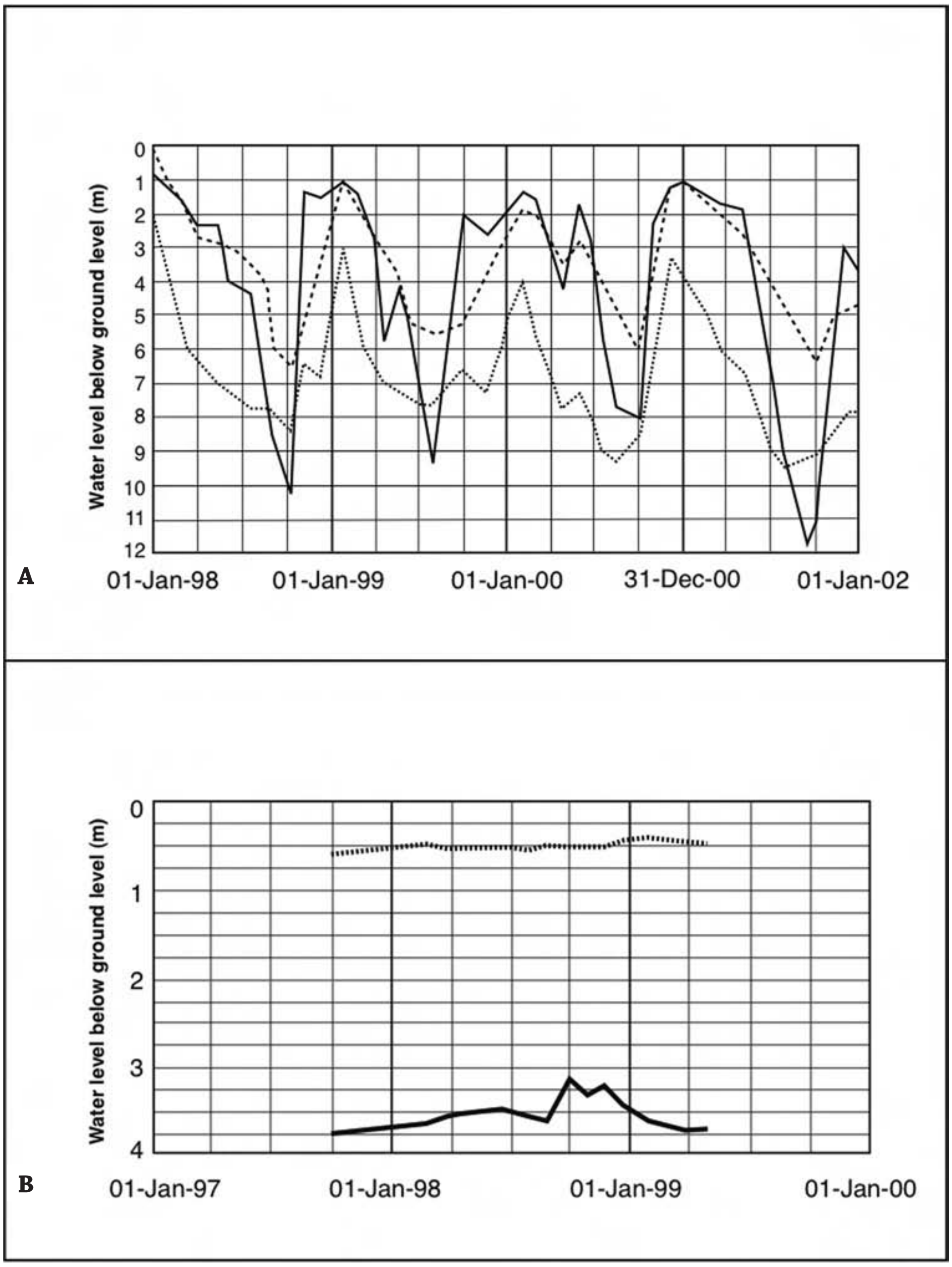


Figure 8.56 Well hydrographs 1998–1999 and 1998–2002 in a limestone aquifer, River Barrow catchment (County Kildare): (A) recharge area (B) discharge area. *(After Geological Survey Ireland, 2017.)*

response to rainfall varied greatly. One borehole had a large annual variation, averaging 15 m, another had an average annual variation of 8 m and the last had a groundwater level variation averaging 3 m annually. The borehole with the largest variation is located at the top of the catchment in the groundwater recharge area, the borehole with medium variation is located in the middle of the catchment and the borehole with the smallest variation is located close to the Nuenna River and adjacent springs in a groundwater discharge area. The dif erences between these closely located hydrographs demonstrates the complexities of karstified limestones, even within a relatively small area.

Figure 8.57 shows dif ering borehole responses to recharge from four boreholes located within a 6 km^2 area of pure limestone near Cregduf Spring at Ballinrobe, County Mayo.

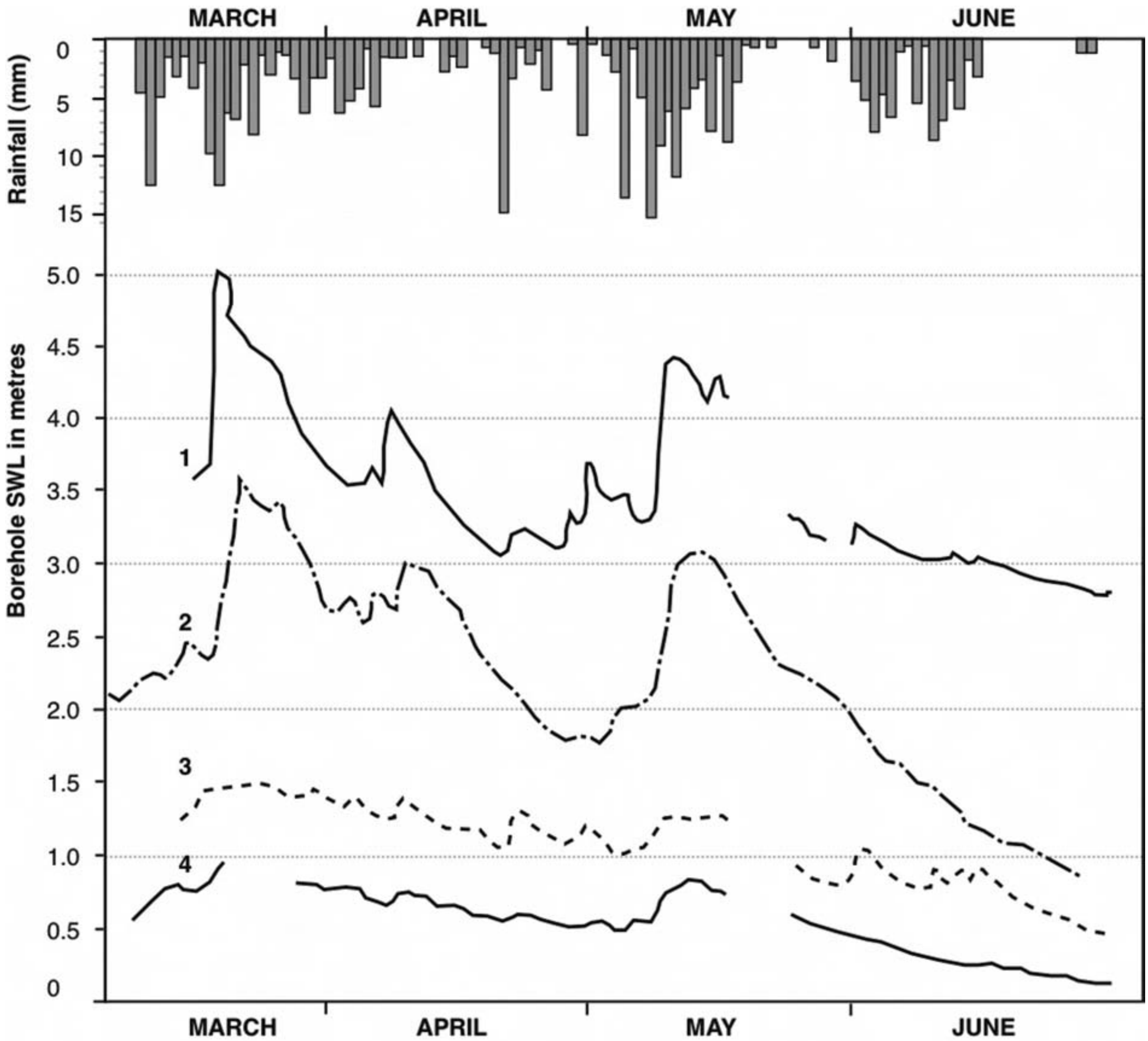


Figure 8.57 Well hydrographs (boreholes 1–4) March–June 1983, karstified limestone aquifer, Ballinrobe area (County Mayo). *(After Coxon and Drew, 1986.)*

Over a three-month period, responses to rain vary considerably. Borehole 1 has a specific capacity of greater than 240 m^3/m/d whilst borehole 3 has a specific capacity of less than 1 m^3/m/d. It is presumed that the greater fluctuation in water level corresponds to a locally higher permeability associated with a well-developed fissure/conduit system, which allows the rapid movement of recharging groundwater through the aquifer.

The locally extremely high permeabilities present in some limestones are reflected in groundwater oscillations in response to marine tides, even in parts of the aquifer distant from the sea. This ef ect is due to backing up of freshwater as the elevated marine saltwater head restricts the discharge of freshwater in the inter-tidal zone. This ef ect is particularly marked in the aquifer on the south and east sides of Galway Bay.

Figure 8.58 shows hydrographs for five boreholes in Bell Harbour, north of the Burren in County Clare, and the tidal sea levels from Galway Bay. The amplitude of the tidal ef ect varies from 0.04 m for B-59, located 2.4 km inland, to 1.4 m at B-05, located 220 m from the

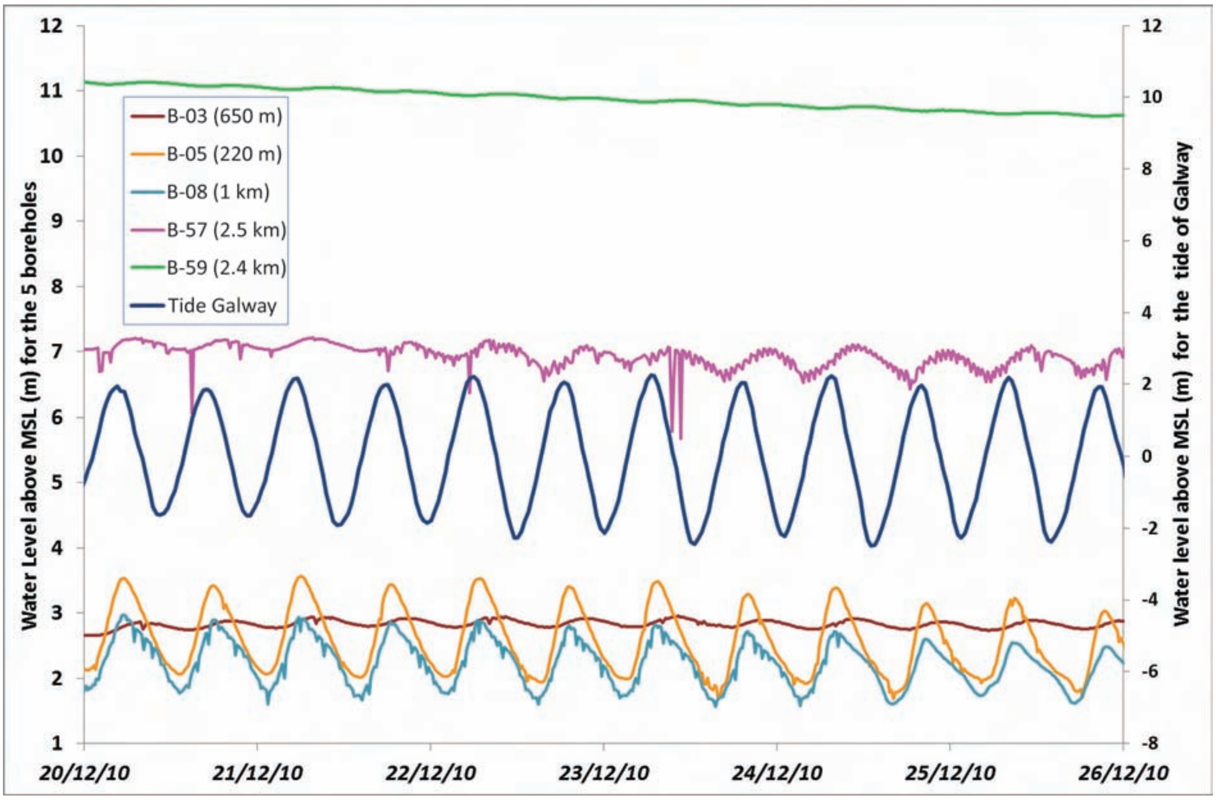


Figure 8.58 Tidally-influenced groundwater level oscillations, Bell Harbour catchment (County Clare). The distance from the boreholes to the coast is marked in brackets in the legend. *(Modified from Perriquet and Henry, 2011.)*

coast, and the lag time is from 1 hour to 5.5 hours, depending on distance. However, it can be seen that borehole B-03 shows a much lower level of oscillation than the nearby boreholes (B-05 and B-08) and lower fluctuations than borehole B-57, which is located further inland. Borehole B-03 is thought to be drilled into the slower-responding small fracture flow system, from evidence provided by limited water level response to rainfall events and high drawdown in response to pumping. All the other boreholes respond rapidly to rainfall events and have groundwater level fluctuations of approximately 10 m (Perriquet and Henry, 2011).

8.7 Groundwater–Surface Water Interactions

8.7.1 Introduction

Over much of the lowland limestones, a surface drainage network of rivers and lakes co-exists with well-developed karstic groundwater systems. In the areas west of the River Shannon much of the surface drainage network is artificial and comprises drainage of turloughs and the construction of 'rivers' where none existed beforehand. The River Clare and the Lavally River, both in County Galway, are examples, as is the River Fergus between Corofin and Ennis (Chapter 7.5). Exchange of water between the fluvial and the aquifer flow systems is both common and complex (Figure 8.37). The fact that the water table is close to the surface for all or most of the year, over most of the lowlands, means that comparatively small changes in head between surface and groundwater bodies can reverse flow directions over short time periods.

Lakes which empty via swallow holes rather than a surface outflow occur in County Galway (Lough Hackett), County Offaly (Pallas Lake), County Limerick (Lough Gur) and many other locations. There are lakes which fill via springs and empty via swallow holes, such as Lough Lene in County Westmeath, and lakes which are apparently permanent water bodies but which periodically disappear underground in a short space of time, for example Lough Funshinagh in County Roscommon (Chapter 7.5) and Lough Nasool in County Sligo (Chapter 7.2).

Although the karst hydrogeology of the western lowlands is not unique in global terms, the sheer complexity and temporal variability of the interactions between the fluvial, lacustrine and groundwater systems make this area one of the world's more remarkable karsts.

8.7.2 Turlough Hydrology

It is likely that many of these groundwater-surface water interactions, particularly in the lowland karsts are, in part, due to the blocking and diversion of surface and underground flow routes by glacial and fluvio-glacial deposits. This is also true of perhaps the most striking and distinctive of the karst landforms associated with surface-groundwater transfers in Ireland, the seasonal bodies of water called turloughs (dry lakes or 'turlach' — dried up places). More than 400 turloughs are recorded in Ireland (Figure 8.59) of which the majority have been drained or modified since the mid nineteenth century.

The size, depth, flooding period and hydrological functioning of turloughs varies, but all are located on limestone, most are located on the purer limestone west of the River Shannon and all of them appear to function karstically, at least in part. In hydrological terms, turloughs may be bedrock hollows which simply intersect the seasonal water table, such as Tullaghnafrankagh Lough; lacustrine swallow holes, for example Rahasane and Blackrock turloughs; hollows which store surplus water forced to the surface from karst conduits (surge tanks), for example Garryland turlough; or hollows in bedrock which intercept shallow, epikarst groundwater flow, for example Lough Aleenaun (Figure 8.61). All of these examples, with the exception of Lough Aleenaun in the Burren, are located within a small area of south County Galway. Turloughs may fill and empty via separate springs and sinks, via a single opening (estavelle), or via distributed solutionally enlarged conduits. They may be associated with a major karst conduit or located in an area of relatively low permeability limestone. The conceptual turlough types are shown in Figure 8.60.

Figure 8.62 shows the changes in water level in response to rainfall for three turloughs in the western lowlands over a 34 month period. Turloughmore exhibits a flashy regime with rapid rises and falls in water level in response to wet and dry periods (multimodal flooding) and corresponds to turlough type (A) in Figure 8.60. Coolcam responds more slowly to winter rains, exhibits few water level fluctuations during the flooded period and has a longer drawn-out recession curve than Turloughmore (unimodal flooding). It probably belongs to the surcharge tank type of turlough (type C in Figure 8.60). Skealoghan turlough water level fluctuations are intermediate in character, between the two extreme hydrogeological types, and this is probably typical of most turloughs. Full descriptions of turlough hydrogeology and morphology are given by Coxon (1987) and by Naughton et al. (2012, 2017).

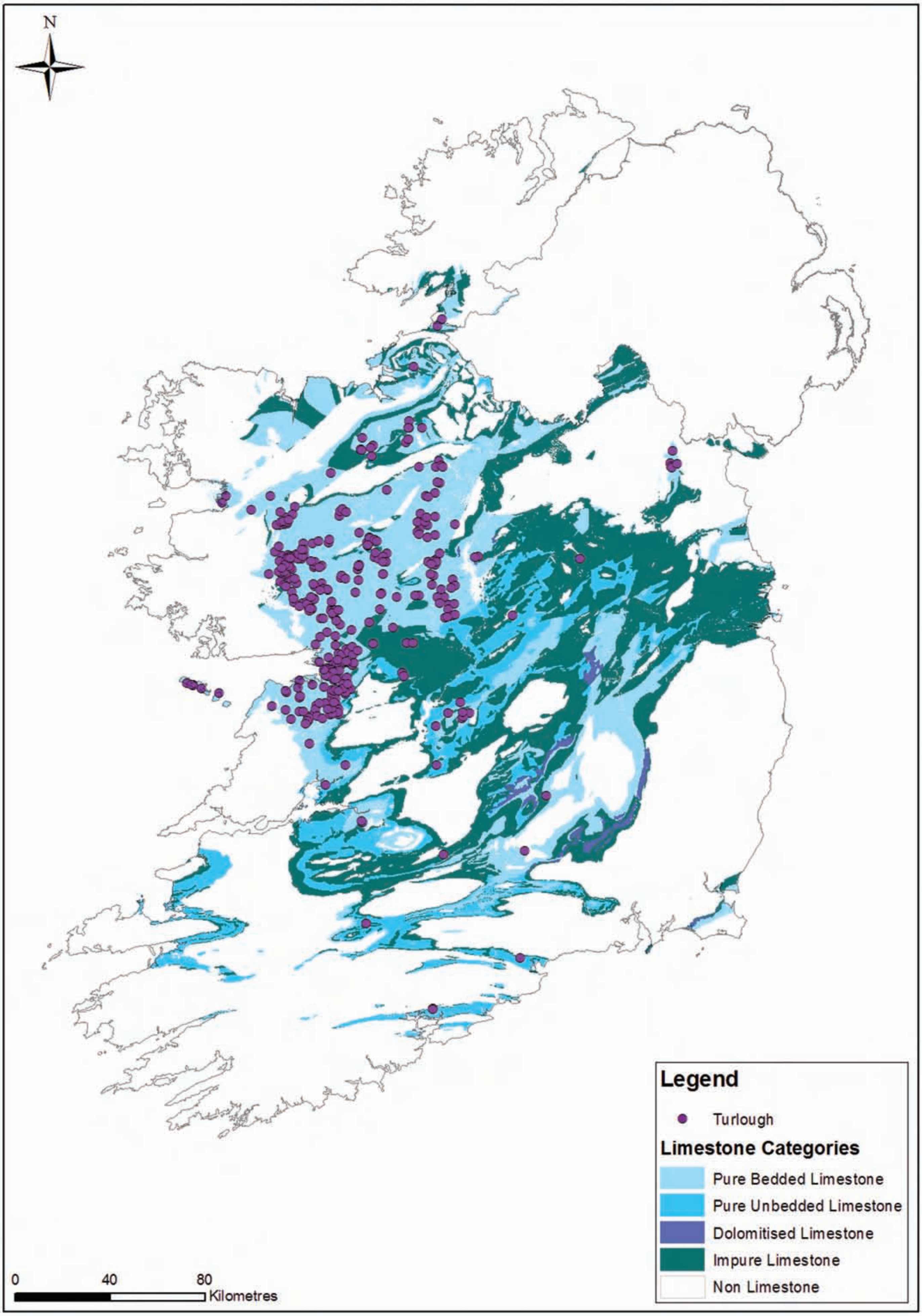


Figure 8.59 The distribution of turloughs in Ireland. *(Data adapted from GSI.)*

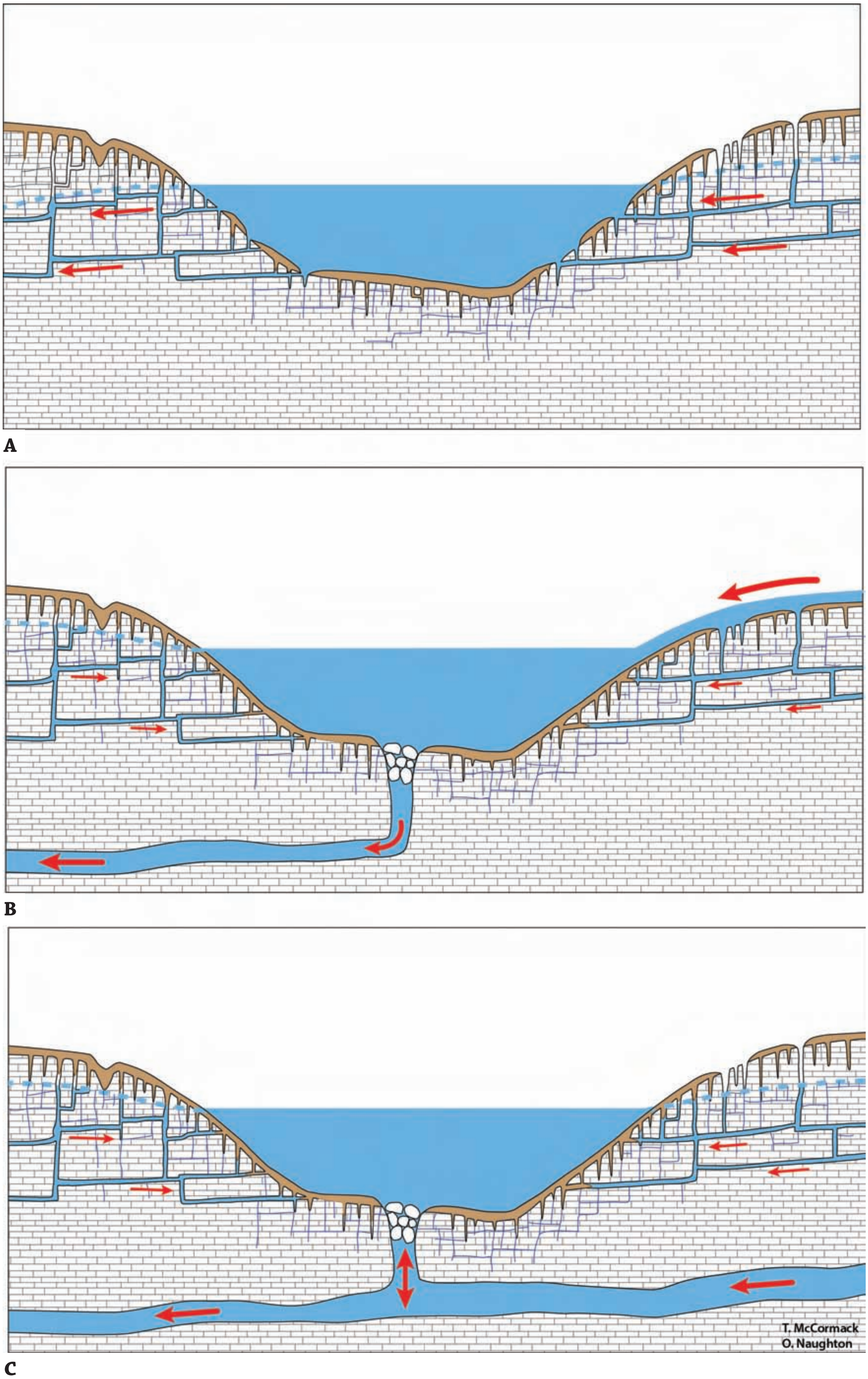


Figure 8.60 Conceptual turlough types. (A) Distributed through-flow. (B) Through-flow with distributed/point recharge and point discharge and (C) surcharge tanks. *(From Naughton et al., 2017.)*

Figure 8.61 Lough Aleenanun, a small turlough in the southern Burren which empties and fills many times annually: (A) The turlough when full, (B) Lough Aleenaun when empty. It is fed by two springs which emerge at the base of the clif and the water then sinks at numerous points on the near side of the hollow. *(Photographs by David Drew)*

Turlough eco-hydrology

As groundwater emerging from karst can be relatively rich in its solutional load, its interaction with the surface environment can create characteristic vegetation and faunal communities. Hence, turloughs are recognised wetland habitats in karst and, as temporary lakes, have distinctive hydro-ecologies involving plant, invertebrate and bird communities.

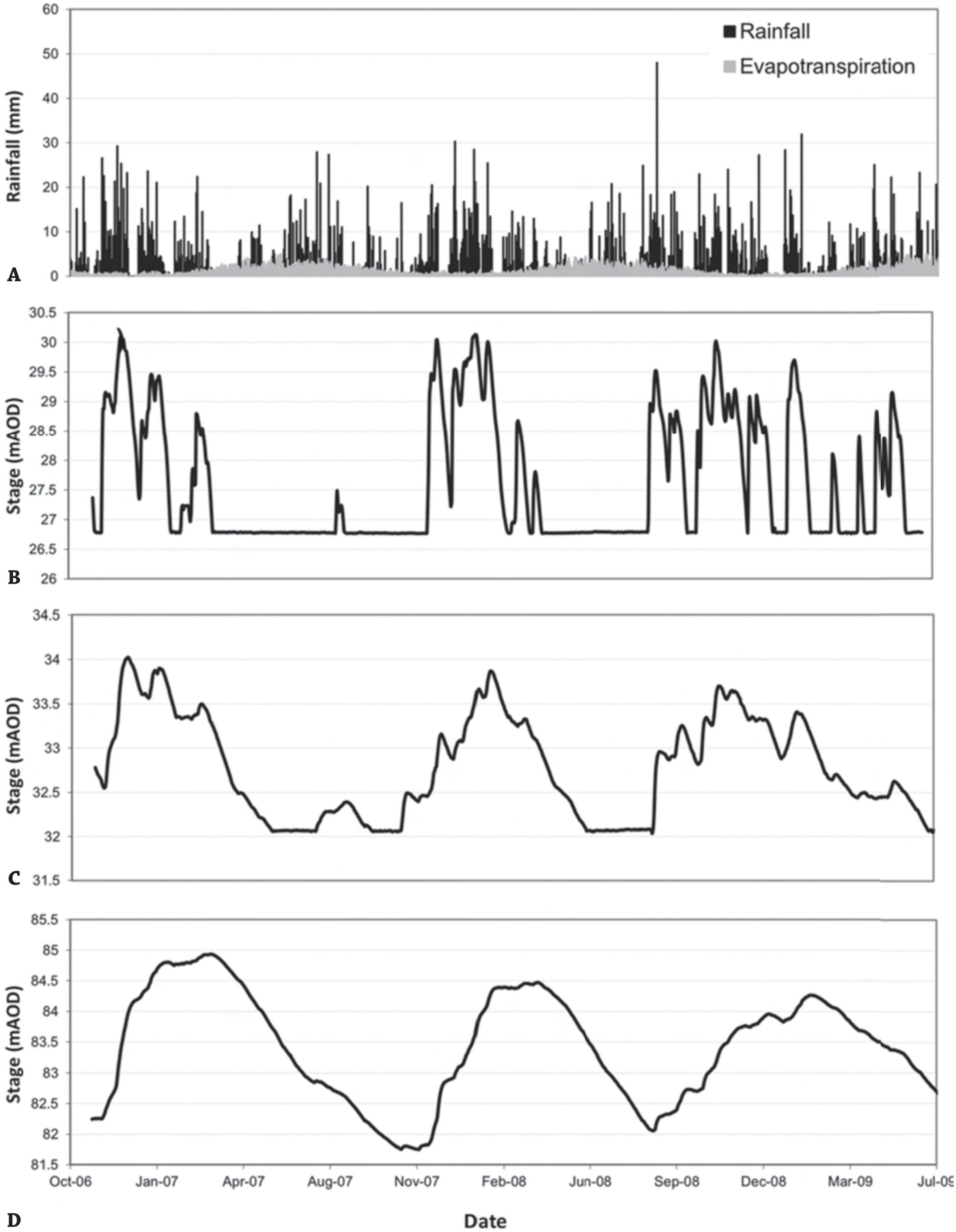


Figure 8.62 Water level changes in three turloughs in relation to precipitation October 2006–July 2009. (B) Turloughmore, County Galway. (C) Skealoghan, County Mayo. (D) Coolcam, County Roscommon. *(Adapted from Naughton et al., 2012.)*

Many turloughs in Ireland are protected under EU Habitats Directive (92/43/EEC) and are designated as Special Areas of Conservation (SACs).

A key hydrogeological control on the ecology is the duration and frequency of inundation from the surrounding karst. Dif erent species communities often exhibit concentric zonation about an estavelle or a swallow hole. For example, the readily recognized black moss *(Cinclidotus fontaniloides)* typically seen on stone walls in the base of turloughs, is correlated with an estimated duration of immersion corresponding to 60% of the year as illustrated in Figure 8.63. Uncommon in karsts elsewhere, turloughs, with their singular karstic hydro-ecology are perhaps the most distinctive and internationally significant karst features found in Ireland.

Figure 8.63 The presence of black moss (*Cinclidotus fontinaloides*) exposed on the rocks at the base of this turlough (Blackrock, south Galway) signifies regular immersion for approximately 60% of the year. *(Photograph by Paul Johnston.)*

Chapter 9

METHODS IN KARST INVESTIGATION

9.1 Introduction

This chapter gives an overview of the methods and techniques that are appropriate for investigating karst groundwater systems. The methods are a subset of the full range used in 'conventional' groundwater investigations, some of which are suitable for karstified aquifers, others which are less so, and some which are mostly only used in investigations of karst groundwater. Those methods which have thus far proved most useful in karst hydrogeological investigations in Ireland are emphasised.

Only an outline is given of most of the methods, with key references to more detailed descriptions being given in the bibliography and examples of their application are presented in Chapter 10.

Traditionally there have been two distinct approaches to investigating karst groundwater systems:

1. Attempting to use and adapt the methodology of 'standard' groundwater investigations by, for example, collecting data from boreholes on water levels and fluctuations, analysing the results of borehole pumping tests, assuming near-Darcian flow systems and modelling groundwater behaviour accordingly.
2. Adopting a speleological/geomorphological approach in which the karst groundwater system is viewed as essentially a sub-surface, three-dimensional, fluvial drainage system. Data from spring flows, from water tracings and from direct exploration of accessible conduits have been regarded as being of primary importance.

In recent years the two approaches have converged, and mathematical models have been developed that explicitly recognise the singularity of karst aquifers, whilst some traditional methods have developed karst-specific approaches – for example the use of geophysics to locate voids and conduit systems.

However, karst groundwater systems still present hydrogeologists with particular problems, both scientific and economic. Increased karstification commonly means increased uncertainty in groundwater resource assessment:

- Often, inadequate data are available as to the character of the karst drainage system in a particular area – the size, location and interconnectedness of fissures and conduits for example – and this limits the quality of the data used in modelling.
- There are universal laws controlling karstification but there is nearly always also a degree of site specificity.
- Therefore, investigations of karst aquifers commonly require a disproportionate input in terms of time and resources in order to achieve a useful output.

9.1.1 The Need for Karst-Specific Methods

Methods commonly used to investigate non-karst aquifers usually assume flow is laminar and dif use. As discussed in Chapter 8.4, flow velocities found in conduits in Irish karst aquifers average 3 km per day (Hickey, 2013) and, therefore, calculations based on Darcy's law are inappropriate and can yield misleading results. Conduits can often be located in massive unproductive rock, making the siting of a successful well dif cult. This extreme spatial and hydraulic heterogeneity often makes it dif cult to draw meaningful potentiometric maps, and hence, estimate flow directions. Figure 9.1 shows the dif erence between inferred groundwater flow lines based on potentiometric maps and proven underground connections from dye tracing experiments. Tracer connections are shown by straight lines, which is unlikely to represent reality.

Effects of scale

Another consequence of the heterogeneity of karst aquifers is that normal well tests, such as pumping tests and downhole geophysics, will not reveal anything about the main groundwater flow pathways unless the wells used penetrate the main conduits in any given aquifer – which is rare. This gives rise to a scale ef ect, where the hydrogeologists must consider both the high hydraulic conductivity pathways and the lower conductivity host rock and smaller fractures. This dual (or sometime triple) permeability can be seen in hydrograph recession analysis, with dif ering slopes of recession limbs representing the dif erent flow systems present in the karst aquifer (Figure 9.19).

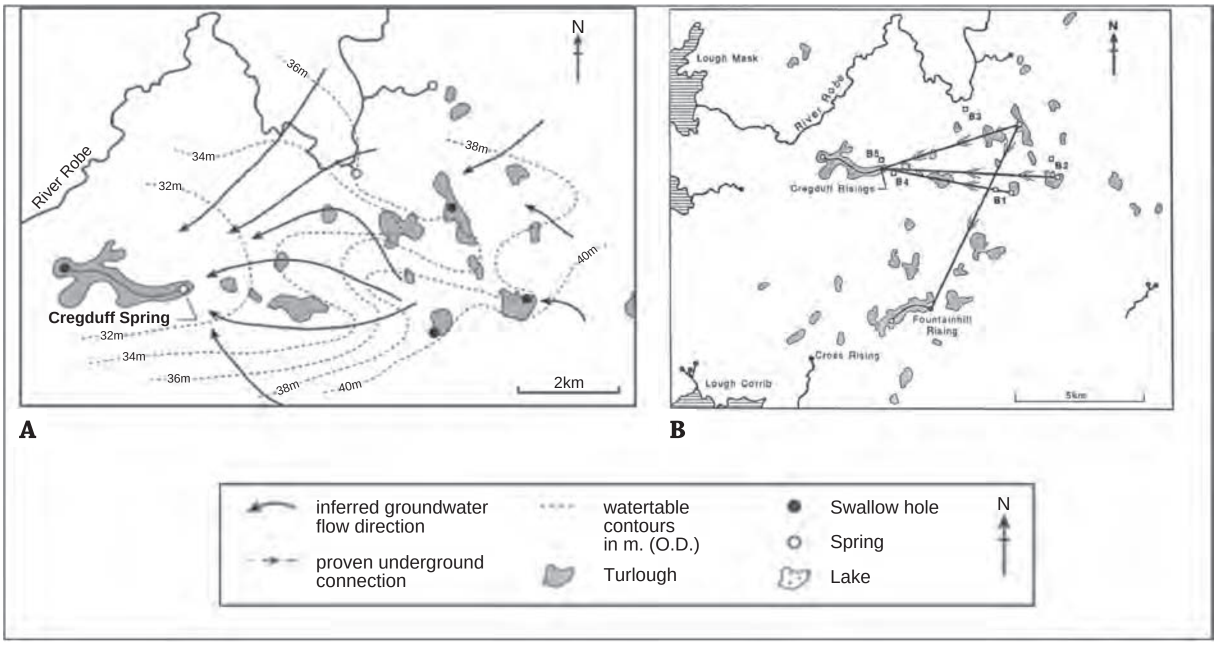


Figure 9.1 Cregduf spring catchment (County Mayo). (A) Groundwater flow inferred from a water table map and (B) Groundwater flow inferred from water tracing. *(Modified after Drew and Daly, 1993.)*

The hierarchical, integrated nature of the groundwater flow system means that representative elemental volumes (REV) dimensions of several cubic kilometres are often necessary (catchment/regional level) if the drainage system is to be conceptualised correctly (Figure 9.1). The REV is considered to be the smallest volume over which a measurement can be made that will yield a value that is representative of the whole. Figure 9.2 illustrates how the REV changes according to the scale and purpose of the investigation. The REV for a homogeneous, isotropic aquifer may be orders of magnitude smaller than that required for a karstif ed, conduit dominated aquifer.

Temporal variations in karst aquifers

Temporal variations are often very signif cant in karst aquifers. This is because of the rapid response to precipitation events that characterise karst aquifers (Chapter 8).

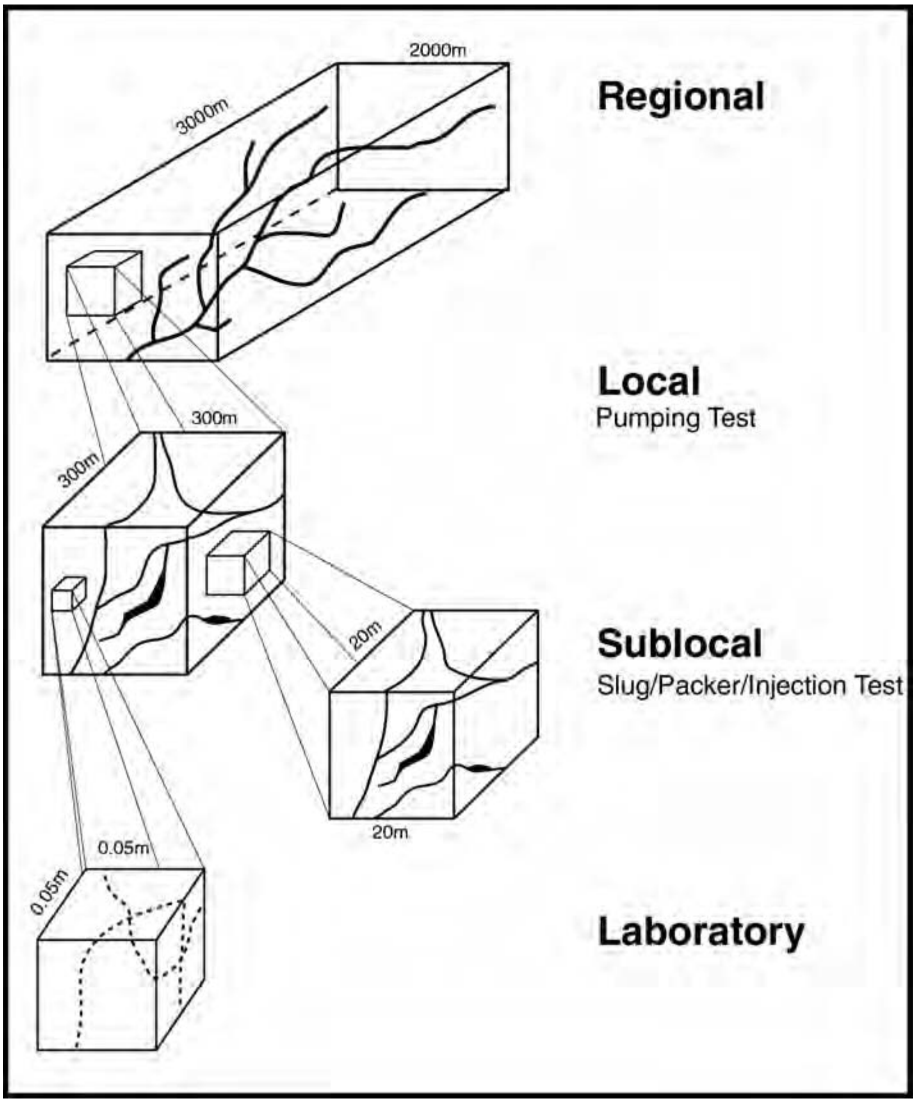


Figure 9.2 Scale dependency of carbonate aquifer permeability. Major conduits are shown as bold lines. *(From Sauter, 1992.)*

A key characteristic of karst springs is their variability of flow depending on stage conditions. Karst spring discharges in Ireland can vary over several orders of magnitude, in a matter of hours (Hickey, 2008; Chance, 2005). Similarly, there is often a large temporal variation in spring hydrochemistry. Many karst springs show a rapid deterioration in water quality, following a storm event (Figure 9.19). Consequently, single-point measurements or even uniform sampling intervals are not always appropriate and event-based sampling is more insightful (Figure 9.3). Figure 9.3 shows a chemograph of turbidity for Corracreigh Spring, in County Roscommon. The graph of continuous turbidity monitoring shows rapid responses in turbidity levels in response to rainfall events. However, spot measurements are generally not coincident with these spikes and they would be missed from spot reading alone. Therefore, to conduct any meaningful study of karst springs and, therefore, aquifer properties long-term hydrographs and chemographs are needed.

9.1.2 Summary of Investigative Methods

Table 9.1 gives a critical evaluation of the most widely used methods for investigating karst groundwater systems. The information that can be obtained and the disadvantages and limitations involved in the use of each method are also summarised. More information on those methods or groups of methods that are most useful in karst is given in the remainder of this chapter.

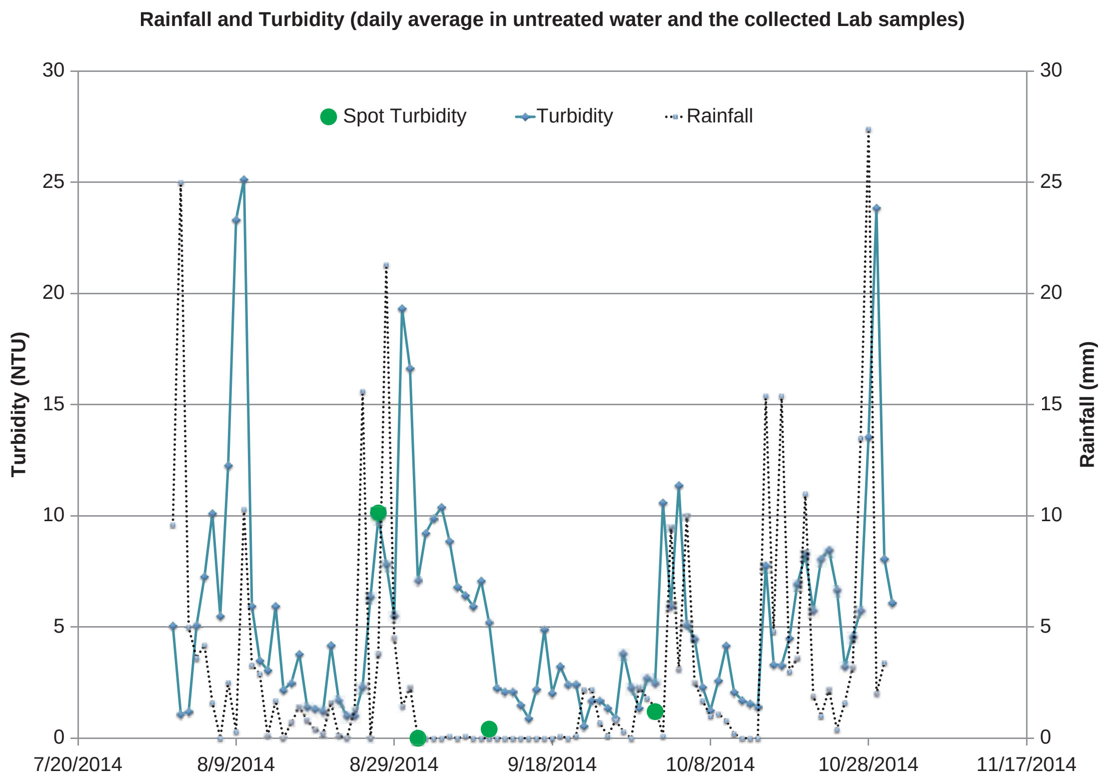


Figure 9.3 Continuous measurements of turbidity versus spot measurements for Corracreigh Spring (County Roscommon). *(Modified after Kelly et al., 2015.)*

Table 9.1 Summary and critical evaluation of methods used in investigations of karstic aquifers

Methods	Data Obtained and Advantages	Limitations and Disadvantages
Geological	• Karstifiability of the rock • Aquifer framework and geometry • Location, type, orientation and frequency of potential flow paths	• Often not a predictable and unambiguous relationship between geology and groundwater
Geomorphological	• Determining degree of karstification • Determining location of karstification • Determining types of recharge and discharge • Determining the historical geomorphology of the area	• Data are often obtained indirectly (from the surface) • Static framework rather than the dynamics of the aquifer • Limited data from covered karsts
Speleological	• Locating and mapping conduits in 3D • Directly monitoring water quantity, quality and locations in an aquifer • Access for intra-aquifer water tracing • Studying the temporal evolution of the conduit systems (aquifer K)	• Only a small and possibly unrepresentative part of the aquifer is accessible • Access to caves may not be possible • Specialist skills required
Hydraulic	• Determining T, K, storage (S) and piezometric levels • Determining groundwater flow direction and velocity (V)	• Many orthodox methods are not appropriate to determine T, S and V in karst aquifers • Pumping tests may not be representative of the wider aquifer, particularly in Rkc aquifers
Hydrochemical	• Hydrochemical characterisation of the groundwater and potential sources of contamination • Use as natural tracers for origin and movement of groundwater	• Difficult to maintain adequate sampling frequency
Hydrological	• Water budget compilation for spring catchments	• Spring catchment boundaries are often not clearly defined
Water tracing	• Determining flow routes and velocities • Delineating spring catchments • Usually yields reliable, precise, unambiguous data	• Difficulties in recognising 'negative' traces • Possible toxicity/visibility problems • Commonly, point-recharge inputs are used so almost no data on diffuse flow is available
Isotopic	• Use as natural tracers • Identifying sources of groundwater and mixing processes	• Requires specialist expertise and equipment • Ambiguities possible in interpreting the data
Geophysical	• Locating fractures, conduits and other preferential flow paths • Data can be obtained over a wide area • Remote data obtainable at relatively low cost	• Difficulty in obtaining high resolution data from depth • Requires specialist expertise and equipment • Ambiguities possible in interpreting the data
Modelling	• Conceptualising all or a part of the aquifer • Understanding of interactions within the aquifer e.g. conduit-fissure-matrix • Simulating groundwater (and contaminant) flow and transport	• Exacting data requirements for holistic modelling • Requires adaptations of conventional Darcian flow models • Very large data requirements to produce meaningful results

9.2 Geological and Geomorphological

9.2.1 Karst Landform Mapping

A number of different data sources exist in Ireland for a desk-study evaluation for locating and mapping karst landforms and these are discussed below.

- geological maps
- Ordnance Survey Ireland (OSI) maps
- remote sensing techniques
    - aerial photography
    - digital elevation models / LiDAR
- GSI's karst database
- GSI's water tracing database
- company reports, literature
- websites and web viewers

Geological maps

Geological maps provide baseline information for the type and degree of karstification, the aquifer framework and geometry. Structural data may yield information on the location, orientation and frequency of potential aquifer flow paths and barriers to flow. Subsoil and soil are an important control on groundwater in any aquifer because they influence the rate, quality and quantity of water that recharges an aquifer. The subsoil geology and depth to bedrock mapping are key variables used to create Geological Survey's groundwater vulnerability maps and groundwater recharge maps.

A variety of geological maps are available on GSI's website (http://www.gsi.ie), for viewing on GSI's web viewers (http://www.gsi.ie/Mapping.htm) and for downloading for use within a GIS (http://www.gsi.ie/Publications+and+Data/Digital+Data/Available+Digital+Data.htm).

Ordnance Survey Ireland maps

There are a range of OSI maps that are useful for karst mapping, as outlined below:

1:10,560 and other large-scale maps

The OSI's 1:10,560 (six-inch to one mile) map series is the principal source of landform and topographical data and, despite its antiquity, is a valuable tool for karst landform mapping. These detailed maps were first completed between 1829 and 1842 and were the first large scale survey of an entire country. They show the road network down to the level of small farm tracks and field boundaries. Drainage networks are also clearly marked, showing not only rivers and streams but smaller drainage ditches and seeps. Drainage direction is also marked on channels (Figure 9.4).

Many karst landforms are marked on these maps. Large springs are clearly marked, medium springs are usually depicted by small circles, usually with a stream leaving them, and smaller springs are usually marked as 'rises' (Figures 9.4 and 9.5B). Swallow holes are often depicted

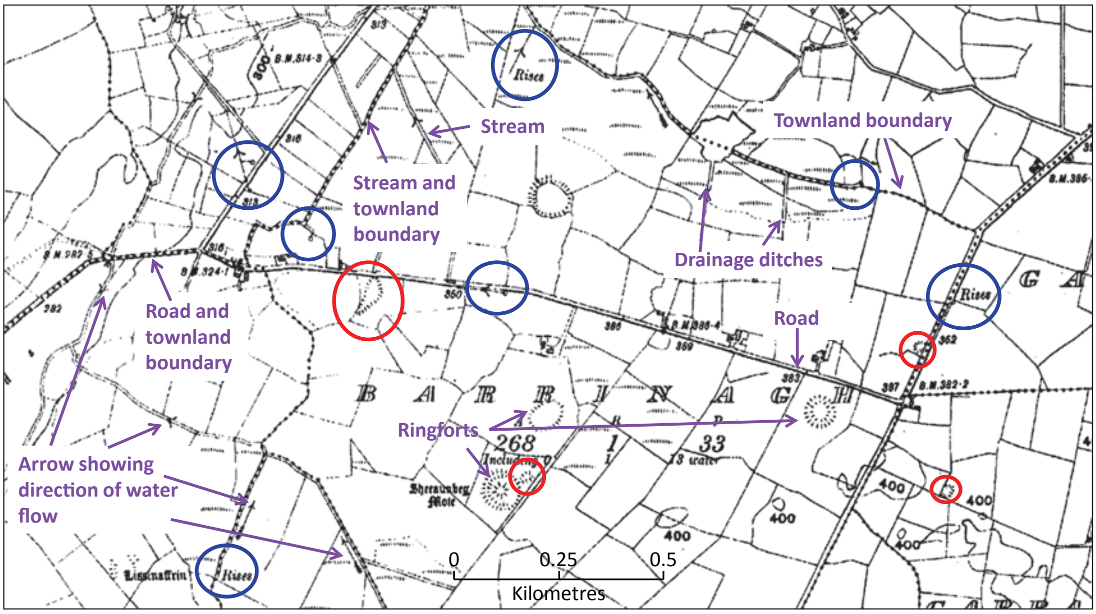
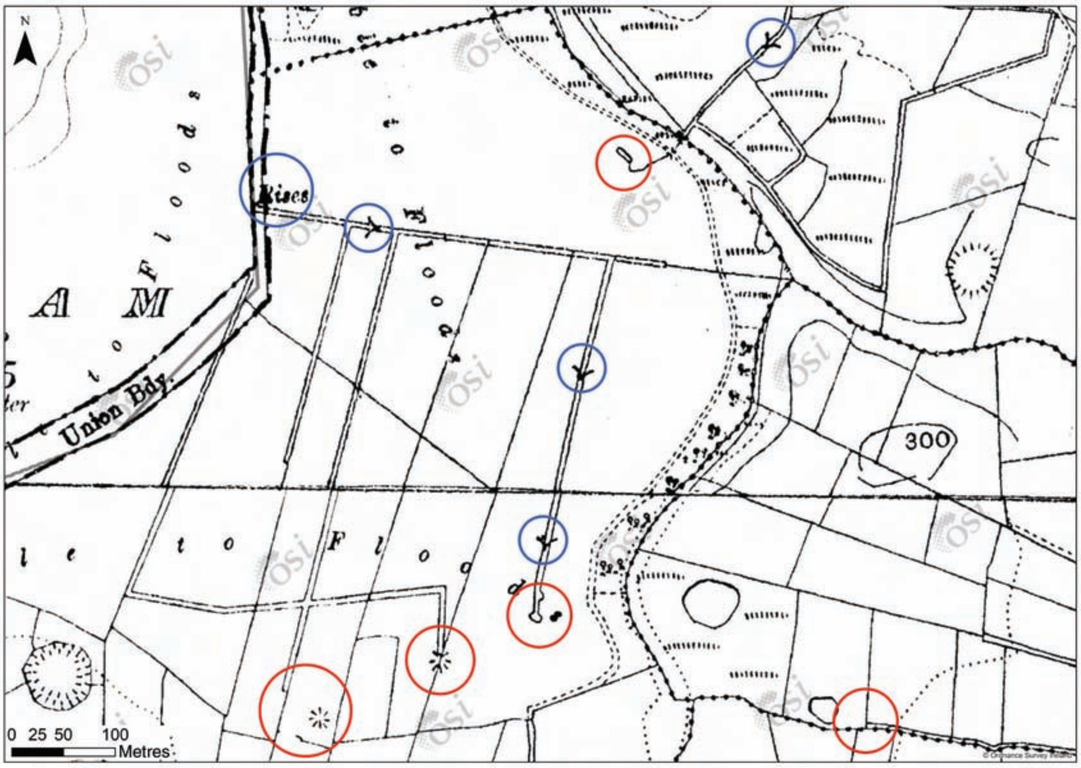


Figure 9.4 A sample of OSI's 1:10,560 (six-inch to one mile) map series. Springs are marked by a blue circles, depression features are marked with red circles. Note arrows showing direction of water movement, ringforts, townland boundaries, roads, drainage ditches and streams. Also note how similar ringforts are to depressions.

by a flowing-water channel ending abruptly and occasionally 'swallow hole', 'sluggaire' or 'sluggary' is written (Figure 9.5–9.7). Smaller topographical features such as hollows, mounds, wells and boreholes are also marked on the maps (Figure 9.4). Turloughs are usually shown as hollows that are 'liable to flood' (Figure 9.7). However, this may also be written along the floodplain of a river that can flood also.

Many springs, caves and dropout dolines have names such as 'Pollnagollum' or 'Tobarlargan' (Figures 9.6 and 9.7). Indeed, many place-names marked on the six-inch sheets are derived from karst landforms, such as Oranmore (big, cold spring), Killaturly (church of the turlough) or Cavetown. Some common words found in Irish place names that may signify karst are:

- 'POLL' or 'POUL'– hole
- 'TUBBER' or 'TOBER' – spring or well
- 'ORAN' – from Uarain (spring of cold water)
- 'TURLOUGH' – temporary or seasonal lake
- 'ISKE' – from *uisce* – water
- 'SUMERA' – from *sumaire* (swallow hole)
- 'SLUGGAIRE' or 'SLUGGARY' – swallow hole
- 'COOS' – from *cuas* (cave)
- 'HOO', 'HOE' or 'WEE' – from *uaimh* (cave)
- 'KEELIN' or 'GEELIN' – from *caolain (disappearing stream)*
- 'CARRICK' or 'CREG' – from *carraig* (rock)
- 'BURREN' – from *boireann* (rocky place)



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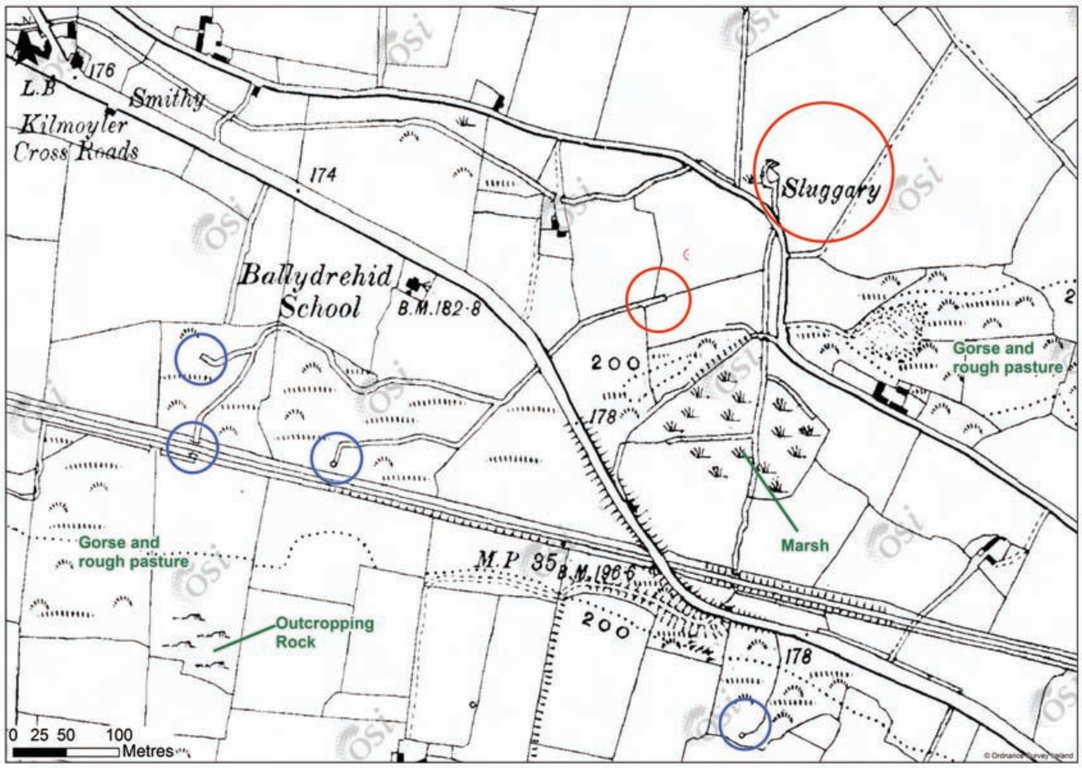


B

Figure 9.5 (A) Swallow holes outlined in red. Note spring and arrows showing water moving towards swallow holes (outlined in blue). (B) Two swallow holes, one marked with the word 'sluggary' and four small springs (marked with blue circles).

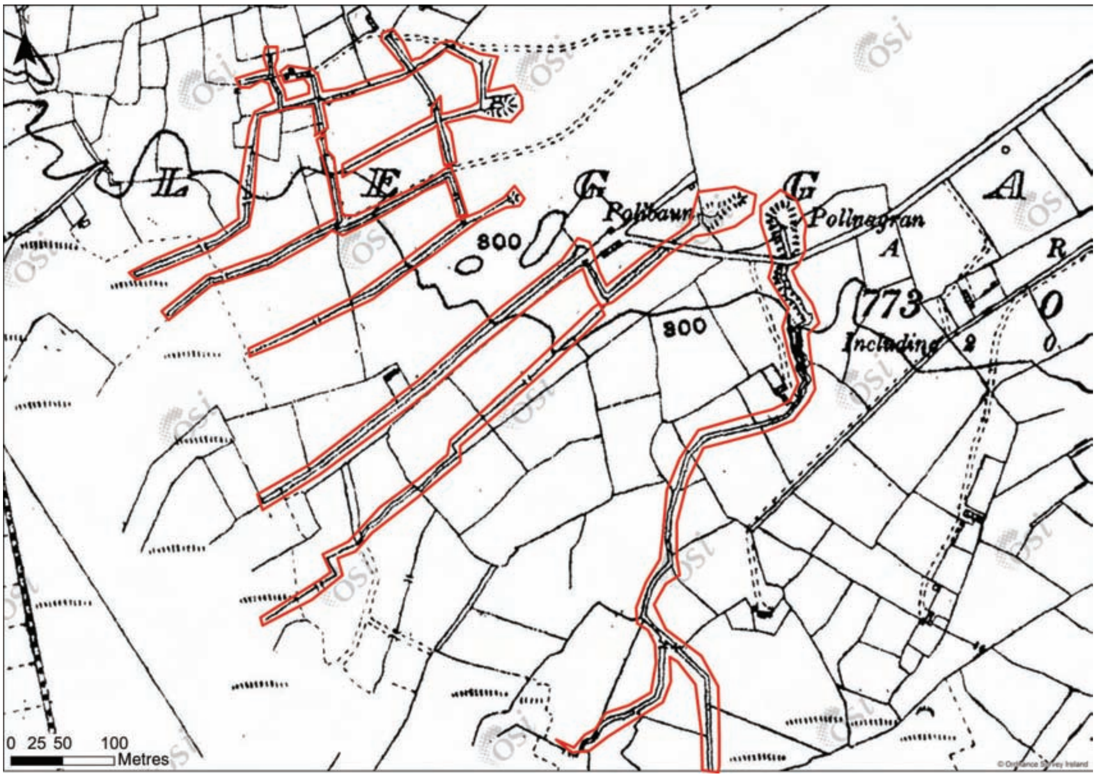


Figure 9.6 Swallow holes located in large, enclosed depressions located along a geological contact. Sinking streams are outlined in red.

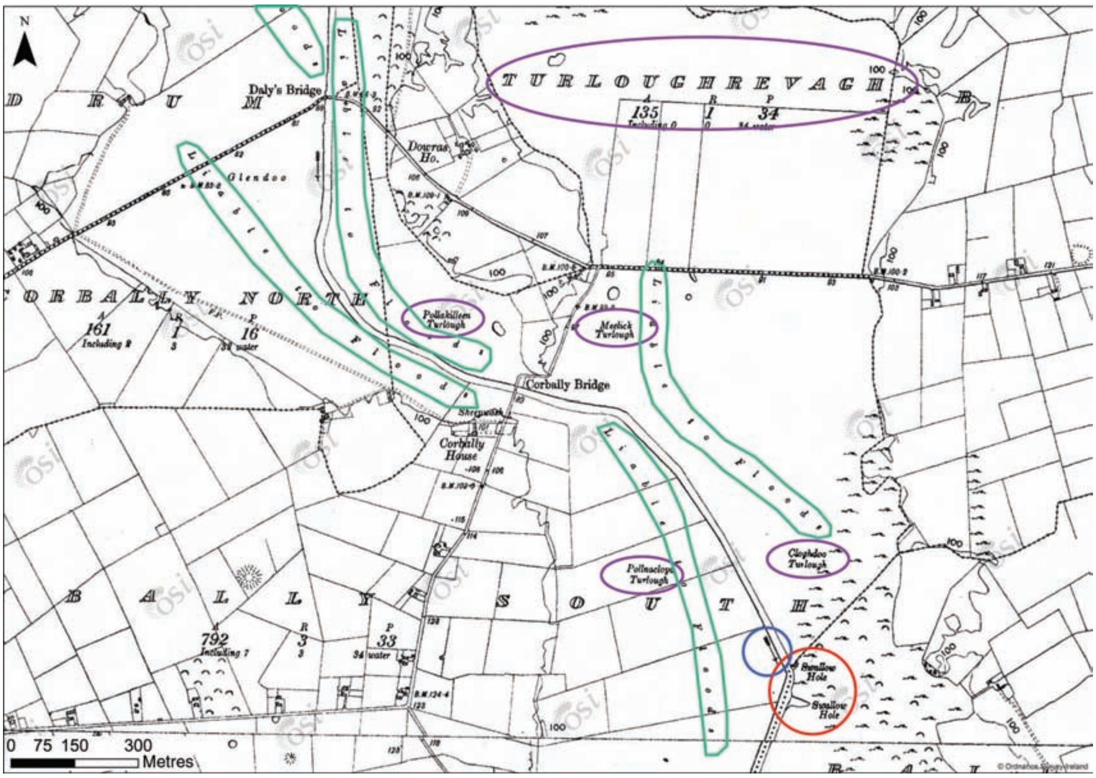


Figure 9.7 An area of turloughs shown on the 1:10,560 map. Some turloughs are named (outlined in purple) and all are depicted with ‘liable to flood’ (outlined in green). There are also two swallow holes marked in the right foreground (in red). Direction of water movement is outlined in blue.

There are limitations to the use of the OSI's 1:10,560 map series. The maps are out of date (the land was surveyed between 1829 and 1842, the last revision took place between 1900 and the 1930s) and some features such as field boundaries, roads and even karst landforms may have changed. As the maps are black and white vector data, line features such as roads can be confused with other line features such as rivers (Figure 9.4). The symbol depicting a hollow (possibly a doline) can be confused with the symbol for a ringfort or rath (Figures 9.4 and 9.6). 'Cave' is sometimes marked in old script on the map, and can mean a man-made 'souterrain' and not a natural karst cave, especially if located near a ringfort or other archaeological feature.

Another limitation of these maps is that many smaller dolines and karst features are not marked at all on the maps. However, if some karst features can be identified, then this gives an indication that there may be more landforms present. There are several editions of the 1:10,560 map series available from OSI and they are available in both paper and digital form. There are other useful maps available from the OSI, such as the '25-inch map' (25 inches to one mile or 1:2,500 scale maps). These show additional details, such as wells and springs, that the 1:10,560 maps do not always depict. These maps can be found on the OSI's online mapping portal called Geohive Mapviewer (http://map.geohive.ie/). They are also available on other map viewers such as Geological Survey Ireland's and EPA's map viewers (http://www.gsi.ie/Mapping.htm and http://gis.epa.ie/Envision). Figures 9.4 to 9.7 show after examples of the 1:10,560 map, with features highlighted (by coloured circles and text) to emphasise the landforms described in the text above.

1:50,000 Discovery Series maps

The 1:50,000 Discovery Series maps published by the OSI are another important data source for topographical information. The Discovery Series maps are full colour maps created digitally from 1:40,000 aerial photography and were published in the 1990s. The grid used is the National Grid of Ireland. These maps are a good source of information on topography, relief with 10 m contour intervals, spot heights, river and stream networks, canals and lakes. The map series provides a good general picture of large areas, with relief (different colour shading at 100 m intervals) and drainage clearly visible.

However, care should be taken when interpreting drainage features from these maps, as occasionally, the drainage features are not accurate. The maps can be used to locate possible springs and swallow holes – where rivers and streams start and stop (Figures 9.8–9.9) and areas with no drainage – as, perhaps, drainage is largely underground (Figure 9.10). This map series is available in both paper form and digitally and can be used in GIS.

Other maps

Another useful data source for karst landform mapping are GSI's geological field sheets. These are the OSI 1:10,560 maps that were made in the field by geologists when they were originally compiling the bedrock series maps. Field observations from this original mapping were often hand-written on the map. Some karst landforms and geological information are noted on these (Figure 9.11). The complete series is available for viewing and download in GSI Goldmine site (https://secure.dcenr.gov.ie/goldmine/index.html).

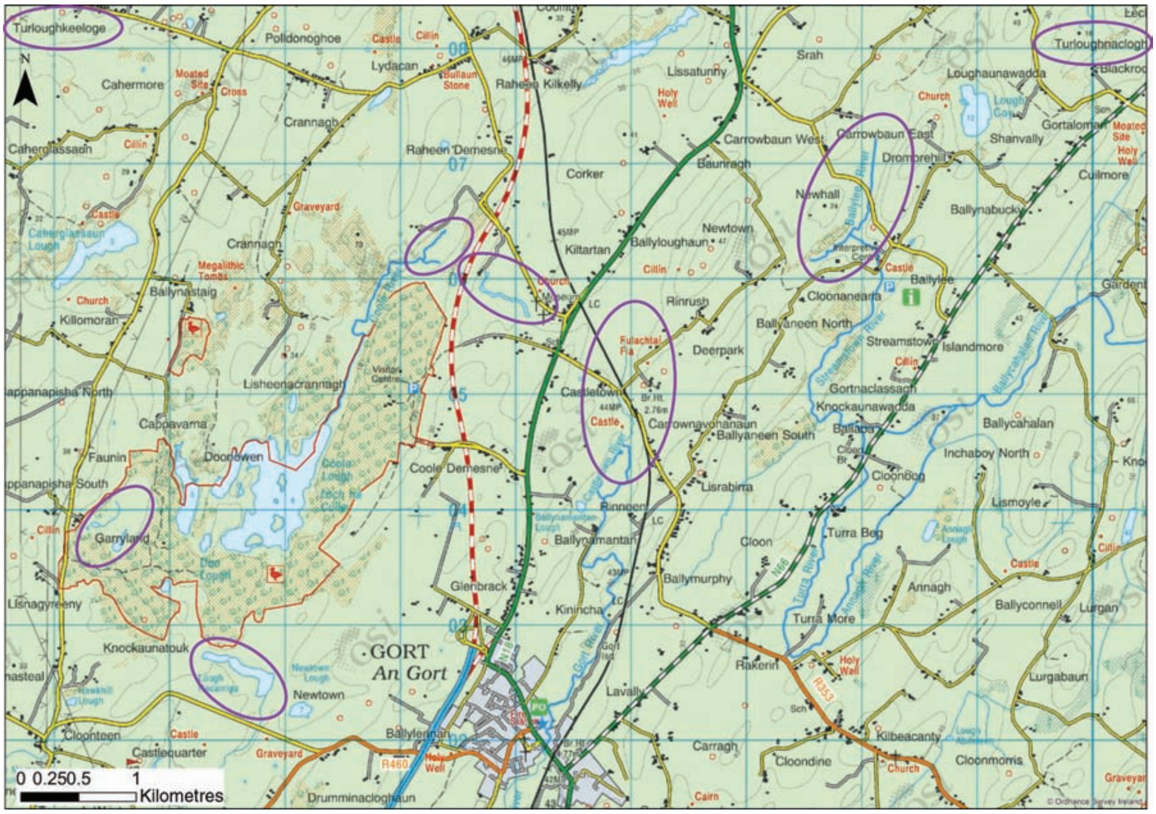


Figure 9.8 Unusual drainage patterns in Gort region, County Galway with large rivers starting and disappearing on the land surface.

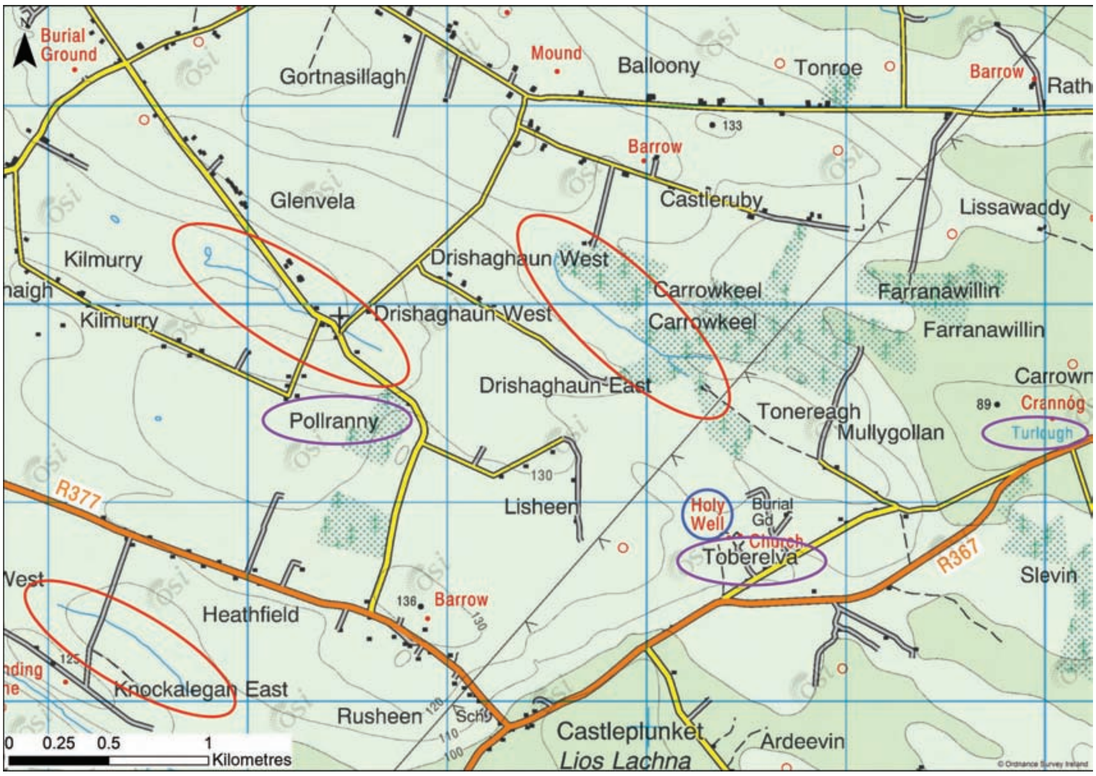


Figure 9.9 Three small streams that sink underground within 1 km of where they rise (outlined in red), Castleplunket (County Roscommon). A turlough is marked to the east (purple outline) but yet the larger Castleplunket turlough is not marked. Placenames signifying karst are also outlined in purple.

Figure 9.10 (A) An upland area of the Plains of Boyle, County Roscommon, with approximately 45 km^2 with no surface drainage (outlined in purple).

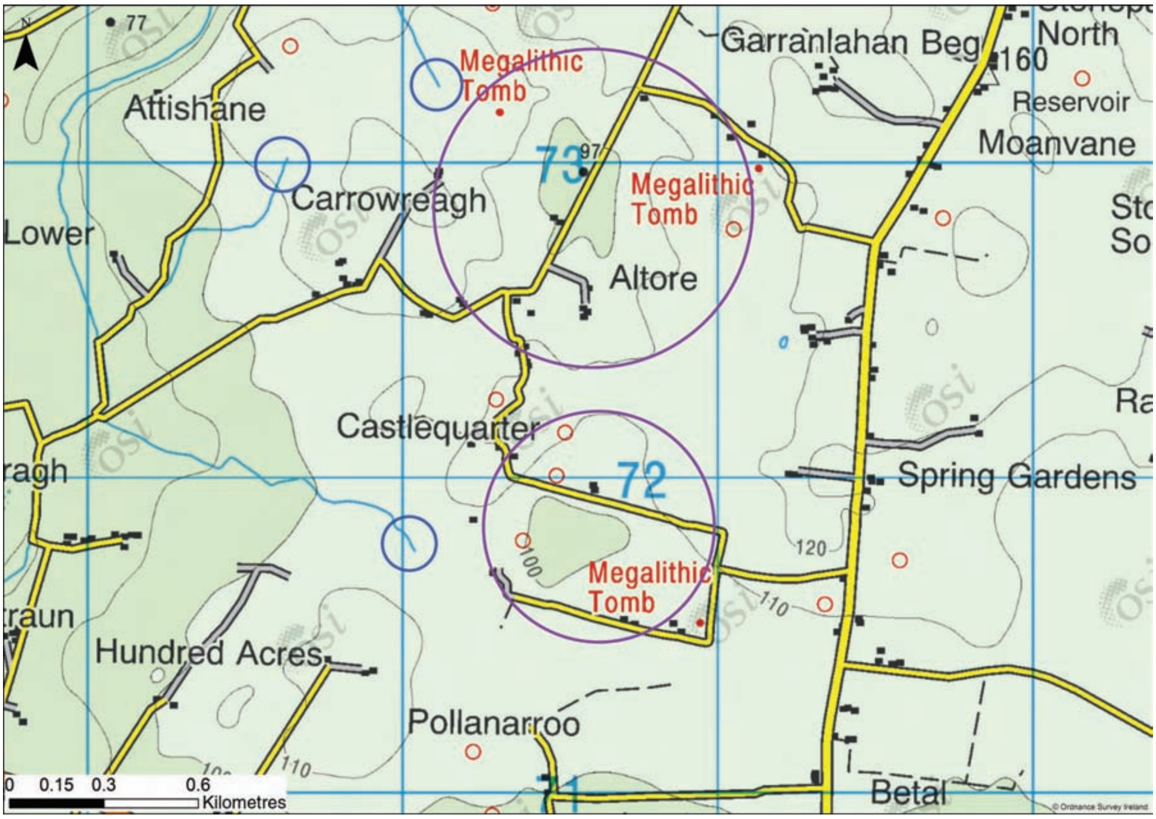


Figure 9.10 (B) An upland area on the Roscommon Galway border, with surface drainage only appearing at the periphery (via springs). Note the springs (blue circles) and two large enclosed dolines which contain many small swallow holes.

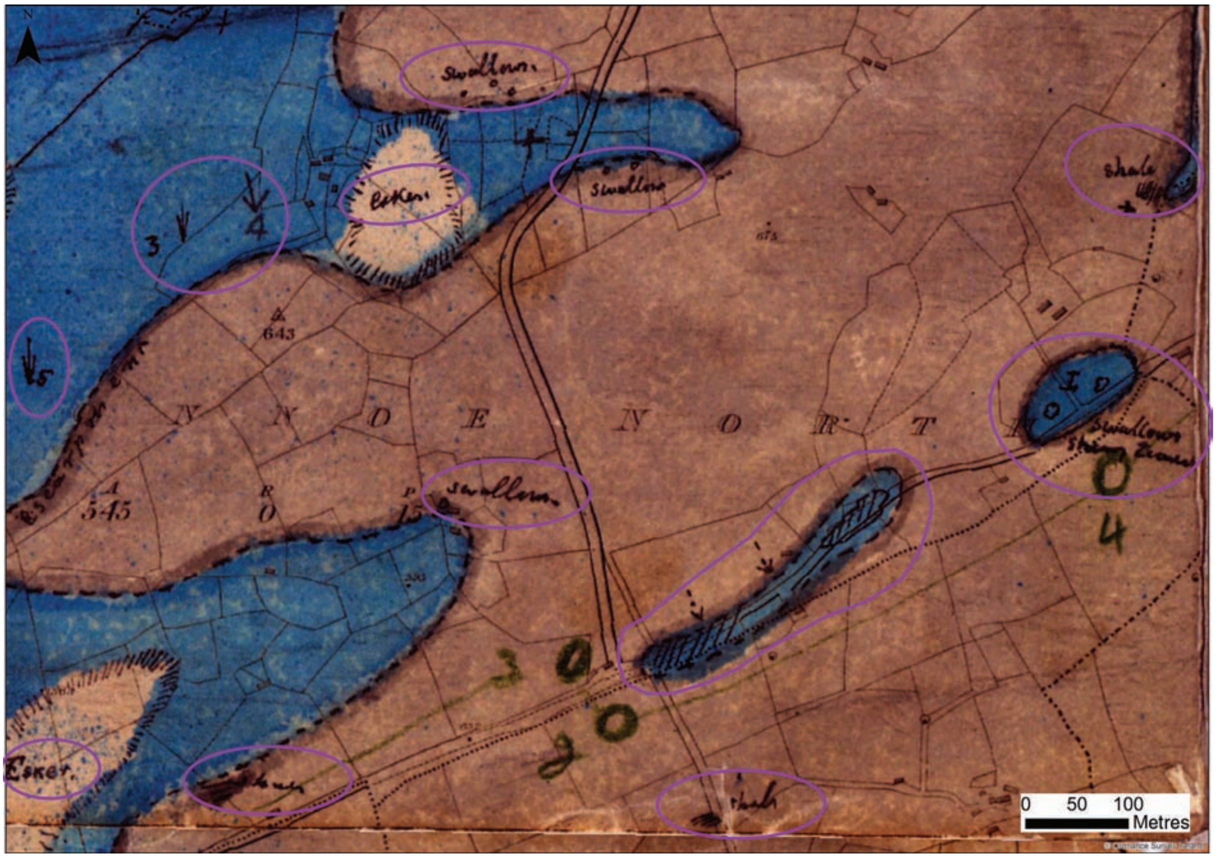


Figure 9.11 An example of a historical geological six-inch map (1:10,560) showing geological information and karst 'swallows', outlined in purple

Remote-sensing techniques

Introduction

Numerous studies have demonstrated the efficiency of karst feature mapping through the use of remotely-sensed topographic data; a broad range of manual and automated analysis techniques have been developed for the manipulation of these data to optimise identification of karst features (Alexander et al., 2013; Basso et al., 2013; Doctor and Young, 2013; Filin et al., 2011; Zandbergen, 2010).

Aerial photographs

Naturally, landforms found from studying aerial photography can only include features that are visible from above. Small landforms such as caves springs and swallow holes may be difficult to detect. However, some of the bigger dolines and springs may be evidenced in aerial photographs from vegetation changes, such as isolated clusters of trees and dense vegetation in an otherwise cleared grass field (Figure 9.12). Figure 9.13 compares karst landforms that can be recognised from the OSI 1:10,560 map compared to landforms mapped from an aerial photograph of the same area and Figure 9.14 shows an aerial photograph used in conjunction with the OSI 1:10,560 map.

Figure 9.12 Large enclosed depressions visible from aerial photography (County Galway).

LiDAR

The collection and availability of LiDAR data has increased substantially in Ireland in recent years and represents a promising data source in karst feature mapping on a large scale. Basic surfaces, such as hillshade and slopeshade images, can be used for guiding visual interpretation as they provide three-dimensional characteristics of the landscapes with high degree of accuracy and resolution. Hillshade images highlight topographic features by illuminating the LiDAR DTM with an artif cial light source (Figures 9.15 and 9.16). More complex hydrological and geo-statistical analysis procedures, such as the f ll-dif erence and topographic position index (TPI) methods, are useful both as visual aids and for quantitative analysis of karst feature characteristics (Naughton, 2014). A fully automated method for the identif cation of karst features has been deemed impractical for Ireland (Naughton 2014). However, automated processes for the delineation and characterisation of karst features, once their position has been validated, should not be discounted.

Other satellite imagery

Maps of land cover and land use from thematic mapping can be used to identify and track changes in the Irish landscape. Remote sensing technologies, such as satellite synthetic aperture radar (SAR) data, are useful tools for mapping karst related changes, for example groundwater and turlough flooding (Figure 9.17) and the development of new enclosed depressions on a catchment scale in real-time.

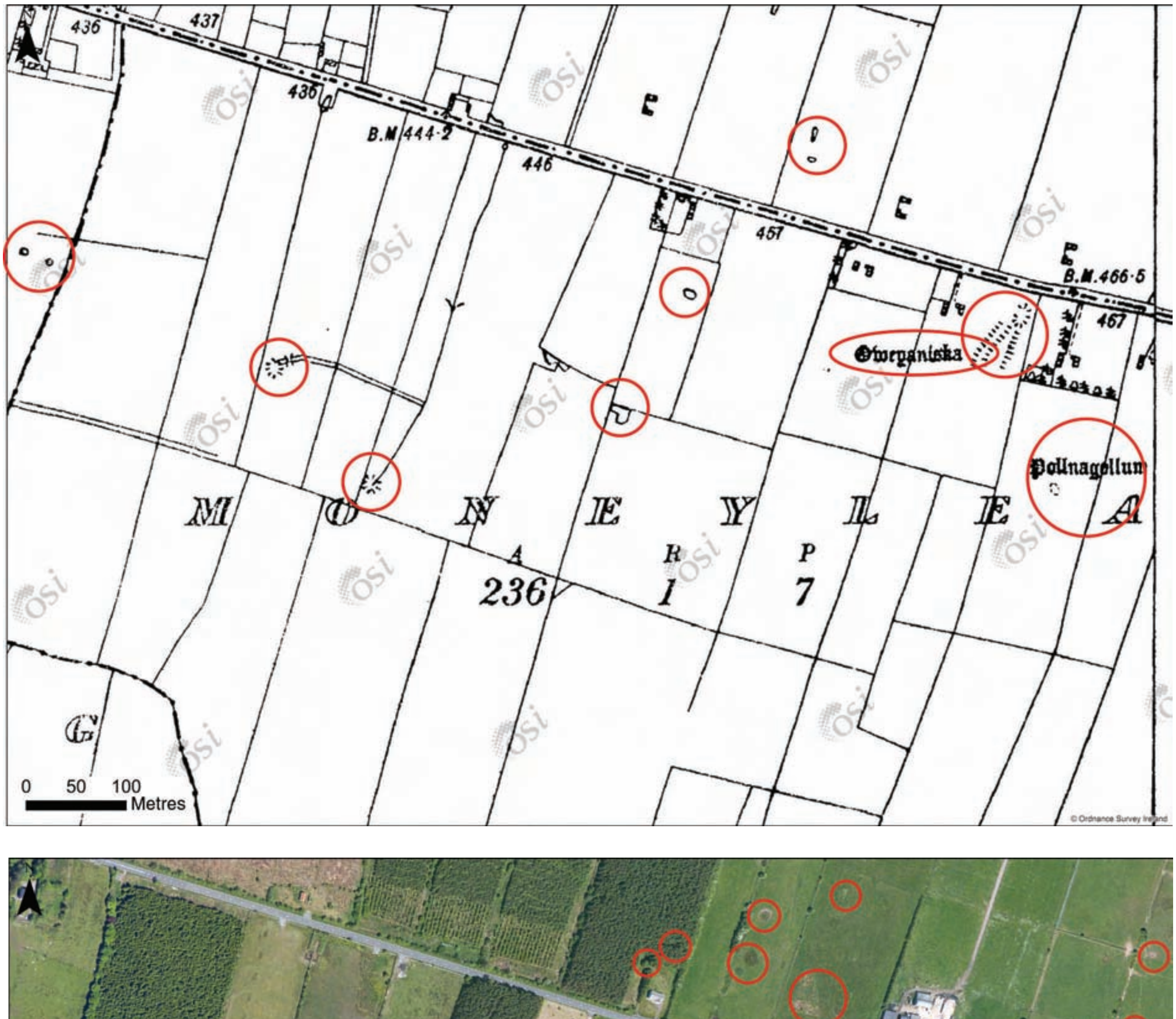


Figure 9.13 An image from a 1:10,560 map and an aerial photograph of the same area. Karst features that can be mapped from each data source are marked in red.

Figure 9.14 Aerial photograph and 1:10,500 map used in conjunction. Here the 1:10,560 map is useful in interpreting the aerial photograph. Enclosed depressions (yellow circles) and swallow holes (eastern end of the red outline) can be clearly seen (Castleblunden, County Kilkenny).

Freely available remote-sensing techniques were successfully used to identify areas of submarine and subaqueous groundwater discharge (Wilson and Rocha, 2012, 2013, 2014, 2016; Figure 8.52). Surface-water temperature patterns generated from Landsat 7 ETM+ Thermal Infrared (TIR) images were used to detect groundwater inputs captured as anomalous cold plumes visibly emanating from 122 shallow lake margins and coastlines during summer months.

The national karst and water-tracing databases

The GSI's national karst database was created in 1998, to record information on the location and attributes of known karst landforms in Ireland (Burke, 1998). The national karst database consists of point features which locate the centre (or in the case of a cave, the entrance) of karst landforms, grouped into 8 types. The eight types of features recorded are caves, enclosed depressions, dry valleys, turloughs, swallow holes, karst springs, estavelles, limestone pavements and karst found in boreholes. Details relevant to all these landform types, such as location and data source (whether remotely or field mapped), are recorded. Each landform type also has a specific set of fields, depending on the attributes of the landform. For example, for caves, information on passage dimensions and length are recorded and for karst springs, information such as mean discharge and variation in discharge is recorded, where available.

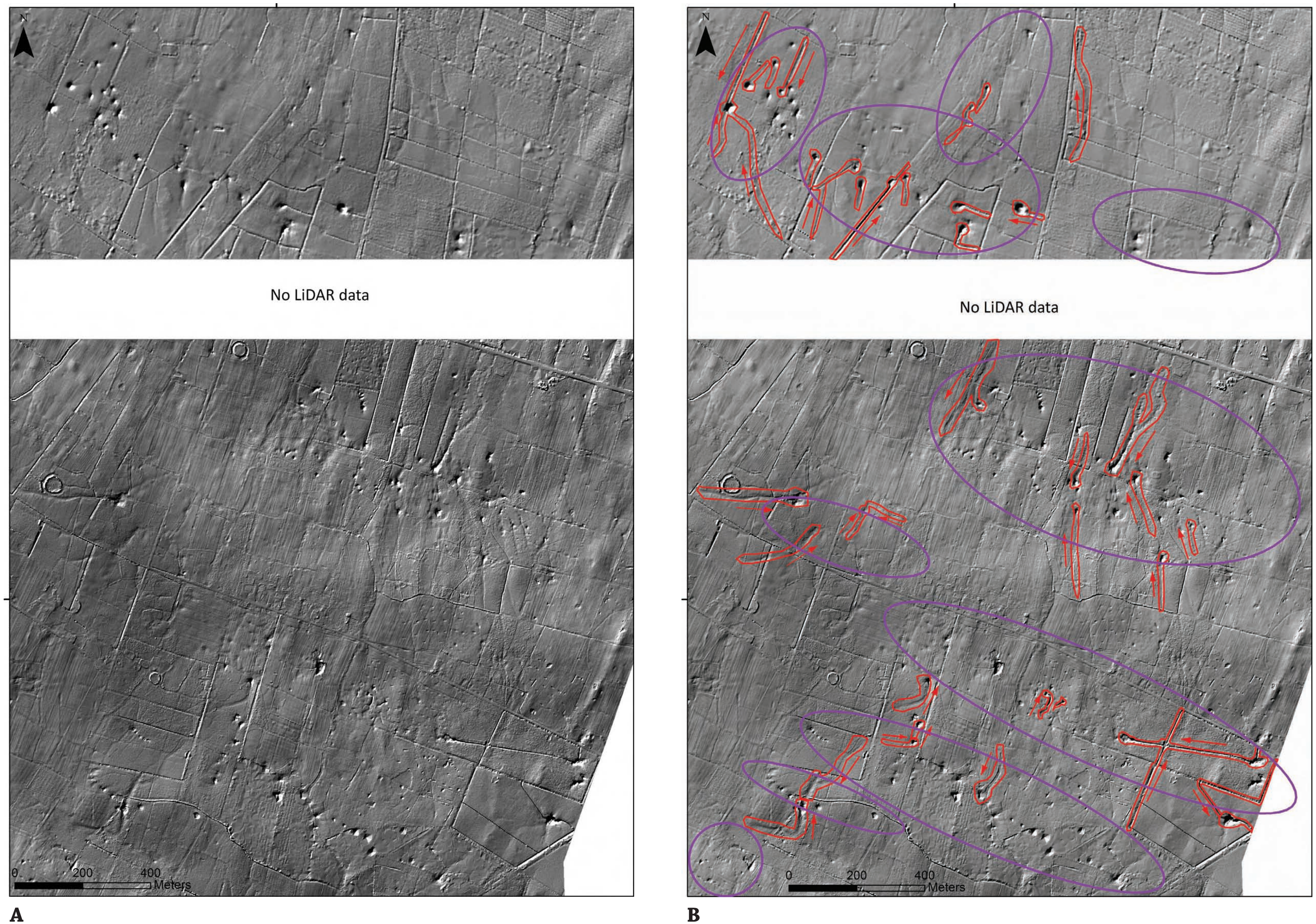
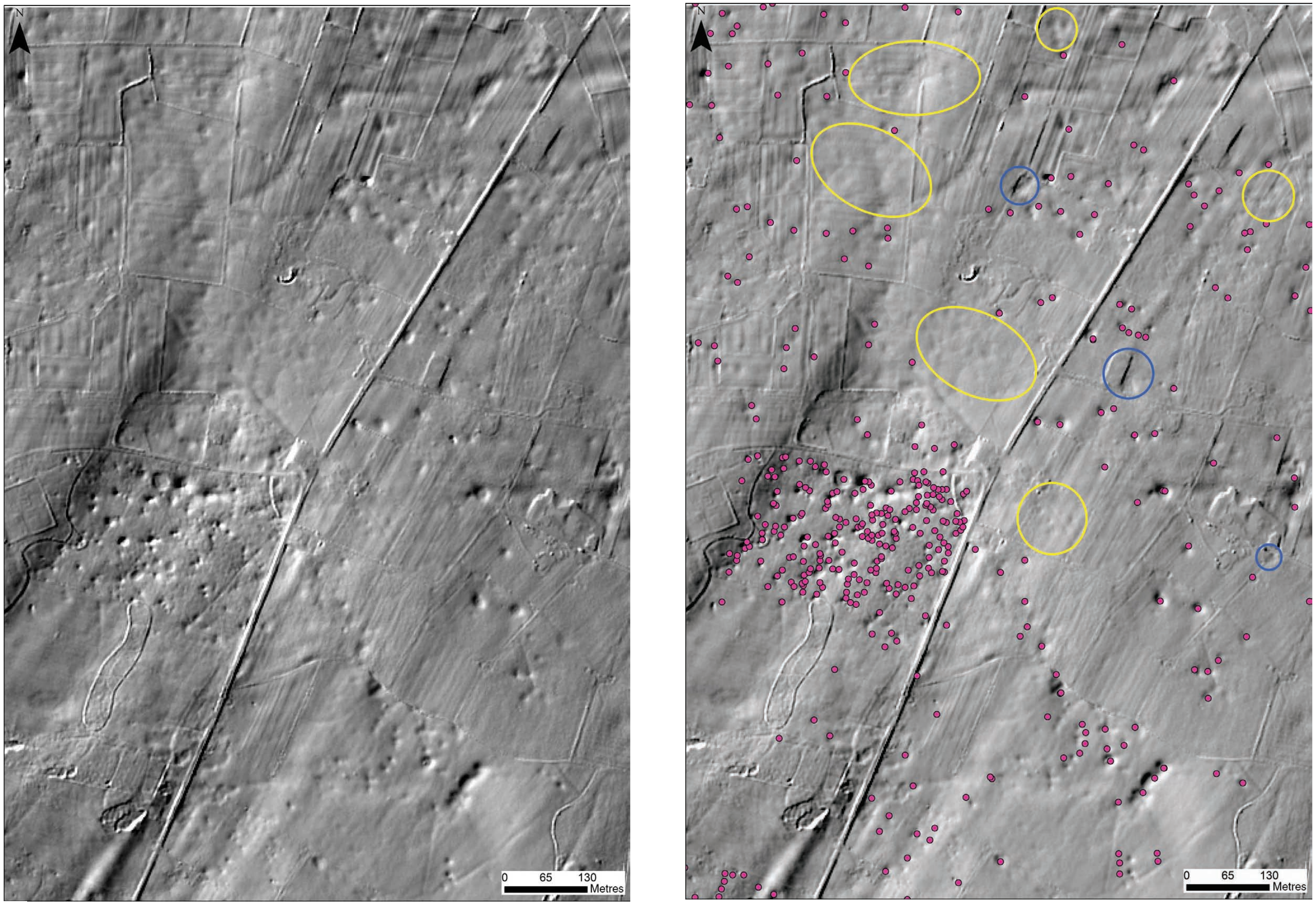


Figure 9.15 (A) LiDAR images of the Rathcroghan Upland (County Roscommon). (B) The same images with major karst landforms outlined (purple marks areas of enclosed depressions and red marks swallow holes).



A **B**

Figure 9.16 (A) A LiDAR image of an area in County Mayo with many enclosed depressions; (B) shows the actual features mapped (pink dots) during an intensive field mapping programme. However, some features (marked by the yellow outlines) identified from the LiDAR, were missed during field mapping. Conversely, features outlined in blue are not karst enclosed depressions and would have been incorrectly identified as such from LiDAR.

Figure 9.17 (A) Landsat8 Image of Gort area taken on 3 April, 2013 (https://earthexplorer.usgs.gov/).

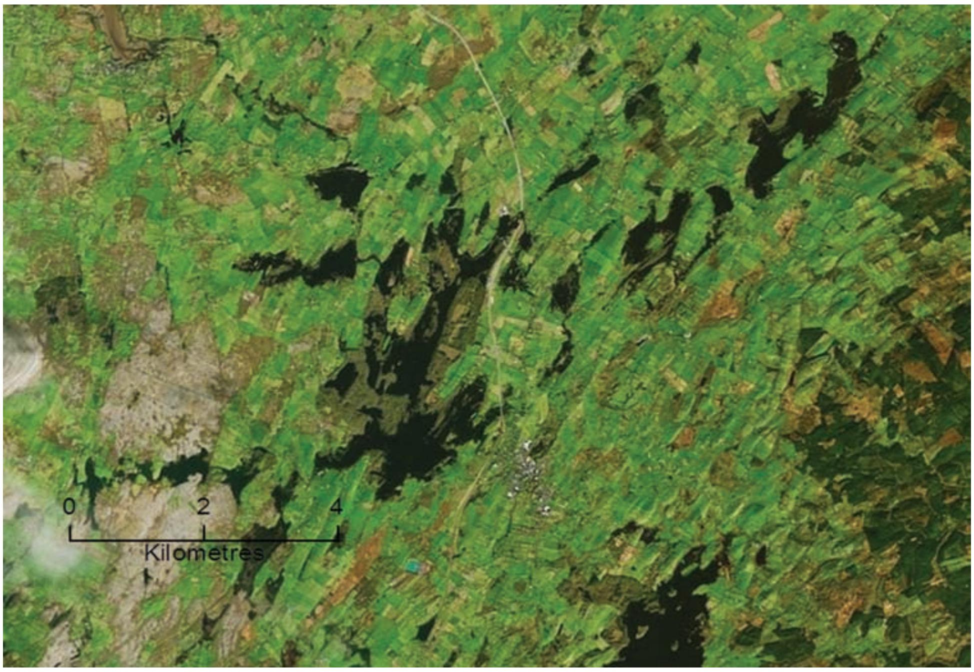


Figure 9.17 (B) Landsat8 image of same area taken on 1 April, 2016, showing groundwater flood conditions at turloughs (https://earthexplorer.usgs.gov/)

The database currently contains details of almost 11,300 landforms (as of early 2017) and is continuously updated as new information becomes available, usually from fieldwork or remote-sensing techniques. However, not all areas have been mapped to the same level or indeed are mapped at all and so the database is not comprehensive. Figures 5.6 and 7.46 are examples of the karst database in map format – which is usually displayed by landform type.

The GSI's water-tracing database was created in 2007 to compile and detail water-tracing experiments carried out in Ireland. It is an inventory of all known water-trace experiments and stores details for each trace. There are twenty fields, which can be queried by topic, location or catchment. Positive traces are recorded as a straight line, input-outflow, and are not necessarily representative of the actual path water may take. The water-tracing database is designed to complement the karst database (Figure 7.46).

Both databases are available as a downloadable layer for use in GIS or can be viewed and queried on GSI's webmapping viewer.

Other Geological Survey Ireland maps and datasets

Groundwater is protected in Ireland by means of Groundwater Protection Schemes, which are county maps of groundwater protection zones, produced by the combination of an aquifer map and a map of the natural vulnerability of the groundwater to pollution. Karst is an important consideration of these schemes. Recharge through karst features such as swallow holes and sinking streams is taken into account in the vulnerability mapping, as areas around these are classified as 'extreme' vulnerable to groundwater pollution. Groundwater is classed as 'extremely' vulnerable within 30 m of certain karst features, including along the area of loss of losing or sinking streams, and within 10 m on either side of losing streams upstream of the area of loss. The distances can be varied depending on the circumstances – for instance, they can be increased where overland surface runoff is likely.

The aquifer map distinguishes between limestones with and without a high degree of karstification (see Chapter 5.2). In the delineation of source-protection zones, two source-protection areas (SPAs) are delineated around each public supply well and spring: an inner protection area (SI), with the boundary defined by a 100-day travel time within the aquifer from any point below the water table to the source, and an outer protection area (SO), encompassing the source catchment area or zone of contribution (ZOC). Karstification is taken into account in these SPAs, firstly because the area in the immediate vicinity of karst features that enable water and pollutants to bypass the subsoil are classed as 'extremely' vulnerable areas and secondly, all the area of karst limestone in the ZOC is generally classed as an inner protection area (SI), as travel times to karst sources are generally rapid.

In the groundwater-protection responses, the greatest degree of restriction is on developments on extremely vulnerable, regionally important karst aquifers. Groundwater Protection Scheme reports, Source Protection Scheme reports, Zone of Contribution reports and other useful reports are freely available on GSI website. Information on karst landforms or other relevant geomorphological features can be sourced from academic and technical reports. Geotechnical reports contain information on boreholes, trial pits, depth to bedrock information, pump tests, karst landforms, springs, collapses, quarries etc.

Websites and web viewers

The main two websites for karst geomorphological mapping are the GSI website (http://www.gsi.ie) and the Environmental Protection Agency (EPA) website (http://www.epa.ie). The GSI groundwater web mapping service is a good starting point (http://spatial.dcenr.gov.ie/GeologicalSurvey/Groundwater/index.html), as it has information about surface water features, geology, aquifers, soils and subsoils, groundwater vulnerability, groundwater recharge, source protection zones and zones of contributions, as well as the national well, karst and water-tracing databases. It also has useful base maps such as the six-inch map series and aerial photographs.

The EPA Envision viewer (http://gis.epa.ie/Envision) has other environmental data, such as surface and groundwater quality information, hydrometric gauges, Water Framework information, Corine landuse for four different years and changes, information on special areas of conservation, national heritage areas and special protection areas, as well as information on mining and quarrying. It also has a digital version of the OSI's Discovery Series 1:50,000 maps series and aerial photography from three different years, all draped over a 10–20 m resolution DTM. The EPA's data are also available for downloading at http://gis.epa.ie/GetData.

The EPA HydroNet (http://www.epa.ie/hydronet) is another useful source of real time information. It has a live feed of water levels and stage for surface water and levels and hydrographs for groundwater (including springs). It contains information from a range of organisations such as the EPA, Office of Public Works, and the Northern Ireland Rivers Agency, with 921 active stations (2,613 in total). This data source is a particularly useful way of remotely monitoring water levels and stage conditions in an area prior to fieldwork. The data is available to view and download as yearly, 3 monthly or the entire record.

The Catchments website (http://www.catchments.ie) contains useful information and maps on water framework directive (WFD) related topics, such as waterbodies, WFD status, WFD risk categories and the significant risks, for each catchment. It also contains interesting articles, reports, catchments stories and education material, as well as the Catchments Newsletter.

9.3 Hydrological Methods

9.3.1 Analysing Spring Flows

Introduction

It is vital for many karst hydrogeological studies to monitor and record information gathered from spring water. Hydrographs are "an extremely powerful way of learning about a karst aquifer" (White, 1999, p. 16). Hydrographs reflect the response of an aquifer to recharge. Groundwater discharge from karstic aquifers is usually via springs and with increasing development of the karst drainage system groundwater flow becomes progressively focused on fewer but larger springs. The hydrographs of these springs are comparable to the hydrograph of a surface river at the basin outlet the form of which is the result of all of the rainfall and catchment characteristics upstream of the gauging point. It has been remarked that a karstic spring is the equivalent of a perfectly located borehole in an aquifer in terms of the information it may yield. The lag time before a response occurs can yield information about input types; the rate of rise to peak gives information about the length and type of flow paths in operation; and the form and rate of recession provides significant information on the storage and structure of the aquifer system sustaining the spring (Ford and Williams, 2007).

Similarly, the flow and water chemistry patterns at a spring reflect the integrated effects of all the aquifer characteristics that modify input pulses of precipitation (recharge). A variety of techniques are available for analysing and interpreting spring-flow data. In part, they are derivatives of methods used to analyse river-flow time series and, in part, they are specific to the analysis of groundwater discharges where (commonly) little direct information is available concerning the nature of the aquifer system. Only a brief overview of commonly-used analysis methods is given below, together with examples of their application to karst springs in Ireland and a list of useful references in the literature.

Although the hydrograph is the primary source of information concerning the aquifer supplying the spring, ideally the flow data should be supplemented with data of equal quality from hyetographs (rainfall), chemographs and quantitative water tracings. Figure 9.18 shows an example of hydrograph recession analysis used to characterise different flow components in a karst aquifer, showing a triple porosity system. Figure 9.19 shows a typical hydrograph and chemograph for a karst spring during a storm event. Precipitation storm water runoff causes a rise in turbidity and a decrease in specific conductivity, prior to and during peak spring discharge. After passage of the storm pulse, conductivity increases as the spring discharge returns to base flow (discharge of water contributed from storage by the slow, diffuse flow karst component) (Taylor and Green, 2008).

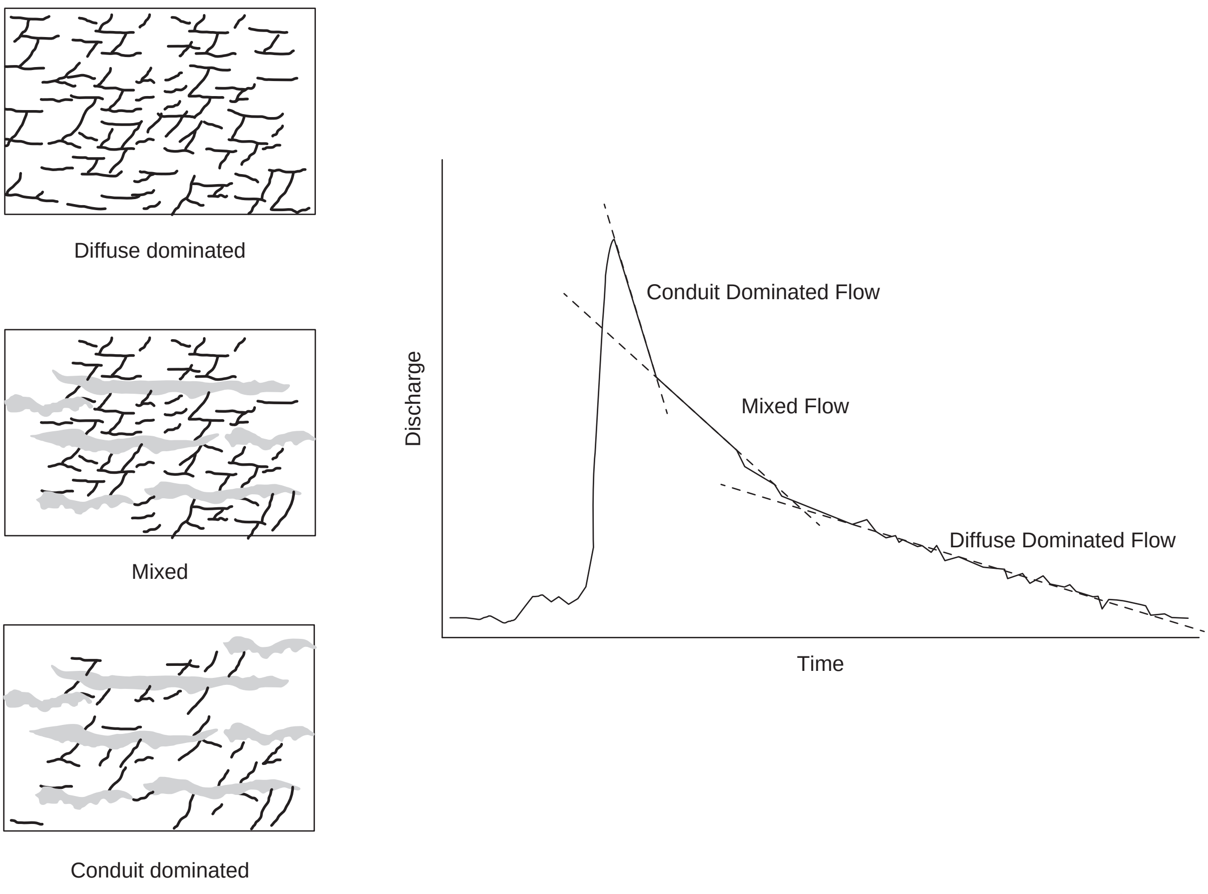


Figure 9.18 Conceptual spring hydrograph displaying typical triple porosity flow regimes found in karst (conduit, mixed, diffuse). *(From Taylor and Greene, 2008.)*

Methods of investigation

Two modes of investigation are available.

- Examining the regime (the average long-term hydrograph) to evaluate how input signals are modif ed into output signals in generalised terms.
- Examining the event/unit hydrograph to evaluate how a unit input of runof is processed in the aquifer (Figure 9.19).

Spring-regime analysis

- derivation of indices characterising spring flow; for example:
  - mean, standard deviation (SD), range, skew, frequency, discharge (Q) ratio
  - baseflow:quickflow ratio, flow duration curves,
  - cumulative discharge versus rainfall
- stochastic analysis of the flow record
- examining simplif ed forms of the hydrograph, such as running means of various resolutions
- univariate methods, e.g. autocorrelation of the recession hydrograph
- bivariate methods, e.g. cross correlation
- non-linear analysis, e.g. spectral analysis

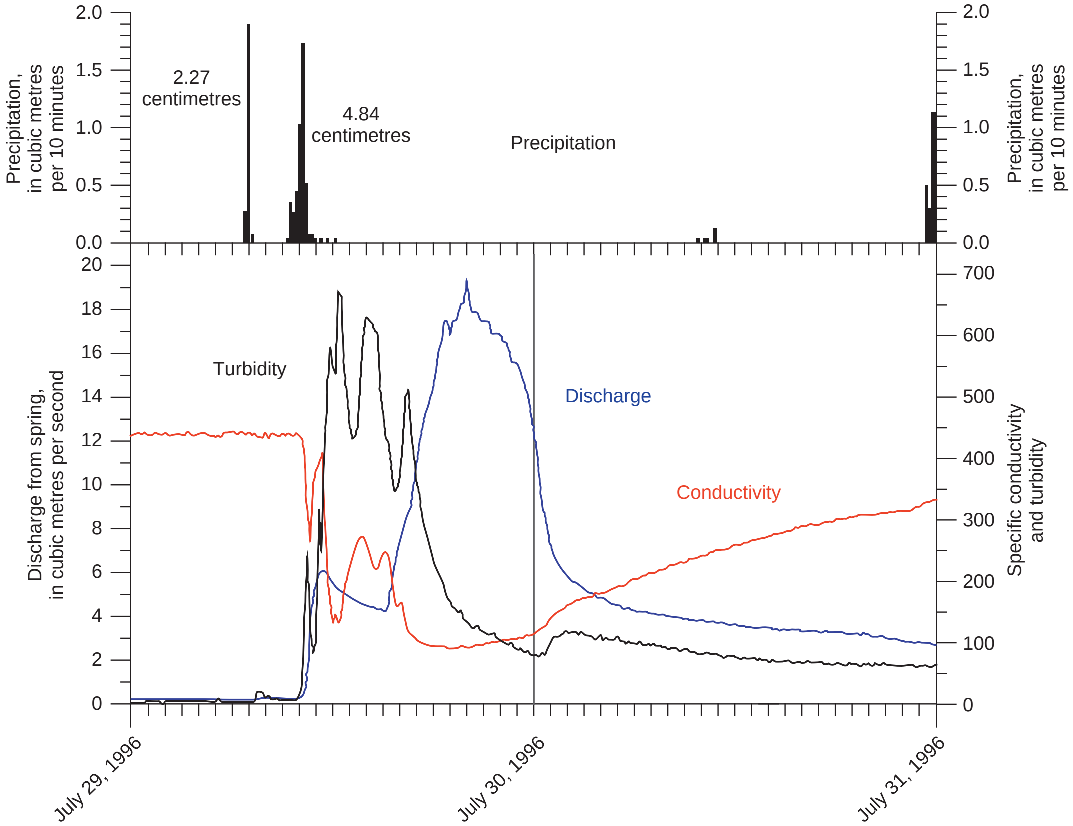
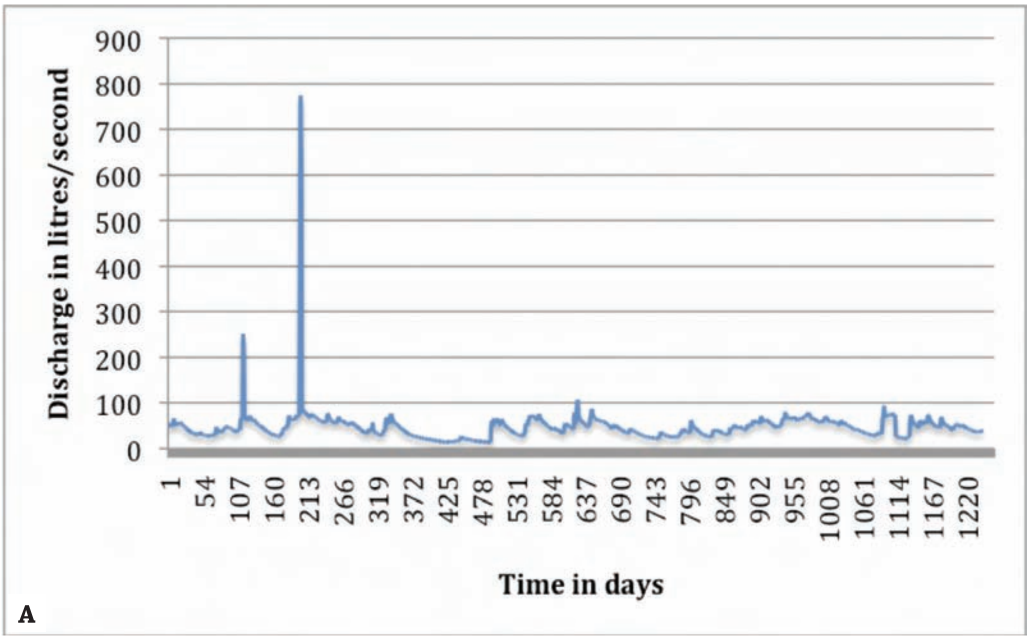


Figure 9.19 Changes in water quality in a karst spring over two days due to a recharge event. *(From Taylor and Green, 2008.)*

Event hydrograph analysis

Characterising the hydrograph:

- response lag time
- time of concentration
- peakedness
- skewness
- modality
- time base
- ratio between precipitation event input and spring outflow
- comparing the hydrograph with the chemograph (Figure 9.19)



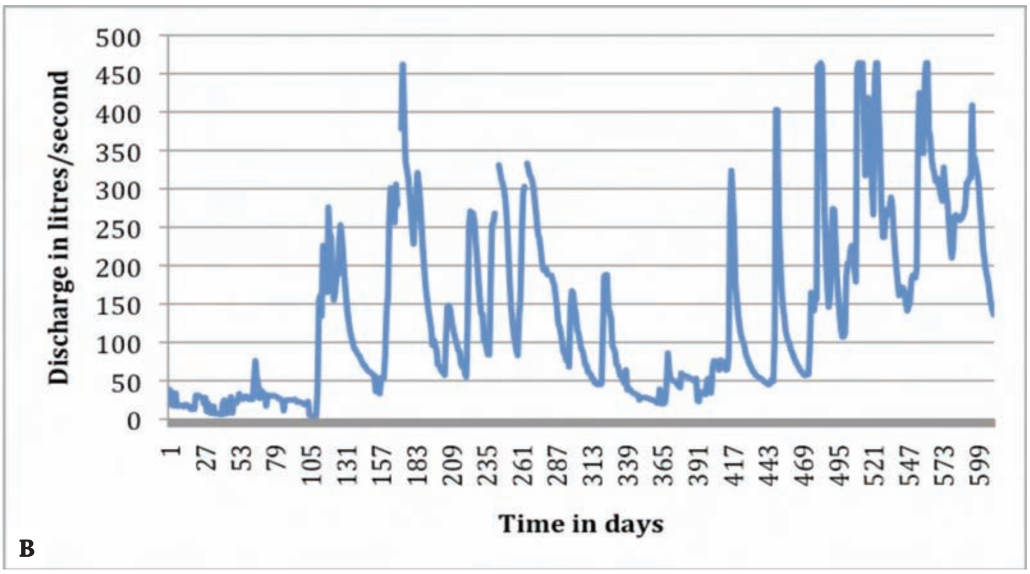


Figure 9.20 Long-term hydrographs for Caltra Spring (A) and Gortgarrow Spring (B), County Galway. *(From EPA data.)*

Examples

Figures 9.20–9.22 and Tables 9.2 and 9.3 present various graphical and tabular summaries of the flow characteristics of two adjacent karst springs in lowland County Galway. Spring 'A' is Caltra, a spring that lacks any known swallow-hole feeders (Chapter 7.5.1 and Figure 7.57) and spring 'B' at Gortgarrow, which is known to derive some of its flow from swallow-hole point sources. The dif erence in flow characteristics is apparent from the long-term hydrographs, with Gortgarrow having a highly flashy regime compared to Caltra, and is crystallised to some degree by the various derived indices, thus making a classif cation of springs via their hydrological behavior feasible.

The histograms of flow frequencies at each spring (Figure 9.21) show the small range of discharges at Caltra in comparison with the extremes of flow characteristic of the

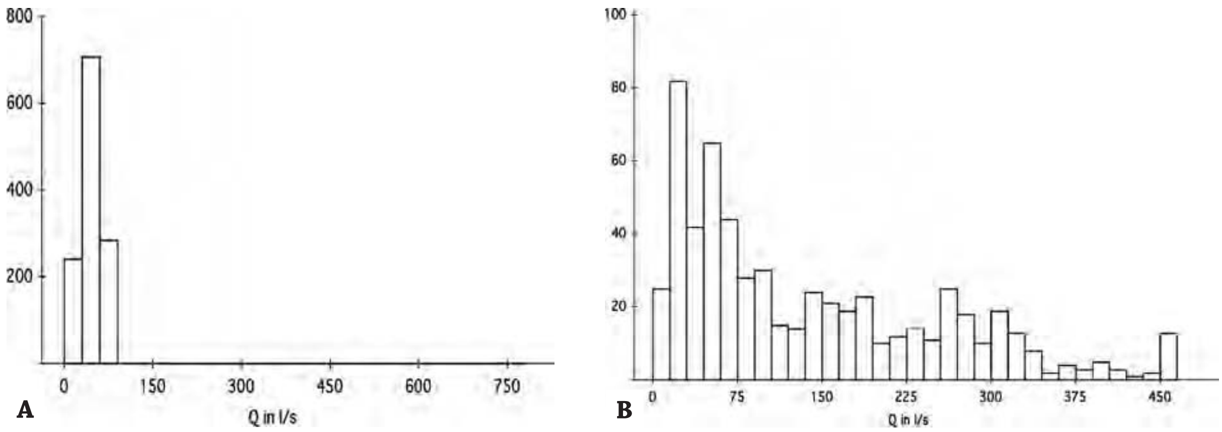


Figure 9.21 Discharge frequency distributions Caltra Spring (A) and Gortgarrow Spring (B), County Galway

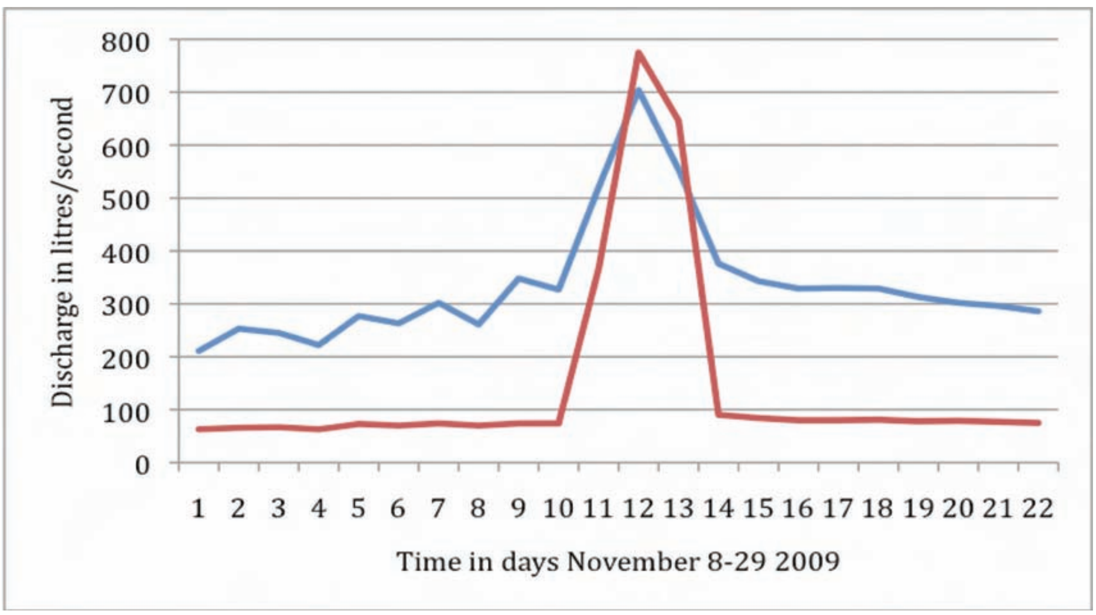


Figure 9.22 The response of the springs at Caltra (blue) and Gortgarrow (red) to an extreme rainfall event. *(From EPA data.)*

Gortgarrow spring. Table 9.2 shows discharge indices for the two springs. Caltra has a much lower deviation from the mean than Gortgarrow and a more normal distribution of flows. Gortgarrow has a strongly negatively skewed distribution.

Table 9.2 Hydrological indices for long-term flows

Regime Hydrograph Indices	Spring 'A' Caltra	Spring 'B' Gortgarrow
Standard deviation of Q	34 l/s	117 l/s
Skewness of Q frequency	+0.6	+1.1
Q_5:Q_{95} ratio	4	20

Event hydrographs for the springs (Figure 9.22) relate to a rainfall event of 103 mm in a 3-day period, preceded by and followed by a succession of heavy but less intense rainfall events. Gortgarrow responds to each rainfall pulse but Caltra to only the two heaviest rainfalls. The Caltra flood hydrograph is almost symmetrical whereas the Gortgarrow hydrograph has a prolonged recession curve.

9.3.2 Water Tracing

Introduction

Water tracing at is simplest involves 'tagging' water as it enters the karst system and monitoring possible exits to see where it re-emerges. The time the tracers take to get from one point to the other is also usually recorded (Ford and Williams, 2007). The purpose of this tagging is usually to establish connections but it may also be an analysis of the flow itself, or the transport of something within the flow. Smart and Worthington (2004, p. 771) summarise water tracing by saying "tracing remains the primary tool of the karst hydrogeologist, and it provides essential information on groundwater flow". A detailed example of water tracing is presented in Chapter 10, in a karst area of County Roscommon.

Questions concerning underground flows that may be posed (and answered) by water tracing include:

- where to? (destination of an input)
- where from? (the origin of waters at a spring or borehole)
- whether? (does A go to B?)
- how? (route, time, dif usion = aquifer hydraulics)

Tracers

Dyes are the principal and most successful tracers used today and are used in approximately 90% of all karst traces carried out worldwide (Drew, 2005). Four main groups of dye are commonly used today: (1) optical brighteners; (2) green dyes; (3) orange dyes; (4) blue dyes, with the f rst three being used in most recent tracing experiments in Ireland (Figures 9.23 and 9.24). The advantages of using dyes are that they are cheap, easy to use, can be detected well below the visual threshold and allow for simultaneous use. However, there are also some disadvantages to using fluorescent dyes. Fluorescent substances are found in many common materials such as detergents, and are therefore present in many surface waters, which can cause interference with the recognition of the dye. Also, most fluorescent dyes are photochemically unstable and break down with exposure to light. Some dyes can adhere to organic material, such as soil and clay and some are pH sensitive. For example, the fluorescence intensity of fluorescein decreases greatly in solutions with low pH values (Kola and Amataj, 2006). Many text books, such as Goldscheider and Drew (2007) outline the advantages and disadvantages of each dye.

The level of success of any water trace is directly proportionate to the level of knowledge about the aquifer, i.e. the location of all possible inlet points (swallow holes) and outlet points (springs). The more suitable input sites found, the greater the choice and potential for multi-trace experiments. Due to the unpredictability of karst environments, all possible outlet points must be known and monitored. Unless the tracer is recovered elsewhere, it is dif cult to say whether a negative result at the outlet point or points of interest means it is not connected or is due to an error in the procedure. Other possible outlet points could be several kilometres outside the area being studied. Therefore, the most important part of any dye-trace experiment is a detailed reconnaissance of the area.

Qualitative traces are usually used to conf rm connections. The use of optical brightener and cotton detectors (Figure 9.25) is a quick and easy way to prove connections. Testing for the presence of the optical brighteners, requires the least amount of processing and equipment but can often be the most dif cult to interpret.

Quantitative traces measure the concentrations of the dye over time, at particular groundwater discharge points, after the injection of a known quantity of dye. Fully

Figure 9.23 Uranine dye being injected in a swallow hole near Ennis (County Clare). (*Photograph by Caoimhe Hickey.*)

Figure 9.24 Rhodamine dye being injected into a swallow hole in County Roscommon. (*Photograph by Caoimhe Hickey.*)

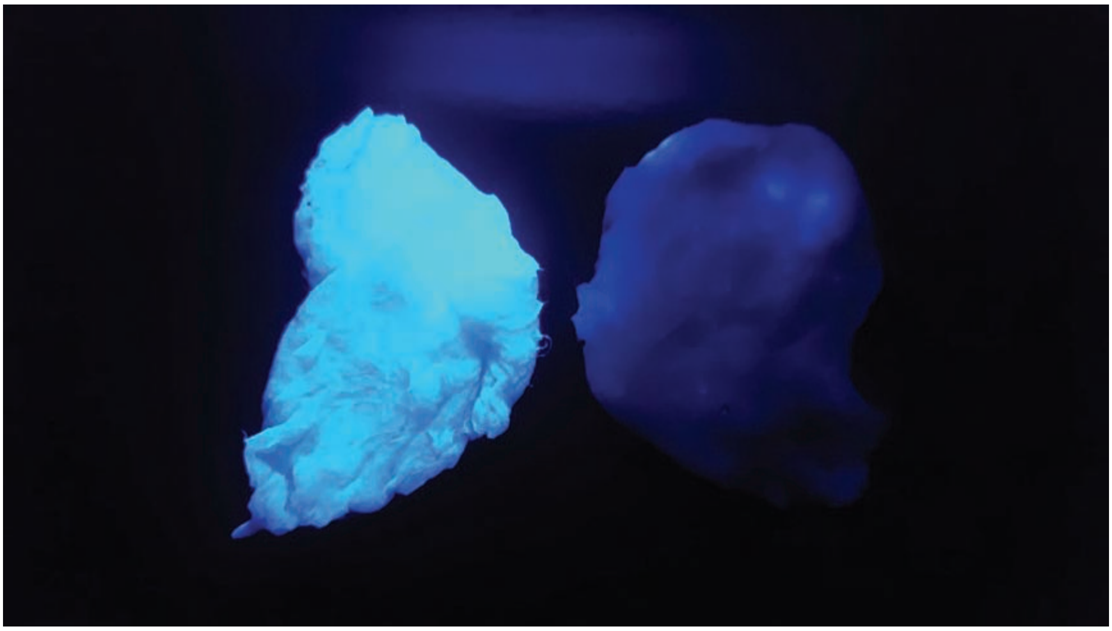


Figure 9.25 The presence of optical brightener is conf rmed in the test cotton, on the left, and not on the control cotton, on the right. (*Photograph by Caoimhe Hickey.*)

quantitative tracer tests require careful measurements of the amount of dye injected, the discharge from the spring or springs and the concentration of dye coming from the aquifer, for the duration of time that the dye emerges from the aquifer. They, therefore, require frequent sampling intervals and frequent discharge measurements.

A fluorometer (Figure 9.26A and 9.26B) is used to analyse the water samples for concentrations of the dye. Automatic f eld through-flow fluorometers (scanning spectro-fluorophotometers) and data loggers enable continuous monitoring of output locations at extremely high resolution (seconds) and are capable of continuously monitoring up to three dif erent dyes, along with turbidity, temperature and electrical conductivity (Figure 9.26B).

During the passage of the tracer, the dye content of each sample is measured. The data obtained from this analysis is plotted against time to produce a dye-recovery (time-concentration) or dye-breakthrough curve. Dye-breakthrough curves can provide a lot of information about the aquifer. The shape of the graph recorded at each spring is a unique reflection of the response of the aquifer to recharge. In particular, the shape of the recession limb of the graph provides information about the storage capacities and structure of the aquifer system, because when the curve is at its peak, dye storage in the system is at a maximum. The slope of the subsequent recession curve shows the withdrawal rate of dye from that storage. The more peaked the graph, the more like surface flow the f ssures and conduits are, indicating a system dominated by allogenic recharge with a well-developed conduit system. The area under the concentration–time curve at a discharge point can give an estimate of the amount of dye recovered and therefore, an indication of the integrity of the pathway.

Figure 9.26 (A) A Cary Eclipse Scanning spectro-fluorophotometer used for analyses of water samples for fluorescent dyes (and other substances). (*Photograph by Caoimhe Hickey*)

Figure 9.26 (B) A GGUN-FL30 Field Fluorometer and data logger in double waterproof housing. (*Photograph by Caoimhe Hickey*)

The important things to consider when interpreting a breakthrough curve are:

- the lag time before the response occurs indicates the groundwater velocities
- the rate of the rise to peak
- the rate of recession as spring fluorescence returns towards its pre-dye outflow
- subsidiary peaks on either limb but especially the recession limb

Figure 9.27 is a dye-breakthrough graph for a spring in County Roscommon. It shows the breakthrough curves for three dif erent dyes, injected at three distinct locations. The time to peak concentrations are the same (probably due to infrequent sample intervals). All three dye-breakthrough curves show a rapid response time (f rst arrival of the dye), but each have dif erent times to leading edge (the start of the rise), peak concentration, dispersion and dye recessions, presumably as a result of characteristics of the individual flow paths between each of the injection sites and the spring. Fluorescein dye was still emerging at the spring more than 20 days after the injection, showing the ef ect of the slower flow paths, possible storage (such as in the epikarst zone) or flow bifurcation.

Tracer recovery is the quantity of the injected tracer that came out at the sampling point(s) versus the amount of dye that was injected. Tracer-recovery calculations are very useful for conf rming the success of the tracing experiment.

9.3.3 Isotope Geochemical Tracing

Karst waters can be characterised by environmental (natural) or anthropogenic tracers (isotopes). Environmental tracers are def ned as constituents of water, which have not been introduced as part of an experiment, that provide information about the hydrological system (Leibundgut *et al.*, 2009). Isotopic measurements of groundwater have become an important tool in groundwater studies since the development and improvements in mass spectrometry from the 1950s.

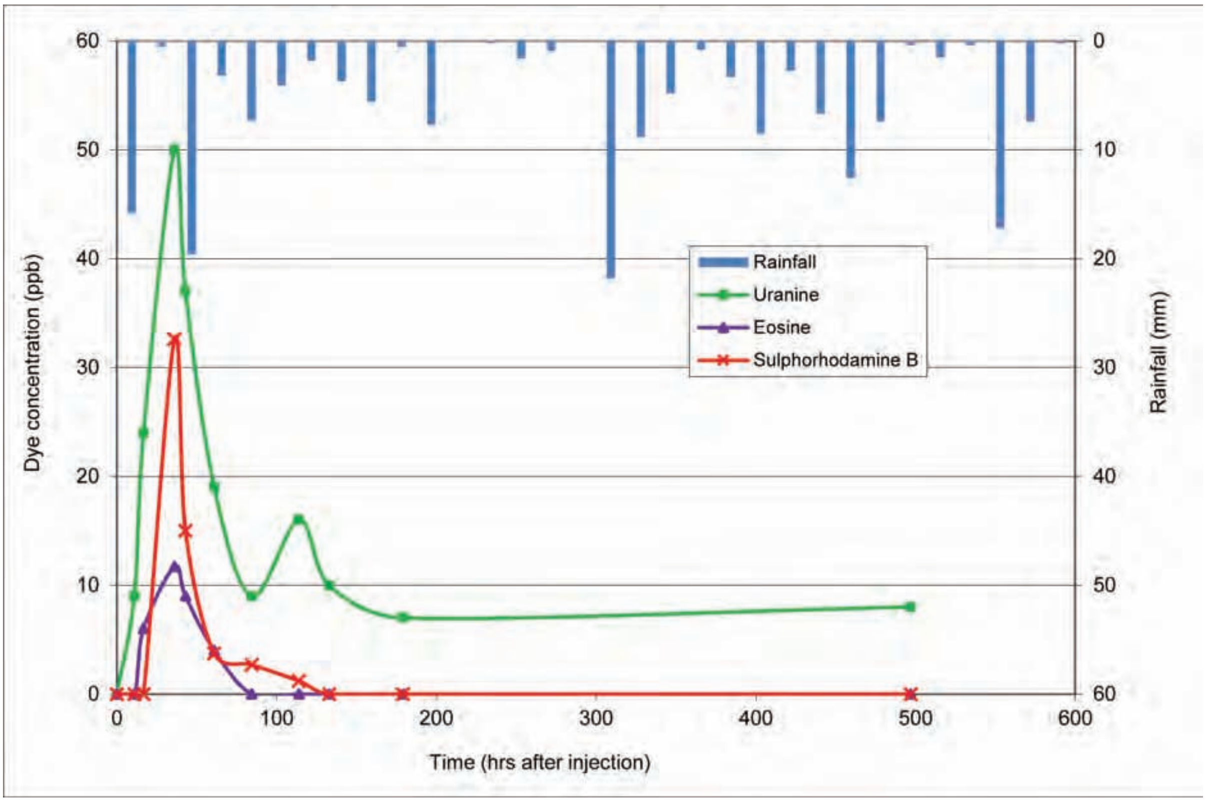


Figure 9.27 Dye breakthrough Curves from Rathleg Spring (County Roscommon). (*Adapted from Hickey, 2008.*)

Dif erent types of environmental tracers can provide dif erent types of information about an aquifer. The concentrations of isotopes in groundwater can be used to identify the source of the water, to trace groundwater flow directions, to date groundwater and the time since a recharge event and characterise recharge conditions at the time of the event (Plummer, 2003). The close interaction of surface and ground waters in karst systems makes the use of isotopic analyses particularly favourable (McCormack, 2014). The most commonly used stable isotopes are ^{18}O and ^{2}H. Stable carbon isotopes are also used to trace karstic groundwaters, as ^{13}C values increase the longer the water comes into contact with carbonate rocks.

Geochemical tracing techniques have been used to verify the presence of submarine groundwater discharge and to provide a qualitative assessment of fresh groundwater inputs to the coastal zone and freshwater lakes all over Ireland (Wilson and Rocha, 2012; Wilson *et al.*, 2016; Wilson and Rocha, 2016), using Radon (Radon-222) and salinity and radon and electrical conductivity. Radon can be used as successful environmental tracer because a distinctive and measurable dif erence exists between radon concentrations in groundwater relative to surface water. Radon was used to conf rm the presence of groundwater 'hotspots' and conductivity or salinity was used to as a secondary tracer to support the radon survey (Figure 8.52). This technique demonstrated the suitability of a multi-tracer approach as comprehensive and cost-ef ective method.

9.4 Geophysical Methods

9.4.1 Introduction

Geophysical investigations provide non-intrusive tools that characterise and map variations in the physical properties of the ground. Geophysical techniques are a valuable tool for investigating subsurface karstification because they may detect voids or areas of missing bedrock, located within competent bedrock. The most successful types of geophysics techniques used to investigate karst are (1) Electrical Resistivity, (2) Gravity and (3) Ground Penetrating Radar (Table 9.3).

Table 9.3 The three principal geophysical techniques for use in karst (O'Connell pers. comm., 2014)

Geophysical Method	Measures/detects	Primary Applications
Resistivity	Variations in ground electrical properties	Overburden type and thickness, rock type, fault zones, voids, karstification, water table
Microgravity	Variations in subsurface density	Caves, cavities, karst/weathered zones, mine shafts, shallow workings
Ground penetrating radar (GPR)	Layer boundaries Buried objects	Service location, location of buried objects, layer boundaries, voids and karstification

9.4.2 Electrical Resistivity

Electrical resistivity tomography (ERT) is the most frequently-used and successful geophysical method for site investigation in karst areas (Zhou et al., 2000). It is a measure of how strongly a material opposes the flow of current.

Saturated porous material will have a much lower apparent resistivity than a dry massive rock and unsaturated sand and gravel deposits. Bedrock such as mudstone and shale typically exhibit low resistivities, while reef limestone typically has high resistivities (O'Connell, 2014). Air filled cavities typically have resistivities of >10,000 Ohm.m.

A great advantage of ERT is that it can be used to image geological features from a few metres to tens of metres in depth, even beneath a water body, and still maintain decent resolution. It is relatively quick to acquire with a single person being able to set up and undertake a typical survey in half a day. Air filled cavities can sometimes be quite difficult to detect as the resistivity of air is infinite, though caves can show up as a region of extremely high resistivity. However, air-filled caves and clay-filled caves have opposite resistivity characteristics, which can interfere with each other, resulting in the data being misinterpreted (Stierman, 2004). Therefore, the more information about the site, the better.

ERT was used in Ireland to locate and map a possible 'cave' some 200 m long (Gibson *et al.*, 2004). The unknown cave was identified adjacent to the Cloyne cave system in County Cork and showed similar resistivity values as the known Cloyne cave system. However, no verification of these features was undertaken. ERT has also been used to identify subsurface pathways beneath Caherglassaun Turlough, in County Galway (O'Connell et al., 2018). A large conduit (25–35 m) was identified from both land- and water-based ERT profiles. It was also used to locate what is inferred to be large conduits, discharging fresh water, beneath Galway Bay (Figure 9.28).

9.4.3 Microgravity

Microgravity is a powerful geophysical technique for use in karst terrains. Microgravity techniques can detect minute changes in the earth's gravitational field due to density variations in the subsurface. Cavities usually present significant density contrasts with their surroundings, which translate into gravitational anomalies. Not only do the anomalies reveal the location of voids and conduits, but they also provide information on their depths and geometry.

A shallow anomaly is usually quite easy to detect because the rock surrounding the cavity is often subject to dissolution. Air-filled cavities offer the largest anomaly because of the complete absence of material. The main drawback of this technique is the large number of corrections (latitudinal, elevational, topographical, tidal and drift) that have to be applied to the data before they are modelled (Gibson et al., 2004). The dimensions of the individual voids are also hard to accurately describe.

Microgravity surveying has been used in karstic terrains in Ireland with a high degree of success (McGrath and Drew, 2002; Hickey and McGrath, 2003/4; Gibson et al., 2004; Styles et al., 2005; Hickey, 2010). Microgravity was successfully employed in Roscommon to detect subsurface pathways beneath a dry valley and lines of dolines. Figure 9.29 shows one of these gravity anomalies, indicating shallow conduits overlying a large deep conduit. Figure 9.30 shows the Bouguer contour map of the same site, displaying a significant gravity anomaly. Subsequent bedrock drilling conducted to ground-truth the gravity results, revealed numerous large conduits at varying depths (with shallow conduits overlying a

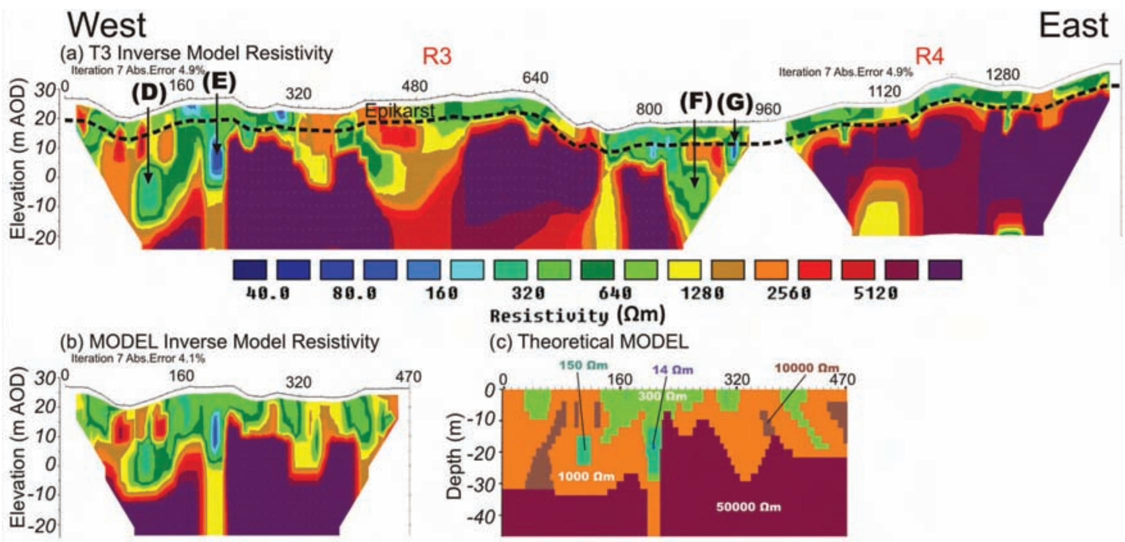


Figure 9.28 Electrical Resisitivity profile in Bell Harbour Catchment, the Burren, County Clare. The shallow resistivity values in the upper 10 m is indicative of shallow epikarst. Other significant resistivity lows (D – G) are interpreted to be fissured or karstified zones. The feature marked at E is interpreted to be a 2 m diameter water filled conduit and D is interpreted to be a 15–20 m karstified zone (McCormack et al 2017).

large deep one). The area had been well studied prior to the geophysical investigations, which greatly aided the success of this technique (Hickey, 2010; Hickey and McGrath, 2003/4).

9.4.4 Ground Penetrating Radar

Ground penetrating radar (GPR) is a useful method for detecting shallow cavities (Chamberlain et al, 2000) in areas not overlain by water-logged overburden. It is also good at acquiring water-table or bedrock surface information. It consists of transmitting electromagnetic (EM) pulses into the ground and measuring the strength and timing of signals that are reflected back from dif erent subsurface interfaces. Reflections are created when the energy pulse moves into a dif erent material. The strength of the reflection is determined by the contrast in the dielectric constants and conductivities of the two materials. Air-f lled cavities and layers with a high water content are strong reflectors of radar.

GPR can only be used for the shallow subsurface; high resolution prof les are limited to the top 5 m of the subsurface and lower resolution prof les (which will not detect the smaller voids) are limited to the top 20–30 m. Water-logged overburden attenuates GPR signals and reduces the shallow depth of penetration even more and this can be a signif cant issue for the use of this technique in Ireland.

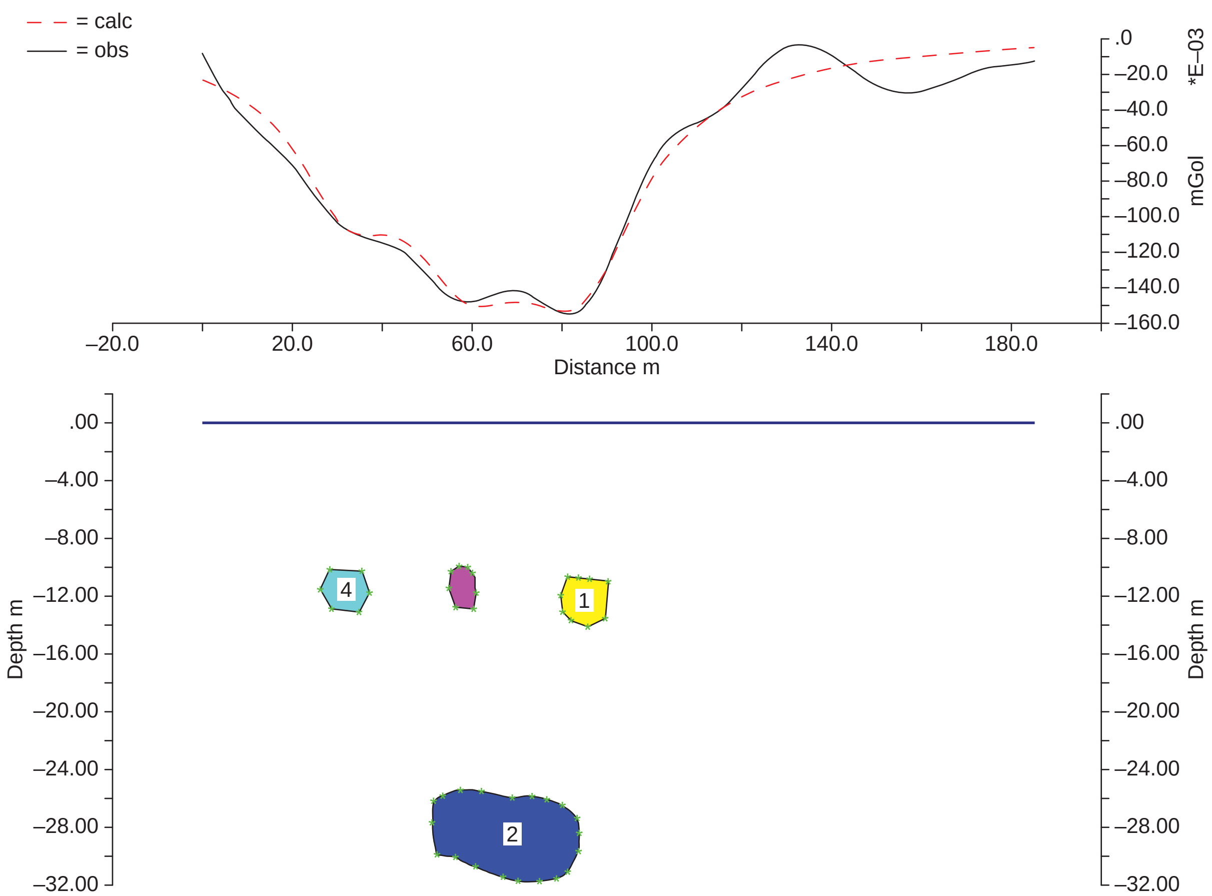


Figure 9.29 Gravmag modelling showing a large deep conduit (dark blue) overlain by shallower conduits (other colours). *(From Hickey and McGrath, 2003.)*

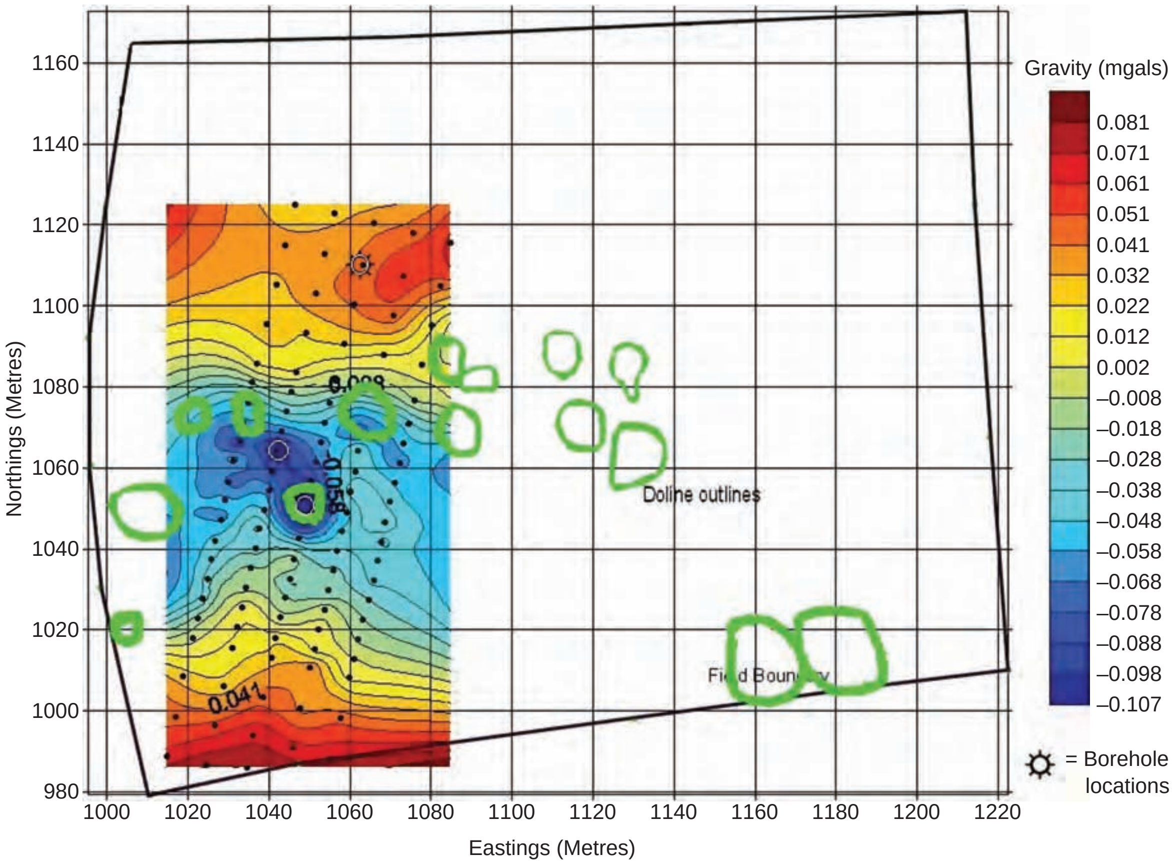


Figure 9.30 Bouguer contour map showing the location of a large conduit underneath a line of enclosed depressions (Castlerea, County Roscommon). *(From Hickey and McGrath, 2003/4.)*

GPR has been used in Ireland to detect shallow voids in areas that are not overlain by water-rich (conductive) overburden: for example, to detect very shallow cavities in the overburden above limestone (Long, 1998) and karst features to a depth of 9 m, for a large development in County Meath (Apex Geoservices Ltd).

No geophysical method is perfect for karst investigations and, depending on the environment to be investigated, some methods are more suitable than others. Of the above geophysical techniques, microgravity and resistivity imaging are likely to be the most successful for the types of conditions that prevail in Ireland. The more that is known about a site prior to undertaking the geophysical investigations, the better the interpretation of the results will be. Nonetheless, with proper constraints and application, geophysical techniques of er cost-ef ective tools for characterising the subsurface in karst environment, especially in localised areas of investigation.

9.5 Modelling

9.5.1 Introduction

Numerical groundwater modelling has become a fundamental technique for groundwater management. Groundwater models are frequently used to improve understanding of hydrological and groundwater processes and to allow predictions about the future.

Classical numerical models have serious limitations in modelling karst groundwater flow. These problems are caused by the anisotropic and heterogeneous nature of most karst, the uniqueness of each karst area and the inability to see and accurately predict what is happening in the three main flow systems (matrix, fissure and conduit), and the interaction between the different systems.

However, over the past two decades mathematical models have been specifically developed to account for the hydraulic characteristics of karst aquifers (Király, 2003; Ghasemizadeh et al., 2012; Kovács and Sauter, 2007). Mathematical models can now characterise development, flow and transport within karst aquifers and can account for turbulent and laminar flow in pipe-like conduits.

Conceptual models are important as they are usually the first step in the development of a mathematical groundwater flow model. In fact, developing a good conceptual model is often considered the most important part of the entire modelling process (Ford and Williams, 2007). They nearly always consider hydrological factors (such as flow regime, recharge, flow and discharge) and the nature of the aquifer framework (such as topography, geology, structure and rock chemistry) and storage (Figure 9.31). A good understanding of as many of these factors as possible is needed, in order to produce meaningful mathematical models. Hence, the availability of reliable, long-term data is critical to the production of a successful mathematical model.

9.5.2 Mathematical Models

Mathematical models are mathematical descriptions of conceptualised flow and transport. In karst aquifer systems, flow and transport behaviour for the matrix, fracture and conduit systems should be considered. The entire system is a combination of these separate flow systems. There are two main modelling approaches for studying and conceptualising karst hydrogeological systems: global models and distributive models.

Global models

Global models (sometimes known as spatially lumped models or lumped parameter models) are based on the assumption that spring discharge represents a reflection of the overall (global) hydrogeological response of karst aquifers. The karst system is seen as a specific controller that transforms input signals into output signals and the models describe this relationship (McCormack, 2014). This type of global 'black box' approach, therefore, focuses on input events and corresponding output response (Ford and Williams, 2007). Two different lumped-parameter modelling approaches are hydrograph-chemograph analyses and rainfall-discharge models. However, as the karst response is 'lumped' they cannot be used to analyse how the aquifer behaves spatially.

Distributive models

Distributed models divide karst aquifers into a grid of homogeneous sub-units with each sub-unit having specific properties. These models can be both spatially and temporally variable and thus are able to characterise groundwater flow and transport in the whole aquifer. However, the ability to define spatially distributed hydraulic properties and boundary

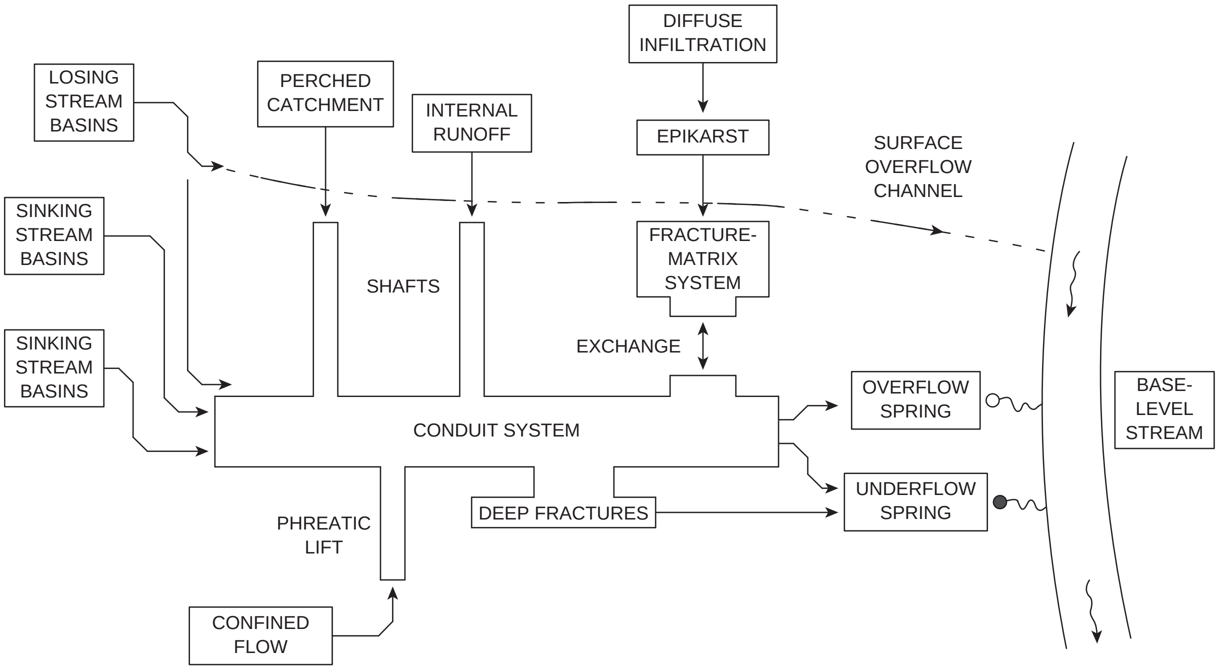


Figure 9.31 Some aspects to consider for a conceptual model of a karst aquifer. *(From White & White, 2003.)*

conditions requires large amounts of data and usually requires extensive investigations (Ghasemizadeh et al., 2012).

The biggest challenge of distributed-modelling approaches is how to cope with the high spatial heterogeneity (matrix, fractures and conduits) of karst aquifers. Some approaches only focus on aquifer porosity and ignore high permeability features (equivalent porous medium approach or EPM), some focus on the fracture or conduit network and treat the matrix as impermeable blocks (discrete fracture or channel network approach or DFN and DCN), or some try to consider both (Combined Discrete-Continuum Approach or CDC).

An example of modelling karst in Ireland is given in Chapter 10. This case study outlines modelling approaches used to model the complex karst of the Gort lowlands, County Galway.

9.6 Combined Use of Methods

Any comprehensive investigation can only be achieved when a combination of as many analytical tools as possible are employed (Bakalowicz, 2005). No single method is perfect, and the use of various methods in conjunction allows the shortcomings of one method to be supplemented by another. For example, geophysical investigations may indicate the location of a karst conduit but may not reveal conduit geometry or flow velocities within it. Drilling can then be used to accurately locate and verify the conduit and to reveal conduit dimensions. Tracing can also be used to give velocities and flow directions within the conduit and aquifer (if accessible). The combined use of methods is also a good way to validate the results of one method of investigation.

Chapter 10

CASE STUDIES OF IRISH KARST

10.1 Introduction

Examples of some recent investigations in karst regions of Ireland are presented as case studies in this chapter. Each case study presents a brief description of the work carried out and a summary of the main findings. The references are included in the main bibliography. The intention is to give the reader an understanding of the steps involved in undertaking an investigation in karst hydrogeology, including the basic data sources required, field investigations, techniques and timelines. The case studies were chosen to illustrate the use of a number of different techniques in differing types of Irish karst. All of the karst areas included in the case studies that follow are described in general terms in Chapters 7 and 8.

The first case study (Section 10.2) describes and explains the phenomenon of flooding in the lowland karsts of the west of Ireland. This study is especially relevant following the extensive flooding events in the 1990s and then again in 2009 and 2015. The study demonstrates that due to the unpredictability of karst, especially during extreme events, flood prediction can only be attempted once each flood area is characterised and understood and this is best achieved by evidence-based assessment.

The second case study (Section 10.3) is concerned with one of the areas liable to groundwater flooding described in Section 10.2: the Gort–Kinvara area of County Galway. A significant hydrological database of accurate long-term hydrometric information exists for this area and it is, therefore, a good candidate for karst groundwater modelling. The study outlines the evolution of the karst groundwater modelling in the area and illustrates how each model has incorporated and built on any shortcomings of the previous models.

The third case study (Section 10.4) looks at karst development in the structurally complicated area of the southern karst region of Ireland. In this area, located in the catchments of two major tributaries of the River Blackwater in north County Cork, water-tracing experiments have yielded no positive results. The interfluves between the major rivers exhibit many karst landforms but the exact nature of the karst drainage systems is not well understood.

The last case study (Section 10.5) outlines the importance of karst-specific techniques for delineating groundwater catchments (zones of contribution) to a series of springs located at the perimeter of an upland area in Roscommon: the Rathcroghan Upland. Most of the springs are drinking-water sources and are prone to contamination. The results of detailed karst mapping and numerous dye tracing experiments are presented, as are the inferred zones of contribution to the springs. The study details the importance of karst specific techniques; the need for significant resource input and the requirement for suitable weather conditions and for sufficient time to satisfactorily complete zone of contribution studies in karst terrains.

A feature common to all the investigations described above is that they are intended to provide answers to questions of practical relevance, whether related to flooding or to water supply in karsts.

10.2 Assessing Groundwater Flood Hazards in Lowland Karst

Owen Naughton and Paul Johnston

Groundwater flooding in Ireland is common on the extensive Carboniferous limestones of the western lowlands, which extend from the River Fergus in County Clare in the south to the areas east of Lough Mask and Lough Corrib in County Galway, southern County Mayo and Roscommon (Mott MacDonald, 2010). The characteristics of karstic groundwater flow systems across the region, namely low aquifer storage, high diffusivity and a shallow vadose (unsaturated) zone, leave them particularly susceptible to groundwater flooding. During periods of intense rainfall, typically during the winter months, the solutionally-enlarged flow paths are unable to drain recharge entering the karst system (Naughton et al., 2015). The limited storage available within the aquifer swiftly reaches capacity and, if rainfall persists, surface flooding can occur in low-lying areas. This recurrent flooding of topographic depressions and bedrock hollows gives rise to a characteristic habitat of the Irish karst landscape: the turlough (Naughton et al., 2012; Sheehy-Skeffington et al., 2006; Visser et al., 2006).

Historically, groundwater flooding has not been recognised as posing a significant flood risk due to the typically local scale of flooding and low density of receptors. As a result, flooding derived from groundwater sources has received relatively little attention in the context of flood risk management. This has started to change in recent years due to the introduction of the EU Floods Directive into Irish legislation in 2007, which requires the State to reduce and manage risk from all forms of flooding, including groundwater. The unprecedented groundwater-related flood events which occurred during the winters of 2009 and 2015 have also brought the issue of groundwater flooding into sharp focus (McCormack and Naughton, 2016; Naughton et al., 2016). Following the extreme flood events of 2009, a study on the assessment of groundwater flooding risks posed by turloughs was carried out by the authors, jointly funded by the Office of Public Works (OPW) and the Irish Research Council. The first element of this study was to look at the fundamental processes governing flooding in Irish lowland groundwater flow systems. The second part of the project, and the subject of this case study, was a detailed flood assessment of key locations identified by the OPW and local authorities as potentially affected by groundwater flooding and requiring further investigation.

Ten sites were highlighted for study; eight in County Galway and one each in County Mayo and County Roscommon (Figure 10.1). Seven sites had been identified as at risk of groundwater flooding during the Groundwater Preliminary Flood Risk Assessment (PFRA) with one, Doughiska Turlough located on the eastern edge of Galway City, categorised as an Area for Further Assessment (AFA) (Mott MacDonald, 2010). PFRA flood boundaries had not been delineated for three sites but these were highlighted due to specific or recurrent flood events in the recent past with a suspected groundwater component. The objective of each

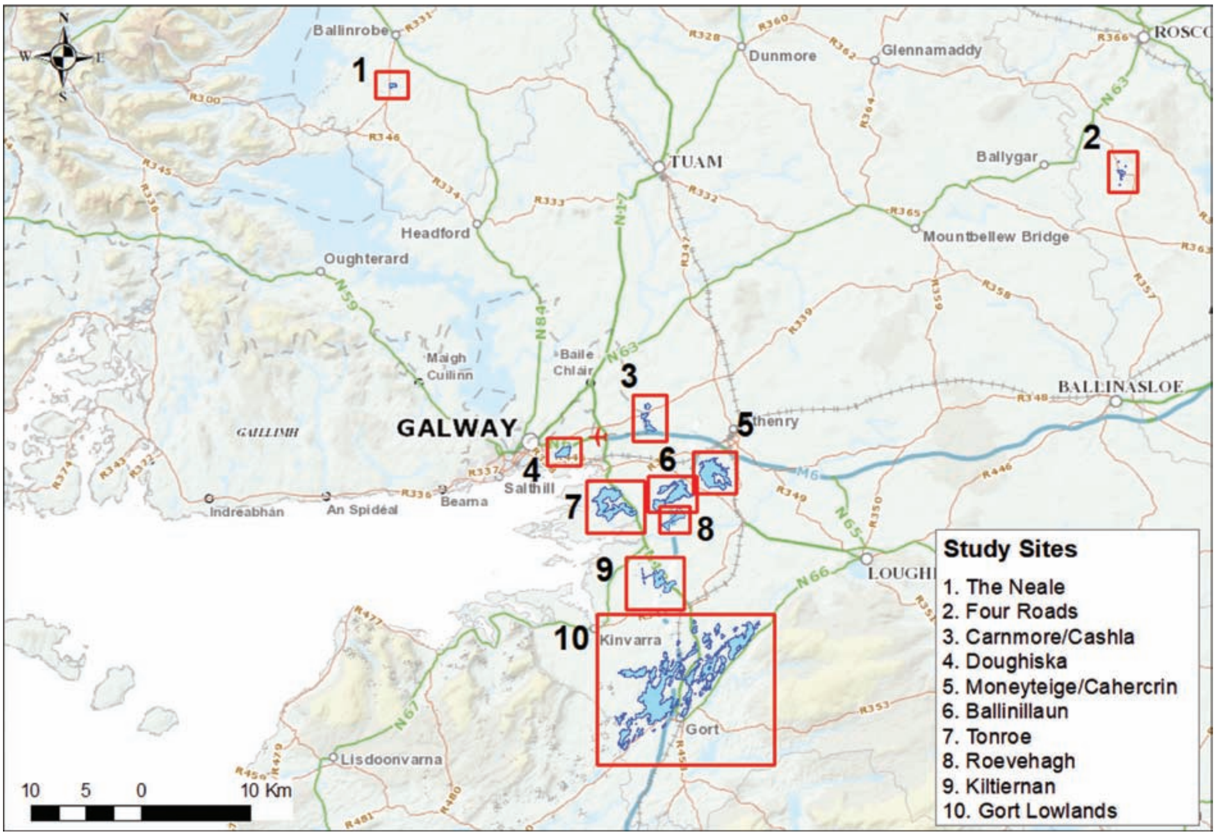


Figure 10.1 The location of the ten study sites.

groundwater flooding case study was to assess the extent, nature and mechanisms of flooding, whether a significant flood risk existed and if groundwater was the key contributor to that risk.

Each site investigation comprised two parts; a desk study and an assessment of flooding. The desk study described the key site attributes in terms of geology, hydrogeology, topography, meteorology, hydrology, ecology and flood receptors. Site visits were carried out to augment and validate information collated during the desk study. The second element of each case study consisted of a flood assessment which incorporated all available information and evidence of flooding. Due to the heterogeneity of karst groundwater flow systems, and the generally poor data availability, the methodology used varied from site to site and had to be tailored to the available data and evidence of historic flooding. Information was derived from a variety of sources, including:

- aerial photography and videography of flood events
- turlough water level data (Trinity College, Dublin)
- river hydrometric data (OPW, Environmental Protection Agency)
- SERTIT satellite flood extent maps
- local authority road closure maps and notices
- OPW National Flood Hazard Mapping website (http://www.floodmaps.ie)
- historical 6″ and 24″ maps (areas "liable to flooding")
- technical reports (e.g. Gort Flood Study, consultant/local council reports, EIAs)
- accounts from local residents
- online resources (photographs, local media reports etc.)

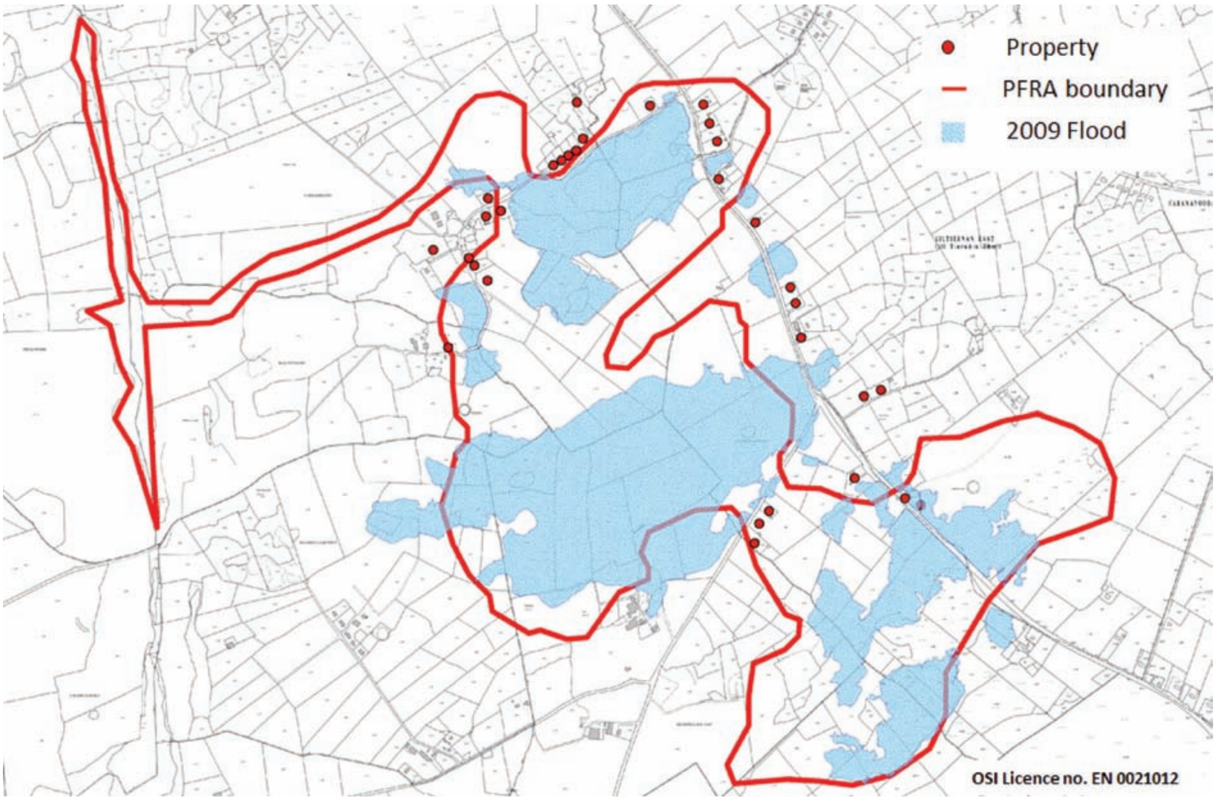


Figure 10.2 Map of Kiltiernan Groundwater PFRA boundary and estimated peak flood levels for November 2009.

Where available, indicative flood hazard boundaries were delineated using a combination of aerial photography, hydrometric measurements and high-resolution topographic (LiDAR) data. The validity of the Groundwater PFRA boundary was assessed in the context of site hydrology, topography and previous flood events. When there was found to be a significant under/over-estimate of the probable area liable to flooding, an alternative indicative flood boundary was delineated (Figure 10.2). Information on the timing of specific flood events was used to assess the critical rainfall duration (or durations) which influenced the magnitude of flooding within the study areas. A comparison of water levels and corresponding rainfall maxima across a range of durations was carried out, providing insights into the hydrological response of karstic groundwater flow systems to extreme recharge events.

A high level of anthropogenic modification of the natural karst groundwater system was identified across a number of sites, resulting in a likely significant overestimate of the risk posed by groundwater flooding there during the PFRA process. For example, at Doughiska turlough its functionality as a wetland had largely disappeared due to partial infill, infrastructural development and artificial drainage and so little or no evidence of significant turlough or turlough-related flooding could be identified. The PFRA boundaries derived for Ballinillaun and Moneyteige/Cahercrin were based on the presence of a number of recorded turloughs within the site boundary. However, historical arterial drainage works had modified the regional hydrology to such an extent that the turloughs appeared to act more as flood plains than turloughs under the current-day hydrological regime. Thus, the primary flood risk in these areas appeared due to fluvial flooding associated with the Clarinbridge River, rather than groundwater flooding. In other locations, such as Kiltiernan, the flooding was essentially groundwater driven and associated with a cluster of turloughs. However, a local drainage scheme enabled surface-water transfer between adjacent flooded depressions and provided increased drainage capacity at high water levels, thereby limiting flood extent and changing the natural flooding behaviour of turloughs in the area.

The flooding at four study sites; Carnmore/Cashla, Four Roads, The Neale and the Gort Lowlands; had a strong groundwater component. However, diverse flood mechanisms were identified as responsible beyond purely turlough flooding. While the primary form of extensive, recurrent groundwater flooding in Ireland originates in turloughs, during extreme groundwater flood events a range of mechanisms beyond simple turlough flooding play a key role, often in combination with each other as well as other forms of flooding. Excess diffuse recharge can overwhelm the storage and drainage capacity of the epikarstic zone, causing the unconfined water table to breach the surface and pond in a manner analogous to pluvial flooding. Fractures and dissolution features in the shallow epikarst may become active flow paths at exceptionally high groundwater levels, giving rise to ephemeral springs and seeps in adjacent topographic depressions previously unaffected by flooding. This probably contributed to the flooding in Carnmore/Cashla area, County Galway.

Groundwater springs and risings can exceed normal discharge levels and cause localised flooding around and downstream of the resurgence, such as happened in Four Roads, County Roscommon. Excess point recharge (such as sinking rivers) can inundate sinks and swallow-holes capable of accommodating recharge under normal conditions. Such cases would clearly have a strong fluvial component, and this is a key flooding mechanism in the Gort Lowlands. This integrated groundwater–fluvial flooding may manifest itself as backwater flooding of the area upstream of the sink, or overland flow into adjacent areas due to overtopping of the topographic depression containing the sink. Such flooding inundated six residential properties in Skehanagh, County Galway, when the floodwaters accumulating around Blackrock Turlough overflowed to the south towards Ballylee.

10.2.1 Conclusions

An understanding of the interactions between recharge, storage and transport mechanisms during flood conditions is a precursor to effective flood risk assessment. However, the heterogeneity of karstic groundwater systems is such that they can often behave in unpredictable ways during extreme weather events, making the development of such an understanding difficult. The lack of an established theoretical foundation for groundwater flood prediction means that an evidence-based approach is the most appropriate for groundwater flood risk management in the Irish context. While it is difficult to ascribe a recurrence interval to the floods of recent years, given the unprecedented nature of rainfall 2009 and 2015 in particular (McCarthy et al., 2016), it is reasonable to assume they represent an extreme event as described by the EU Floods Directive. Therefore, by considering evidence of flooding from recent events, together with the possible flood mechanisms outlined above, it is possible for the practitioner to develop an understanding of groundwater flood hazards in lowland karst.

10.2.2 Acknowledgements

The work described here was jointly funded and supported by the OPW and the Irish Research Council. The authors would like to thank Mark Adamson and Richael Duffy of the OPW for their assistance throughout the project. The authors would also like to thank the Irish Meteorological Service (Met Eireann) for the provision of rainfall data; Galway County Council and Galway City Council for the provision of aerial photography, GIS data and documentation; the Environmental Protection Agency for the provision of hydrometric data; and the OPW for the provision of LiDAR, hydrometric and aerial photography data. Ordnance Survey Ireland data reproduced under OSI Licence number EN 0021013 (Office of Public Works).

10.3 Modelling the Gort Lowlands Conduit Network Model

Ted McCormack, Laurence Gill, Paul Johnston and Owen Naughton

The Gort Lowland is a highly karstified environment with a well-developed conduit system transmitting allogenic runoff from the Old Red Sandstone Slieve Aughty uplands towards the sea at Kinvara via a network of rivers, conduits and interlinked turloughs (Chapter 7). The complex flow routes within the karst have been the subject of research by academics, speleologists and engineers over past decades and, as such, the underground conduit network is relatively well understood and a significant historic database of hydrometric data is available. This knowledgebase provides the opportunity to apply distributive numerical modelling to the catchment.

The first of these models was developed as part of the Gort Flood Studies (Southern Water Global, 1998). The model was built using urban drainage network design software, *Hydroworks* (Wallingford Software), which is capable of modelling the hydraulic conditions in both open channel and pressurised flow channels, and is thus highly suitable for modelling a well-developed karst conduit network with much groundwater–surface water interaction, such as the Gort Lowlands catchment. The model performed sufficiently for the purposes of the study but suffered from a lack of long term data and an inability to model diffuse groundwater flux leading to poor accuracy in many areas of the catchment.

In 2010, a new and more advanced model was constructed by the Department of Civil, Structural and Environmental Engineering in Trinity College Dublin (TCD). This model, which was constructed using *Infoworks CS* (a successor of the original *Hydroworks* modelling engine), benefited from long-term accurate hydrometric data, improved rating curves and survey data, as well as a mechanism to model diffuse groundwater flux to the conduit network (Gill, 2010). The model allowed for the simulation of groundwater–surface water flux between the active conduit network and a series of interconnected turloughs within the lowlands.

Distributive models are built by dividing a hydrogeological system into sub-units which can be described by basic physical laws (Kovacs and Sauter, 2007). This type of model can then be used to produce a quantitative characterisation of the karst system by assessing spatial and temporal changes in hydrogeological parameters. In a complex karst system such as the Gort Lowlands, a considerable quantity of real-world hydrometric data are required to build and calibrate the model. For the Gort model, the required information included:

- OPW hydrometric data for the rivers entering the catchment. These data were then enhanced using TCD-derived rating curves to provide accurate discharge data at low and high flow conditions.

- Rainfall and evapotranspiration data from TCD and Met Éireann rain gauges within and nearby the catchment.
- Topographic information for turlough basins (based on LiDAR and walk-over surveys).
- Long-term turlough water-level data (6 years of data were available at the time of calibration).

The model, constructed using a discrete conduit network approach, represents the main conduit flow system as a series of pipes (conduits) and tanks (turloughs). Allogenic recharge enters the model at three locations, corresponding to the three main rivers feeding the Gort Lowlands (the Owenshree, Ballycahalan and Beagh; Figure 10.3). Autogenic recharge is incorporated into the model via a series of sub-catchments and permeable pipes which represent diffuse epikarstic storage and flux into the mainline conduit system (Figure 10.4). The turloughs operate as surcharge tanks, offering additional storage capacity when the underground conduit network has exceeded capacity. The flood behaviour in these modelled turloughs was calibrated against the field data, mainly by adjustments to the main pipe layout and diameters, particularly at the sections just downstream of the turlough known as throttle pipes. Additional hydrogeological controls and conduit configurations in the hydraulic systems were determined using a variety of time-series analytical techniques on the measured water-level data (Gill et al., 2013a). The model also simulates the changes in sea level at the outlet of the system where it discharges at a tidally impacted spring at Kinvara.

Nash Sutcliffe r^2 (i.e. goodness of fit) values of between 0.81–0.97 were achieved for turlough water levels after calibration. This level of accuracy allowed the model to be used

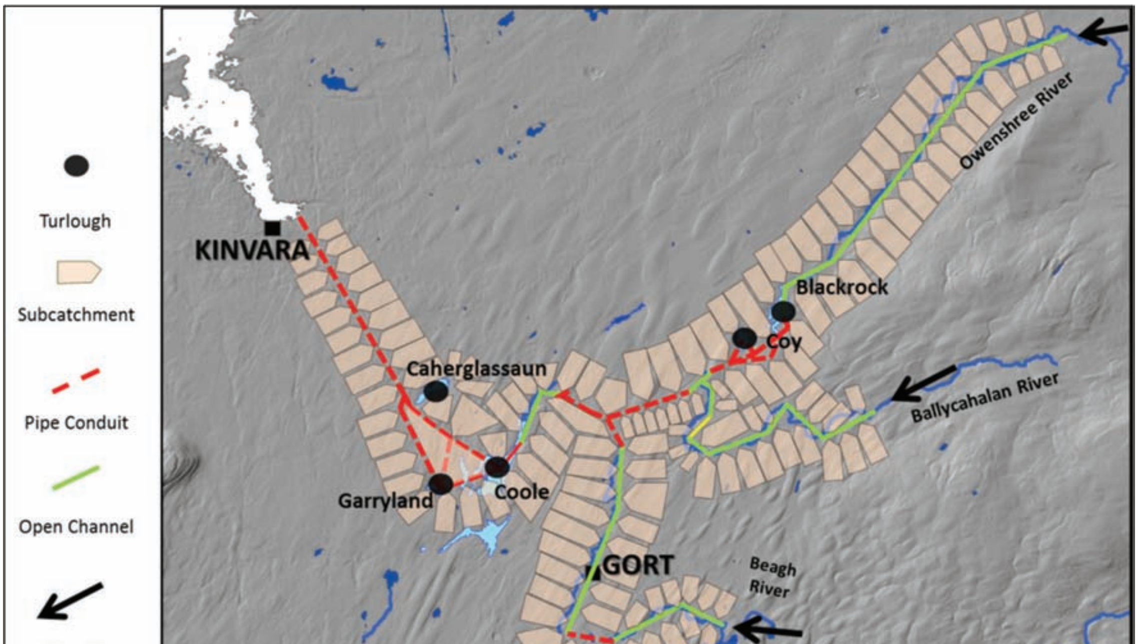


Figure 10.3 Conduit network model schematic.

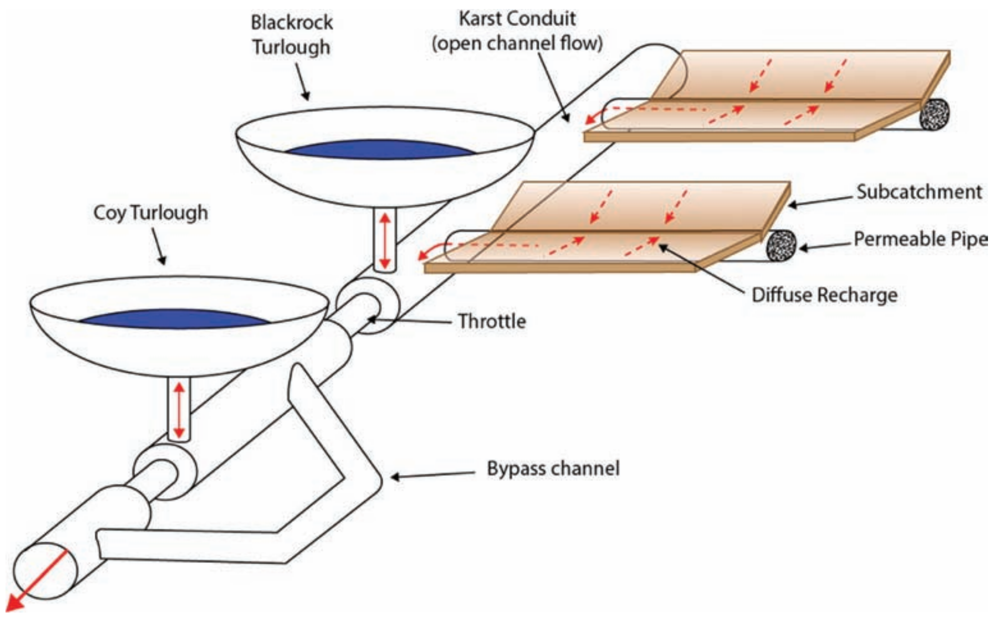


Figure 10.4 Conceptual model of Blackrock and Coy turloughs showing pipes, tanks, throttles, bypass channel and sub–catchments.

to investigate hydrogeological relationships between turloughs (Gill et al., 2013b), the hydrochemical functioning of the turloughs (McCormack et al., 2016) and the submarine groundwater discharges at the Kinvara outlet (McCormack et al., 2014). Further research on groundwater flooding and climate change impacts using the model is currently on-going in TCD.

Hydrogeological models of karst systems range in complexity depending on available information and the desired outputs of the model. Choosing the correct modelling approach is of critical importance when beginning any modelling study. Global models transform an input signal into an output based on a mathematical function (which can be a relatively simple equation) whereas distributive models can be intricate tools requiring detailed information of hydraulic parameters, recharge conditions and aquifer geometry. The knowledge base built up in the Gort Lowlands after many years of investigation and monitoring by TCD allowed for a distributive model to be chosen and successfully applied. This case study is thus an example of using an applicable modelling technique for an appropriate purpose.

10.4 Karst Hydrogeology, North County Cork

Coran Kelly

10.4.1 Introduction

In north County Cork, groundwater provides over 30,000 m^3/d of drinking water *via* public water supplies, the majority of which are karst springs (Figure 10.5). Many of these are also part of the National Groundwater Monitoring Network. Hydrogeological investigations have been conducted by GSI and the EPA in relation to the karst springs that provide the majority of the public water supply (Kelly, 2000, 2010, 2012, 2014, and 2016).

10.4.2 Physical Setting

The study area is situated in the Upper Blackwater River catchment, specifically, the fluviokarst terrain cut by the Awbeg and Funshion river systems (Figure 10.5). These rivers are two major left bank tributaries of the Blackwater itself. The area forms part of what is referred to as the "Munster Synclines or the "Munster Ridge and Valley Province", the characteristic form of which comprises east–west trending anticlines (sandstone ridges) and synclines (limestone valleys).

The limestone 'valleys' form a landscape that comprises a broad interfluve gently undulating between 60–110 m OD. The northerly extent of the interfluve occurs at the foot of the Ballyhoura Mountains. At this point the land rises steeply to approximately 500 m OD from approximately 110 m OD. The Blackwater River demarks the southern extent of the plateau. The topography of the interfluve can be subdivided into distinct landforms. Glacial deposits are present but glacial landforms are not very apparent. Though glacial landforms are not obvious, there is a fluvial/karst intermix; fluvial in the main river valleys and karst on the interfluves (plateau) — a fluviokarst landscape.

The main rivers are the Awbeg, Funshion, Farahy (a tributary of the River Funshion), Ogeen and Bregoge (both tributaries of the River Awbeg). The Awbeg initially flows west to east and then turns south just downstream of Shanballymore Spring, joining the Blackwater River south of Castletownroche. The Funshion flows in a well-defined valley, joining the

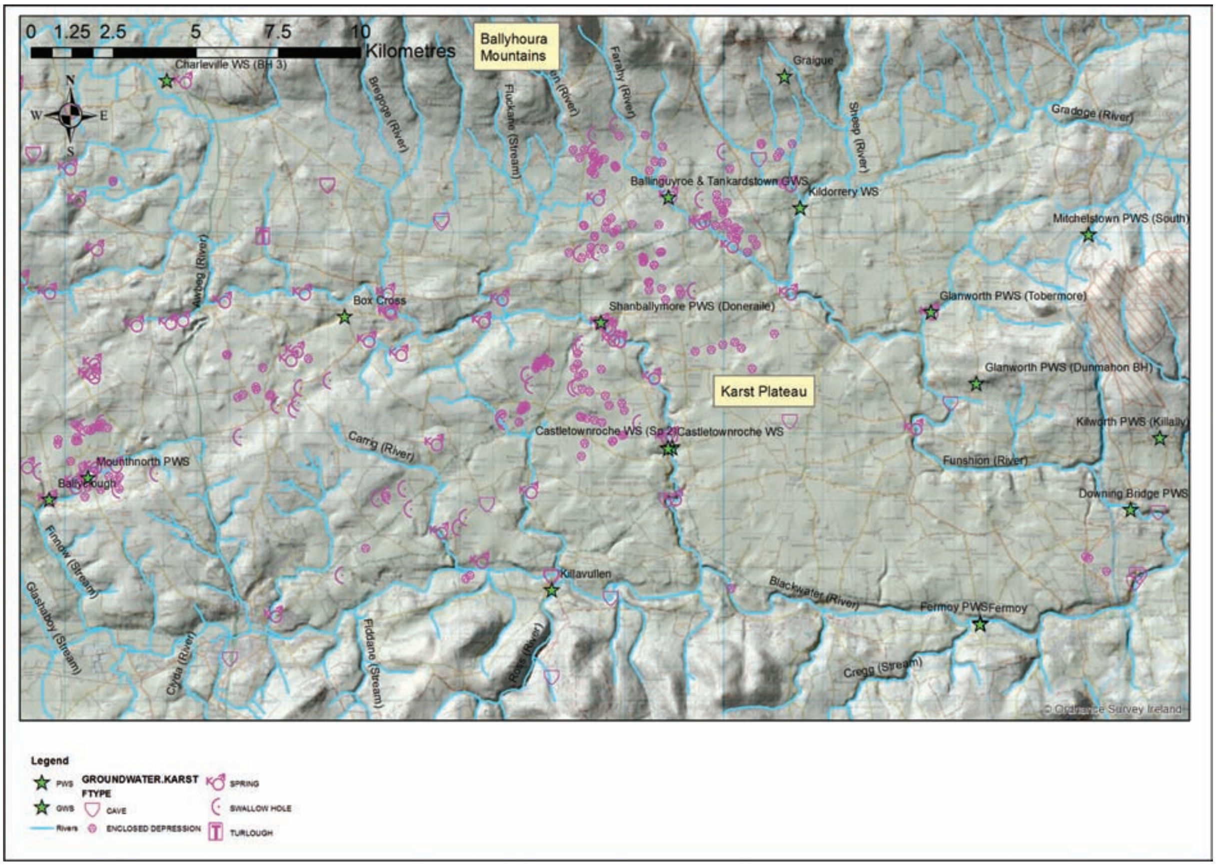


Figure 10.5 Physical landscape, topography, rivers, karst features and water supplies (PWS – Public Water Supply and GWS – Group Water Scheme).

Blackwater River, east of Fermoy. The rivers flow in deep valleys which are particularly pronounced in places, for example in the vicinity of Shanballymore spring and as far as Castletownroche along the Awbeg River.

The plateau within which the rivers are incised covers over 100 km^2 and is devoid of a surface drainage system. However, the surface area of the plateau is pitted by recognisable karst landforms, including dry valleys, springs, sinks/swallow holes, caves and enclosed depressions. Some main points about the karst features are outlined below:

- The springs occur in the valley floors at the interface between the karst and fluvio environments.
- There are several dry valley tributaries to each of the rivers: for example, into the Awbeg just downstream of Shanballymore Spring.
- Active swallow holes are present.
- Local farmers indicate that small collapse features, a few metres in depth and width, ('sluggeras') appear in the fields. There are a few enclosed infilled depressions in the area, holding stagnant water. Dolines and depressions occur on the plateau but are not common.
- The Bregoge River has several obvious sinks in the river bed. The adjacent Ogeen is thought to infiltrate also but no obvious sinks are evident. Recent work done by Geological Survey Ireland shows that the Funshion River infiltrates along identified reaches of its channel.

The main ridges, consist of sandstones (Devonian) and shales (Namurian) and the valley areas are underlain principally by massive unbedded limestones (Sleeman and McConnell, 1995) (Figure 10.6). The geology in the region of Shanballymore Spring is complex, with a combination of varied lithology and intense structural deformation and history (Pracht, 2016). GSI mapped and logged bedrock exposures and drilled four diamond drill holes into undifferentiated limestones in the vicinity of Shanballymore to better understand the stratigraphy and structure and to improve the current published geology map. An improved geological map is presented in Figure 10.6 based on a report by GSI (Pracht, 2016).

10.4.3 Hydrogeological Investigations 2009–2016

The springs are principally concentrated along the Awbeg and Funshion, with smaller springs discharging to the Farahy, Ogeen and Bregoge. In general, the springs are discrete outflows. Only Shanballymore and the Castletownroche springs have any historical 'spot' flow data. A crude approximation of the outflows indicates a total discharge 250–350 l/s. The topographic area that could discharge to springs is in the order of 115 km^2, which potentially could generate over 700 l/s.

Tracing has been conducted at eight active swallow holes in the vicinity of Shanballymore and Mountnorth springs and Box Cross PWS shown in Figure 10.7, and sampling sites included all of the springs along the Awbeg, Funshion and Finnow streams. Details of the tracing are provided the groundwater source protection zone reports (Kelly, 2010, 2012). None of the tracer injected to date has been recovered. The negative tracing results suggest that the bulk of the groundwater does not discharge at the springs.

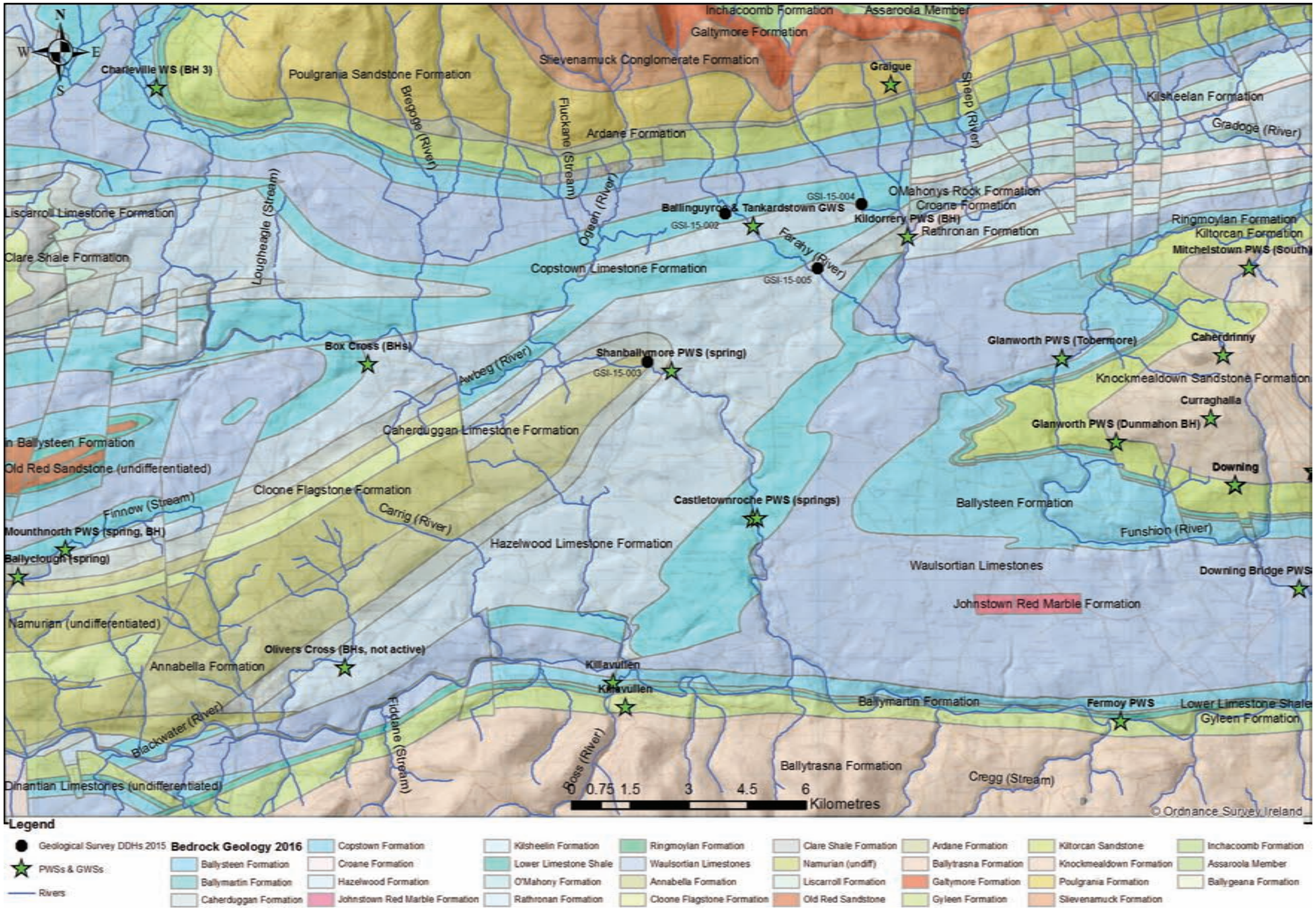


Figure 10.6 The geology and main springs of the region. *(After Sleeman and McConnell, 1995 and Pracht, 2016.)* (DDH – diamond drill hole; PWS – public water supply; GWS – group water scheme).

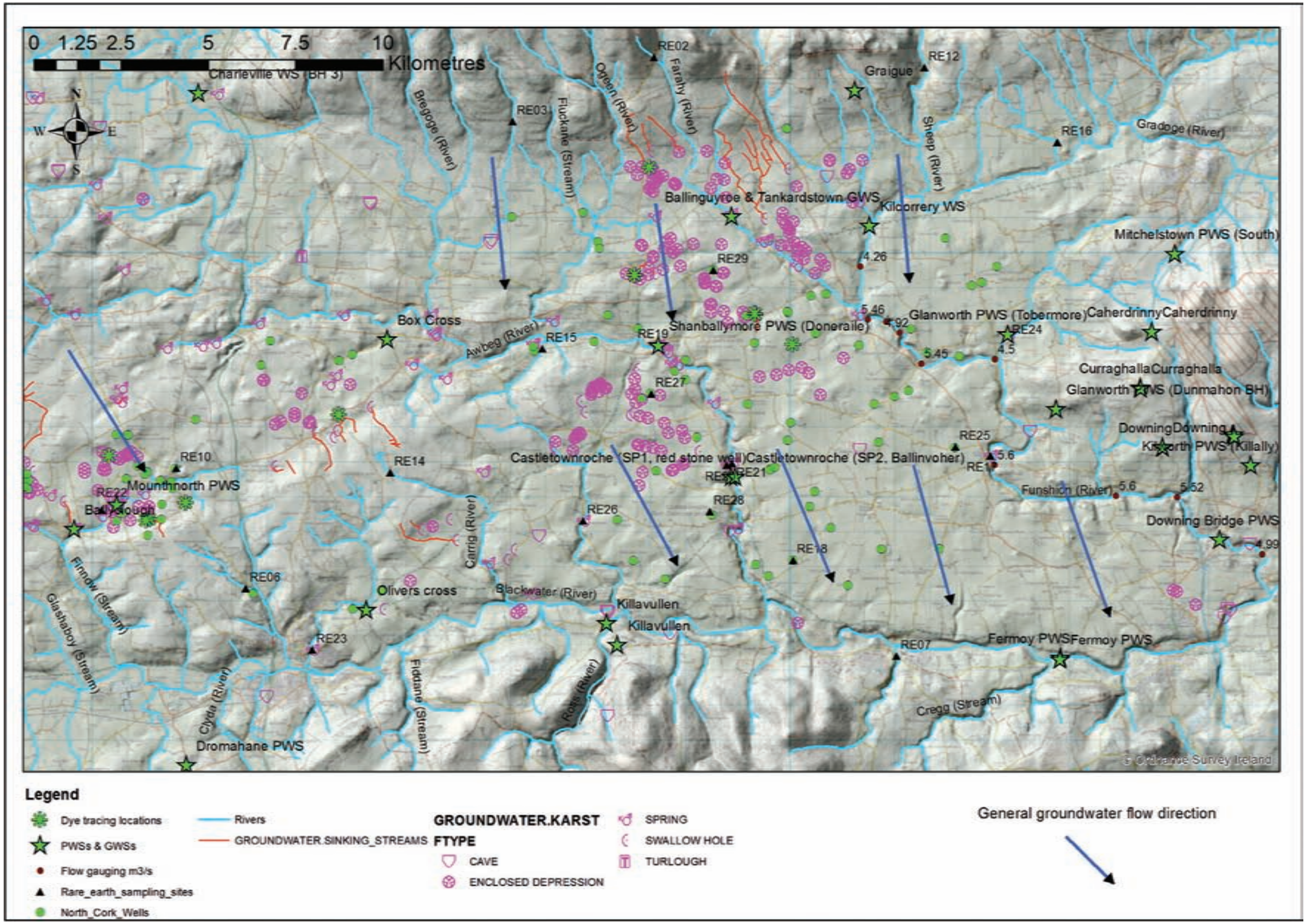


Figure 10.7 Wells surveyed 2015/2016; Flow gauging on the Funshion river, swallow holes used for tracing, groundwater flow direction in limestone and rare earth sampling locations.

Extensive well surveys were conducted, principally across the limestone interfluve areas, an area of approximately 100 km^2 (Figure 10.7). Approximately 100 wells were visited and water levels were recorded from the majority of useable wells. This has enabled water levels across the area to be examined and allows for interpretations of the groundwater flow directions at different points in time. The data suggest that there is a significant north to south component to the groundwater flow direction, with localised variations that may be due to geological and structural influences.

Flow gauging was carried out along the Funshion River, in August and October 2016, to investigate if there were losing sections: results indicate that there are several losing sections (Figure 10.7).

Rare-earth water sampling was conducted by TCD as part of the TCD GSI IRC funded study in north Cork (Figure 10.7). A full suite of rare earth elements (REEs) plus yttrium (REY), and additional trace elements were used to provide characteristic fingerprints of different groundwater origin and pathways through aquifers of contrasting mineralogy. The hydrochemical signatures can distinguish sandstone, shales and limestones and can also distinguish different formations of the same rock type. The data suggest that the springs at Shanballymore, Castletownroche and Mallow are of solely limestone origin.

10.4.4 Regional Hydrogeological Model

The negative tracing results, the bedrock drilling, the groundwater level investigations, flow gauging, hydrochemical river surveys, bedrock mapping, karst feature mapping and rare-earth water sampling have, in combination, provided information on the bedrock, karst features, hydrology and hydrogeology of north Cork and has advanced the conceptual understanding of the regional hydrogeology, in particular the characteristics of the fluviokarst terrain cut by the Awbeg and Funshion river systems. A regional hydrogeological model has been developed:

- The region comprises a fluviokarst system – a karstic interfluve (plateau) with a fluvial system in the valleys, comprising principally the Awbeg and Funshion Rivers which flow to the River Blackwater. Numerous small streams also flow off the non-limestone ridges to the Blackwater.
- The karst groundwater system comprises solutionally-enlarged channels and other karst features at the surface but appears to comprise a distributed rather than a hierarchically organised/focussed system, and does not appear to be as dominated by conduit flow, as in other karst areas of Ireland.
- The springs, generally single outflows, occur along the banks of the rivers at the base of the karst plateaus. The springs may occur where there is a local focus of groundwater flow, possibly related to structure.
- It appears that groundwater flow is mainly north to south towards the springs and the rivers.
- The analysis of water level data, dry weather flow data, dye tracing, hydrogeological mapping and the surface-water flow measurements indicate a complicated groundwater

flow regime. The negative tracing results support the concept that there is a significant flow component that does not discharge at any of the springs.

- It is considered that the groundwater flow patterns in the area comprise diffuse and conduit flow; with the springs representative of shallow, possibly conduit driven groundwater and that there is a significant component of deeper groundwater flowing south, ultimately discharging diffusely as baseflow to the River Blackwater.

10.5 The Rathcroghan Area, County Roscommon

Coran Kelly

The Rathcroghan Upland in County Roscommon is a karst limestone plateau of approximately 200 km^2 and 40–150 m above sea level. The upland generally receives 800 mm of rainfall per year and is characterised by sinking streams, swallow holes, turloughs, an absence of surface water courses and relatively large springs dotted around its perimeter (Figure 10.8). Several of these springs supply drinking water to Public and Group Water Schemes. Contamination of these springs is relatively common, and severe pollution incidents have occurred.

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

Lee and Kelly (2003c), Drew (2005), and Hickey (2008) provide important insights into the groundwater behaviour in the uplands. These investigations, predominantly tracer studies, established ZOCs to the water supply springs at Castlerea and Rockfield (no longer in use) located on the western and southern perimeter of the uplands (Figure 10.8). One of the working assumptions made in understanding groundwater behaviour in the region is that the Rathcroghan Uplands are both a topographic/surface water divide and a groundwater divide, with groundwater flow directions expected to broadly follow the topography (Hickey, 2008). Whilst this is broadly true, the tracing by Drew (2005b) in the Rockfield spring area, show groundwater flow directions contrary to surface water flow, indicating complicated interactions between surface water and groundwater. All these investigations suggest that dye tracing is one of the most important tools available to determine flow directions in such terrain.

GSI in collaboration with the National Federation of Group Water Schemes (NFGWS) prepared desk-based ZOCs for each of the Group Water Schemes (GWSs), shown in Figure 10.9 A, as part of a national programme (Kelly, et al., 2015; Meehan, et al., 2015a and b). Knowing the uncertainties on groundwater flow direction, multi-dye tracing investigations were carried out in 2015 and 2016 on and around the Rathcroghan Uplands in an attempt to establish geo-scientific ZOCs for all the water supplies in the area

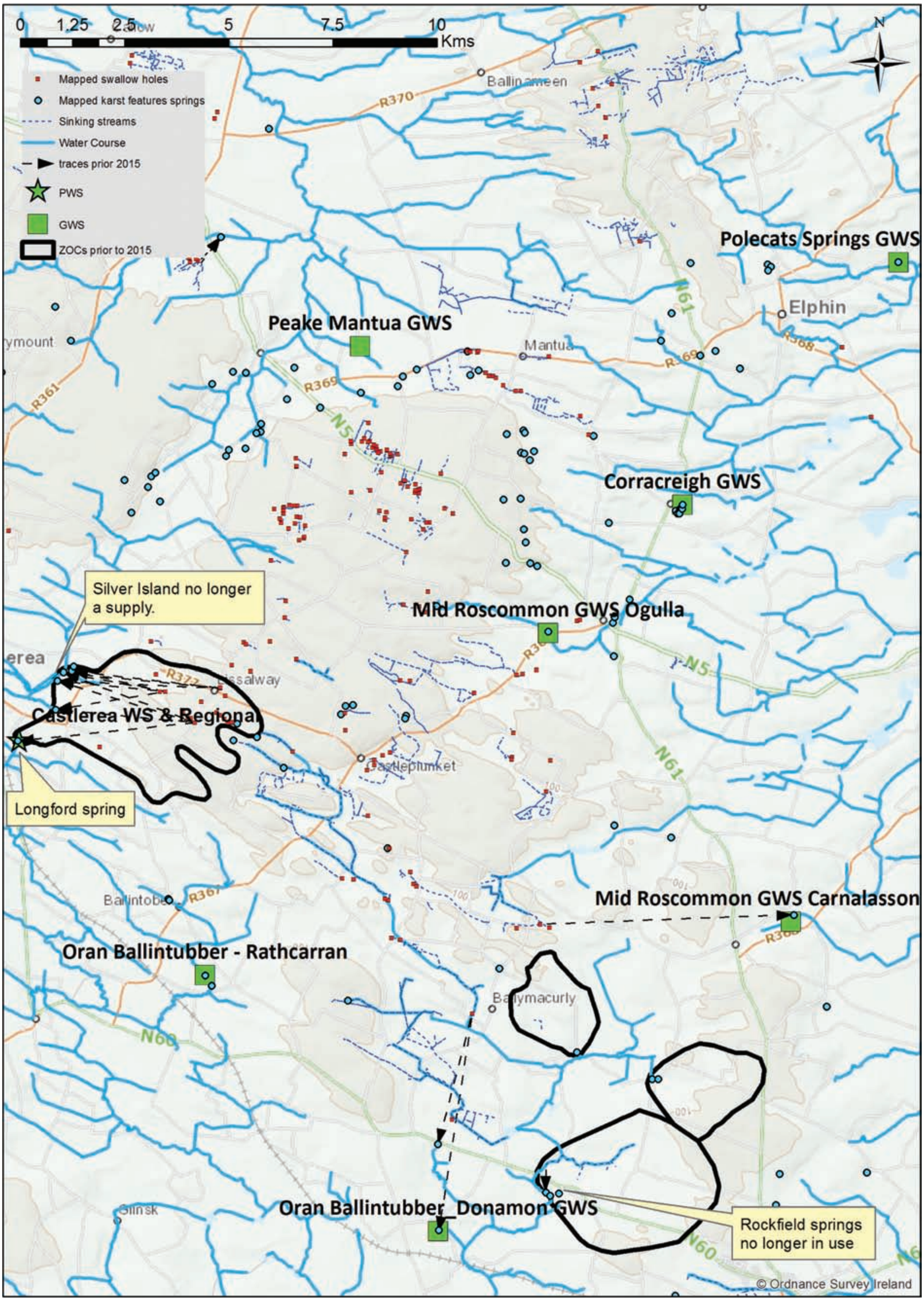


Figure 10.8 Rathcroghan Uplands, water courses, springs (including PWS – Public Water Supply and GWS – Group Water Scheme Springs) and zones of contribution delineated prior to 2014.

(Duncan et al., 2015, 2016, Duncan, 2017). This case study highlights and summarises the main findings from the work done to date.

10.5.1 Delineation of ZOCs and Conceptual Model

The tracing in 2015 and 2016 comprised dye inputs at 16 swallow holes and sampling of some 90 sample points, including springs and surface water courses. This work also included tracing done in conjunction with GSI, as part of an environmental study for a road realignment proposal for the N5. The resulting data provided sufficient information on the overall groundwater flow directions to the main springs to enable ZOCs to be delineated with some confidence and the creation of site specific conceptual models. Figure 10.10 shows a conceptual model for the flow to Ogulla Spring.

The groundwater velocities were rapid, with dye appearing in the springs within days, including those that travelled significant distances, up to 10 km in some cases (Figure 10.9 B). The results highlight an intricate network of flow with some unexpected directions, and provided evidence for delineating a 'jigsaw puzzle' of abutting ZOCs across the entire uplands. The results demonstrate that each of the springs is fed by groundwater originating in the uplands and also that each of the main springs is fed by a specific ZOC. The total area encompassed by the ZOCs is approximately 200 km^2. The difference between the original desk-based ZOCs and updated ZOCs is illustrated in Figures 10.9A and 10.9B and demonstrates the importance of detailed, karst specific, investigation in karst.

Whilst the tracing has been successful in establishing robust ZOCs (based on the tracing and topography), uncertainties remain. Each boundary needs to be treated with caution, in particular, the boundaries to the southwestern portion of the Polecats GWS ZOC which adjoins the Corracreigh ZOC; the overlapping area of the Corracreigh/Polecats ZOCs where dye injected at one swallow hole arrived at both springs; and the southwestern portion of the Rathcarran ZOC. The traces also suggest that surface water and groundwater divides are not coincident in all cases, e.g. traces to Corracreigh, Rathcarran and Donamon.

The area of the Rathcroghan Upland west of Ogulla and Corracreigh springs ZOCs and northwest of Rathcarran ZOCs is assumed to feed water westwards, where there are several springs and water courses. One trace was attempted from this area but the tracer was not recovered at any of the sampling locations.

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

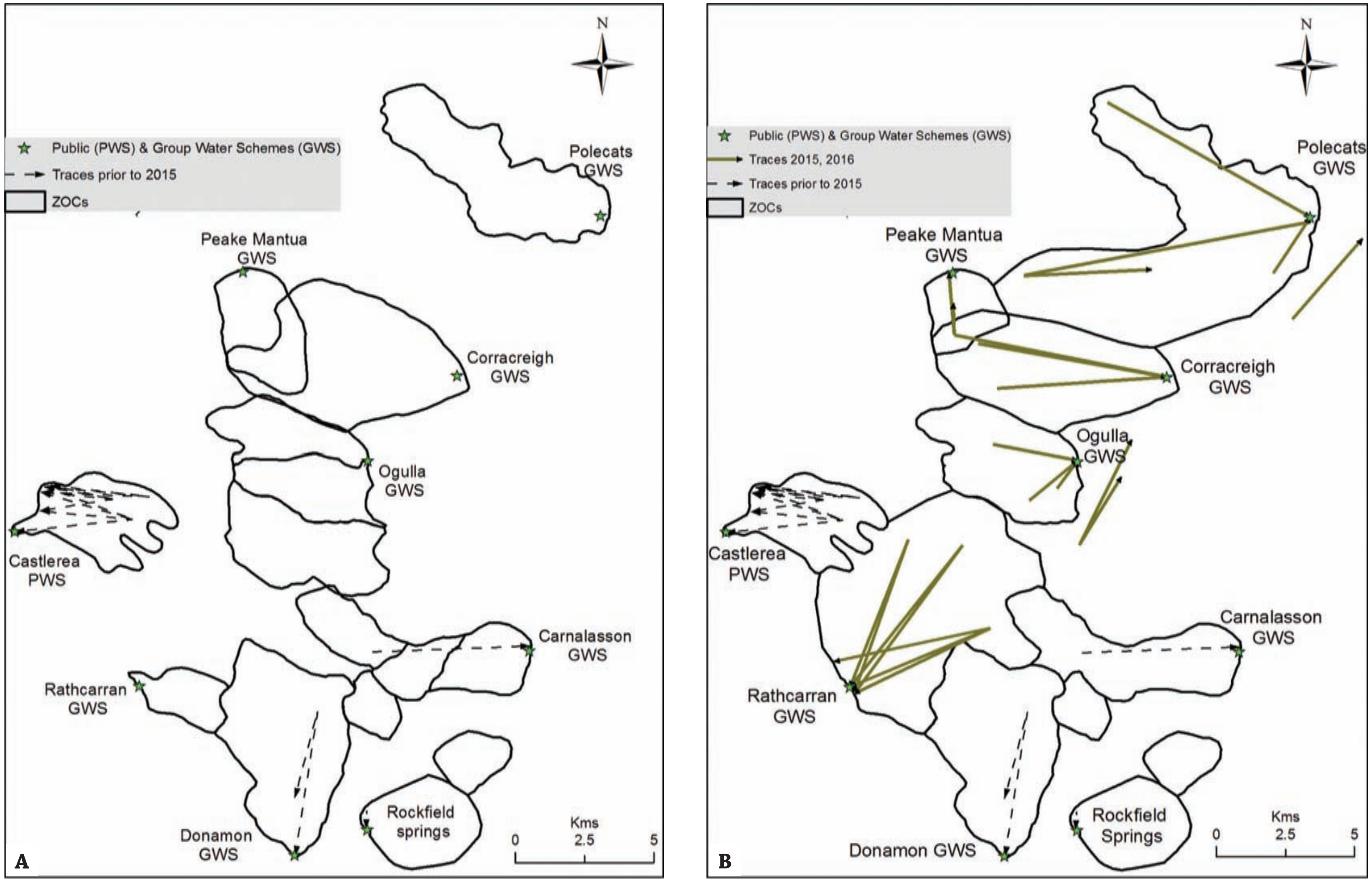


Figure 10.9 (A) Proven tracings prior to 2015 and consequent protection zones established. (B) Protection zones established in 2017 based on subsequent tracing.

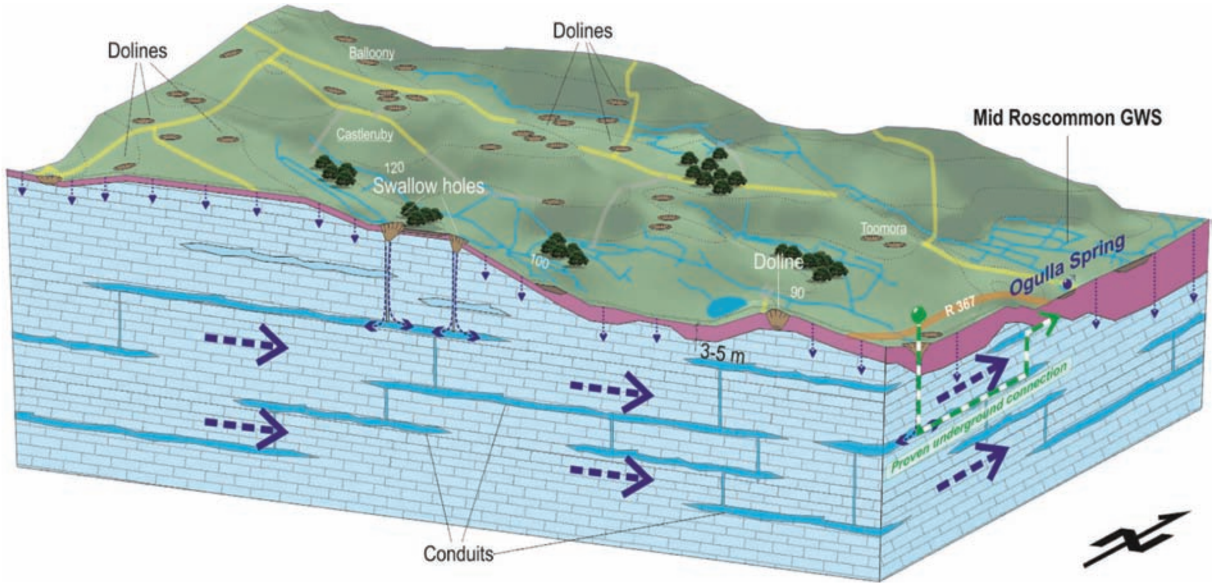


Figure 10.10 Conceptual model to Ogulla Spring showing one of the traces.

The area encompassed by the ZOCs is large and, in terms of groundwater protection, presents a challenge to the individual water supply schemes. Given the abutting nature of the ZOCs it may be an opportunity for the schemes to work together to protect their schemes as a whole, rather than individually. Working with the stakeholders will be an important factor in the success of managing the catchments. There are areas within the ZOCs that are riskier than others and thus there is a hierarchy that can assist the schemes to tackle priority sites, i.e. swallow holes and sinking streams.

10.5.2 Conclusions

Given the uncertainties in flow directions, establishing ZOCs in karst requires specific techniques, significant resources, suitable antecedent weather conditions, and time. As Figure 10.9 demonstrates, the confidence in the ZOCs is directly proportional to the amount of resources invested. The dye tracing conducted in the Rathcroghan Uplands has provided a great deal of information on the groundwater characteristics, specifically groundwater flow directions and rates. The information obtained enabled individual ZOCs to be defined for each of the water supply schemes and highlights vulnerable areas within these catchments.

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Introduction

The material listed in the bibliography includes both fully refereed papers published in journals and books together with grey literature including published and unpublished reports such as field trip guides. Theses are not cited unless the contents have not been published elsewhere in a more accessible form. Groundwater reports with some karstic content, mainly produced by GSI and the EPA, are included where new material is presented which is not available elsewhere (for example Source Protection reports for springs and Groundwater Protection schemes for individual counties) but not basic data summaries such as site information reports for individual public water supply sources. The publications searched include not just conventional hydrogeological literature but also literature from speleological, engineering, ecological, geomorphological and other sources. The coverage extends to December 2017. The bibliography does not purport to be exhaustive. So, for example, when several papers have been published relating to a single topic only those with most comprehensive and up-to-date coverage are normally listed. Not all literature prior to c.1990 is included, particularly if the material presented is outdated or has been summarised well in later publications.

The thematic bibliography consists of a listing of significant references grouped as follows:

1. Overview and summary literature on general aspects of karst and karst hydrogeology in relation to 'conventional' hydrogeology. The list is not exhaustive but is intended to include the most useful and accessible sources of information for the non-specialist in karst.
2. Overview and summary literature relating to aspects of karst and karst hydrogeology in Ireland as a whole.
3. Literature wholly or in part relating to particular areas in Ireland underlain by Carboniferous limestone. The subdivisions correspond, in the main, to those used in the main body of this handbook.

References, which include material relating to more than one of the sub-divisions listed above, are included (repeated) in each relevant sub-section.

All the references cited in the thematic bibliography are listed, alphabetically, in the consolidated bibliography.

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Appendix A

GLOSSARY

(The terms are defined in a specifically karstic context. Terms in italic are defined elsewhere in the glossary)

ALLOGENIC (runoff/water/stream/recharge)
Water derived from rain falling on adjacent, (non-carbonate) rocks and flowing onto the limestone outcrop.

ANASTOMOSES
A network of small (mm to cm) branching, intersecting channels in a limestone aquifer, often developed on a bedding plane surface. They represent the early stages of karst conduit development on an *inception horizon*.

AQUIFER
A rock or sediment deposit that stores and transmits water in usable quantities.

AUTOGENIC (runoff/water/stream/recharge)
Water derived wholly from rain falling onto the (limestone) rock outcrop.

BASE LEVEL
The lowest level to which groundwater circulation and hence solutional erosion and karstification can proceed in a particular area (e.g. the elevation of a major river channel or sea-level)

BASEFLOW
The discharge that is maintained in a stream or from a spring under dry-weather conditions

BEDDING PLANE
A lamination feature in limestone an other sedimentary rocks resulting from changes in the original depositional environment. Bedding planes are often *inception horizons* for conduit initiation.

A plane that marks the surface of one sedimentary layer from the next, resulting from changes in the original depositional environment.

CALCITE
The commonest mineral form of *calcium carbonate*.

CALP
A dark coloured limestone containing a significant proportion of clay impurities.

CALCIUM CARBONATE
The major component of carbonate rocks. See: *calcite*.

CARBONIFEROUS PERIOD
The geological time period from 359–299 million years ago. Most limestone in Ireland was laid down during the Lower Carboniferous (Dinantian), 359–333 million years ago. The Upper Carboniferous includes the Namurian (326–313 Ma)

CATCHMENT AREA
The area of land that drains into a particular water body such as a stream, lake or spring.

CHALK
A rock unit of Cretaceous age (146–66 million years ago) composed of relatively soft and porous white limestone. However, the Chalk outcrop in north-eastern Ireland, locally termed Ulster White Limestone, is relatively well lithified and has a low porosity.

CHERT
A very hard fine-grained silica rock that commonly occurs as sheets, nodules or lenses within limestones. Unlike limestone it is virtually insoluble in water.

DARCIAN FLOW
Groundwater flow that is governed by the law originally formulated by Henri Darcy (Darcy's Law), that flow velocity is directly proportional to hydraulic gradient and to the hydraulic conductivity of the rock through which the water is moving. This flow regime is assumed to be *laminar*.

DOLINE
An enclosed, internally draining depression with diameter and depth up to hundreds of metres. A diagnostic *karst* landform.

DOLOMITE
A carbonate rock in which some of the calcium has been replaced by magnesium – a calcium-magnesium carbonate. Dolomitic rocks are often highly karstifiable.

DRY VALLEY
A valley cut by a surface stream which now sinks underground leaving the valley in part or entirely, without a stream.

EPIKARST
The uppermost (2–5m typically) part of the limestone bedrock where maximum dissolution of limestone has taken place.

ESTAVELLE
A karst features which can function as a spring or as a swallow hole depending upon underground water levels.

EXSURGENCE
A spring that is fed only by diffuse recharge.

FAULT (geological)
A *fracture* in rock along which there has been vertical and/or horizontal displacement of the rock strata.

FISSURE
A *joint* or *fracture* in a rock, which, in a *karstified aquifer*, has been widened by *solutional erosion* to a limited extent.

FLOW DURATION CURVE
A graph of cumulative stream flow versus the percentage of time for which that flow is equalled or exceeded.

FRACTURE (JOINT)
A break in rock produced by earth movements.

GAINING STREAM
A stream into which groundwater discharges along all or a part of its course. Opposite of See: *losing stream*.

GYPSUM
A evaporate mineral (hydrated calcium sulphate) which is soluble in water and can develop karsts. In Ireland it is confined to the Kingscourt area of County Cavan, Monaghan and Meath.

HOLOCENE EPOCH
The more recent Epoch (time period) of the *Quaternary Period*, comprising the last 11,700 years.

INCEPTION HORIZON
A preferred flow route within a limestone aquifer which may then develop conduit flow. *Bedding planes, joints and wayboards* are examples of possible inception horizons.

INLIER
An outcrop of older rocks surrounded by younger rocks, typically formed by erosion of part of the younger rocks

JOINT
A planar *fracture* in a rock across which there is no discernible displacement

KARREN
Small scale (mm to m) *solution* features (channels and hollows) developed on limestone bedrock surfaces.

KARST
An area of limestone or other soluble rock in which the dominant landforms, surface and subsurface, are of *solutional* origin.

KARSTIFICATION
The process whereby karstic landforms (surface and underground) and karstic processes become dominant in an area.

LAMINAR FLOW
Groundwater flow in which flow direction remains constant at all points through time (cf *turbulent flow*).

LIMESTONE
A sedimentary rock largely composed of *calcium carbonate*.

LIMESTONE PAVEMENT
A bare limestone surface from which overlying material and weathered bedrock has been stripped – usually by ice action.

LITHOLOGY
The physical and chemical characteristics of a rock such as grain size, mineralogy, and grain size.

LOSING STREAM
A stream in which surface water -discharges into the ground. See: *gaining stream*.

MARBLE
Metamorphosed limestone rock; recrystallized and hardened.

OUTLIER (geological)
An isolated outcrop of younger rocks surrounded by older rocks.

OVERFLOW SPRING
A spring that becomes operative only when the capacity of a lower outlet (*underflow spring*) is exceeded.

PERMEABILITY (hydraulic conductivity)
A measure of the ease with which water can pass through rock or loose material.

PHREATIC ZONE
The groundwater zone below the watertable in which all voids are water-filled. In non-karstic aquifers the corresponding term is 'saturated zone'.

POLJE
A large (several km^2) enclosed depression with steep sides and complicated internal hydrology.

POLYGONAL KARST
A highly karstified terrain in which dolines are the predominant landform.

POROSITY
The quantity of water that can be stored within a given volume of rock; usually expressed as a percentage of the rock volume. In karstified Carboniferous limestone in Ireland the porosity often closely approximates to the *specific yield*.

QUATERNARY PERIOD
The geological time period from 2.6 million years ago and which includes the Ice Ages.

RECHARGE
The process whereby excess rainfall (runoff) is added to groundwater.

RESURGENCE
A spring that is fed in part by point recharge (sinking steams).

SOLUTION (dissolution)
The dissociation of limestone (*calcium carbonate*) mainly by carbonic acid produced when carbon dioxide dissolves in water. The basic process involved in *karstification*.

SPECIFIC CAPACITY
The discharge of water from a well (borehole) divided by the fall in water level in the well corresponding to that yield.

SPECIFIC YIELD
The quantity of 'useful' i.e. accessible water, stored in a volume of rock. Usually expressed as a percentage of the rock volume. See: *porosity*.

SPRING
Point of discharge of groundwater, characteristic of karst areas, but common in other landscapes too. The point at which groundwater becomes surface water.

SUBSOIL
In Ireland, the layer of unconsolidated material between the base of the soil and the bedrock.

SUFFOSION
Down-washing of soil and subsoil particles into an underlying enlarged fissure: the process that creates suffosion *dolines*.

SWALLOW HOLE
The point at which a surface stream sinks underground.

TILL
Unsorted, unstratified material deposited beneath glacial ice.

TRANSMISSIVITY
A measure of the rate at which groundwater is transmitted through a certain thickness of an aquifer.

TURBULENT FLOW
Flow of water in a conduit (cave) in which velocity and direction of flow at a point varies continuously. Turbulent flow is initiated when conduit diameter exceeds 5–15mm. See *laminar flow*.

TURLOUGH
A karst depression which is periodically flooded by groundwater.

UNDERFIT STREAM
A stream that is obviously smaller than the stream that originally eroded the valley in which it flows.

UNDERFLOW SPRING
A spring located at the lowest point of an underground drainage basin which preferentially drains *baseflow*. See: *overflow spring*

VADOSE ZONE
That part of the groundwater system that flows under gravity, above the watertable. It is commonly used in karst hydrogeology in place of 'unsaturated zone'.

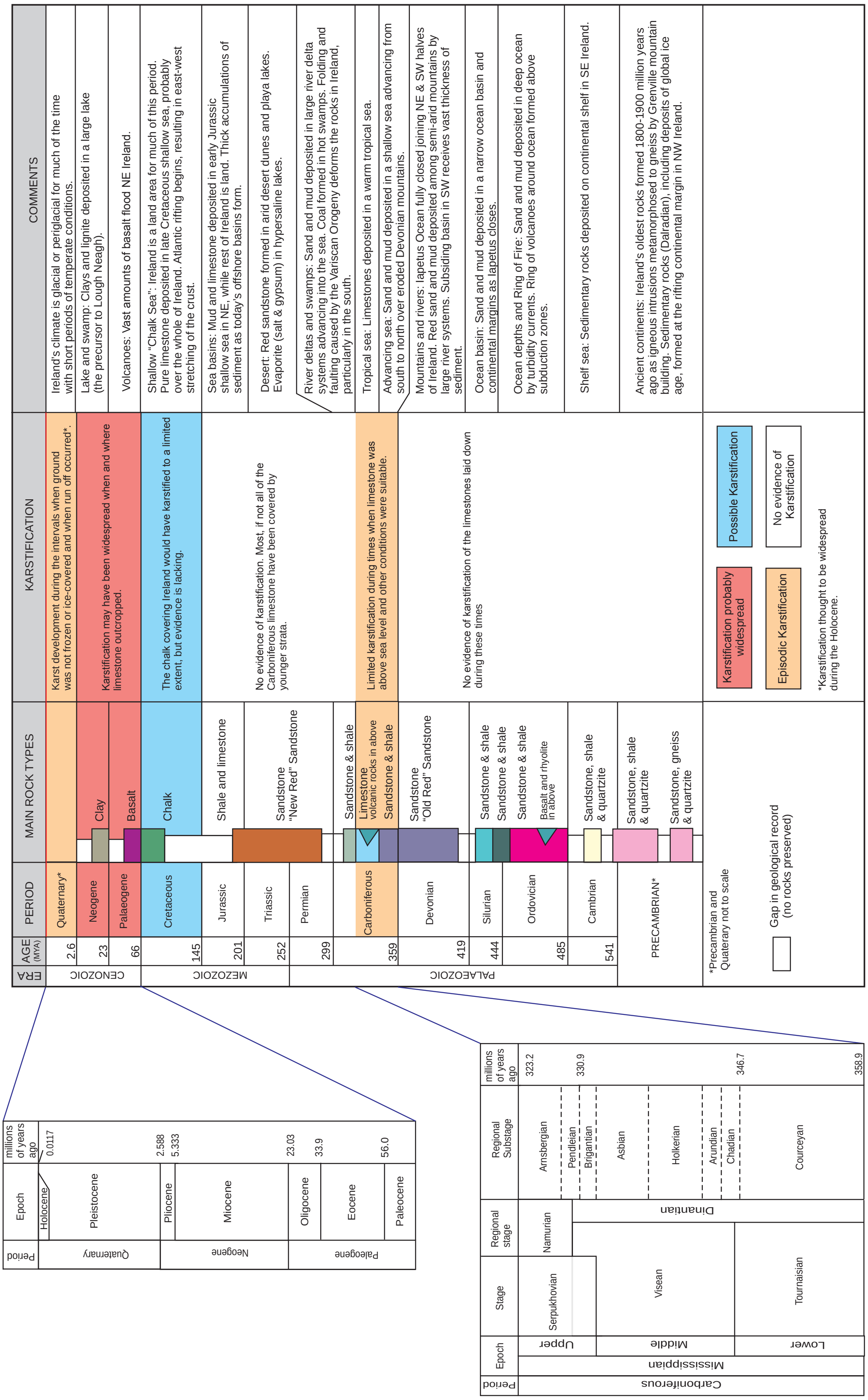
VEINS (geological)
A mineral filled fracture in a host rock. Veins may act as *inception horizons* for preferential solutional erosion.

WAULSORTIAN LIMESTONE
Massive carbonate mudbank limestones. Such limestones, of Lower Carboniferous age, are widespread, particularly in the south Midlands of Ireland

WAYBOARD
A thin band of clay, interbedded in some limestones, which may act as a barrier to groundwater flow and/or an *inception horizon*.

Appendix B

THE GEOLOGICAL COLUMN

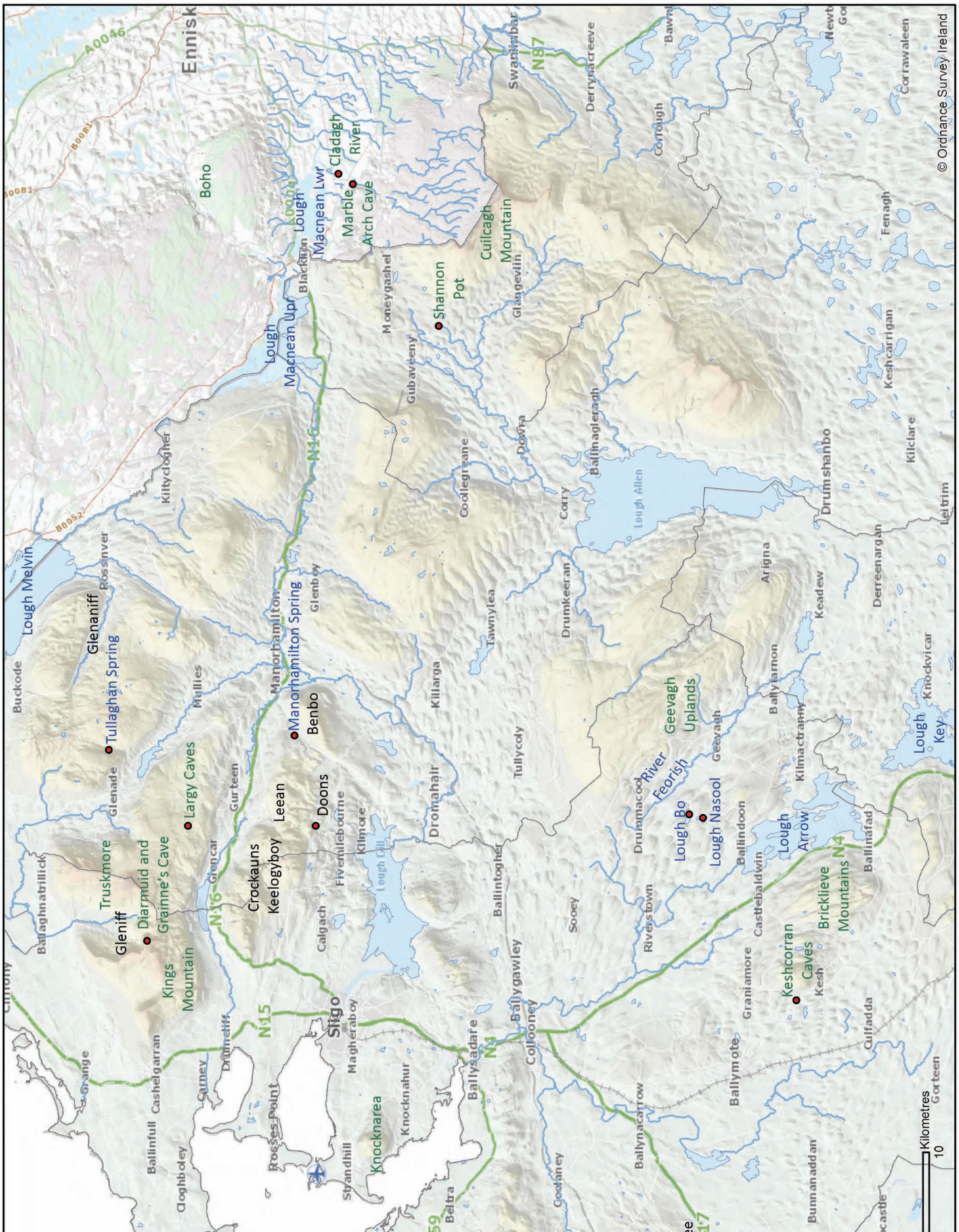


Appendix C

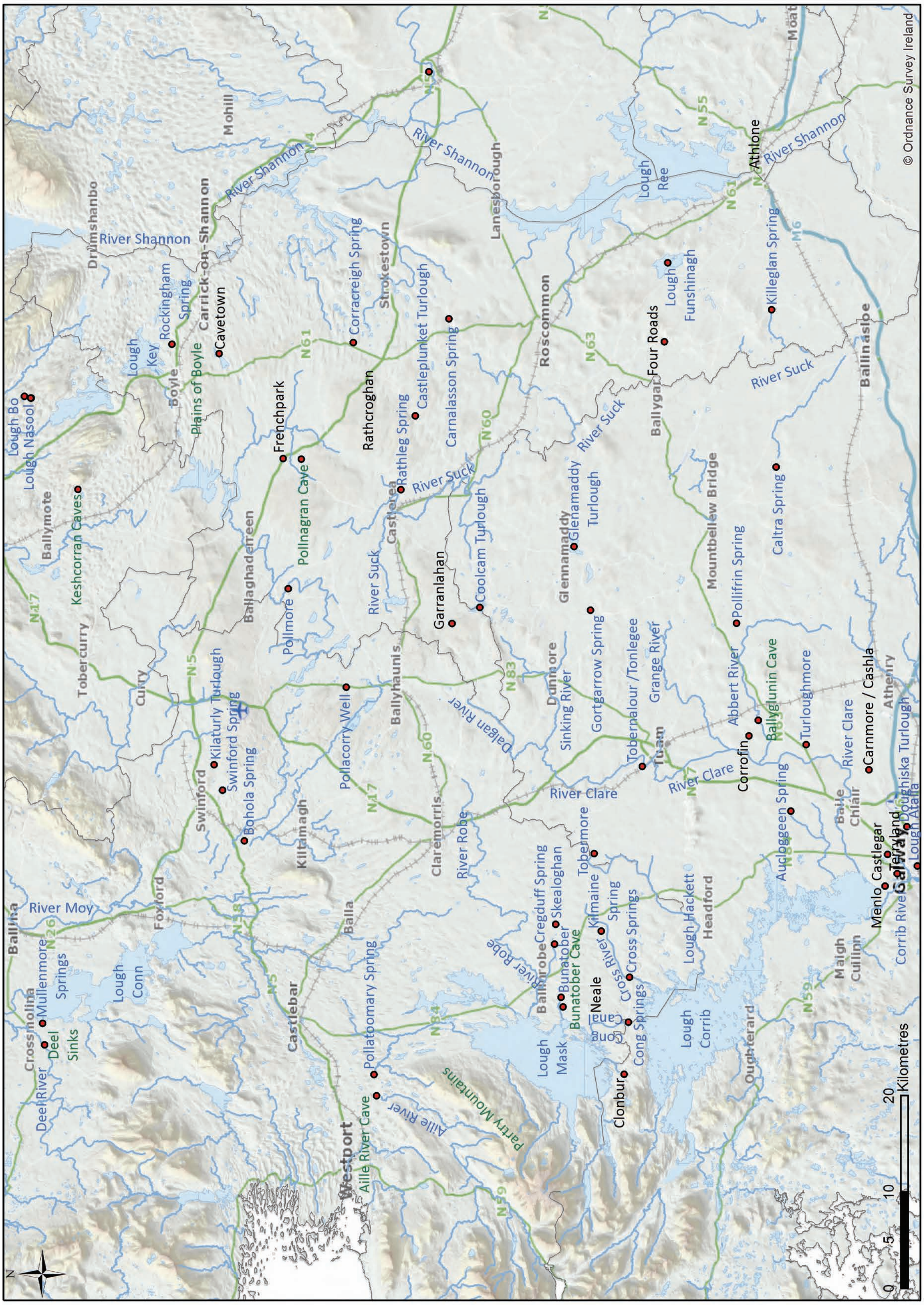
MAPS (1–6) SHOWING LOCATIONS MENTIONED IN THE TEXT

Map 1 Eastern Ireland

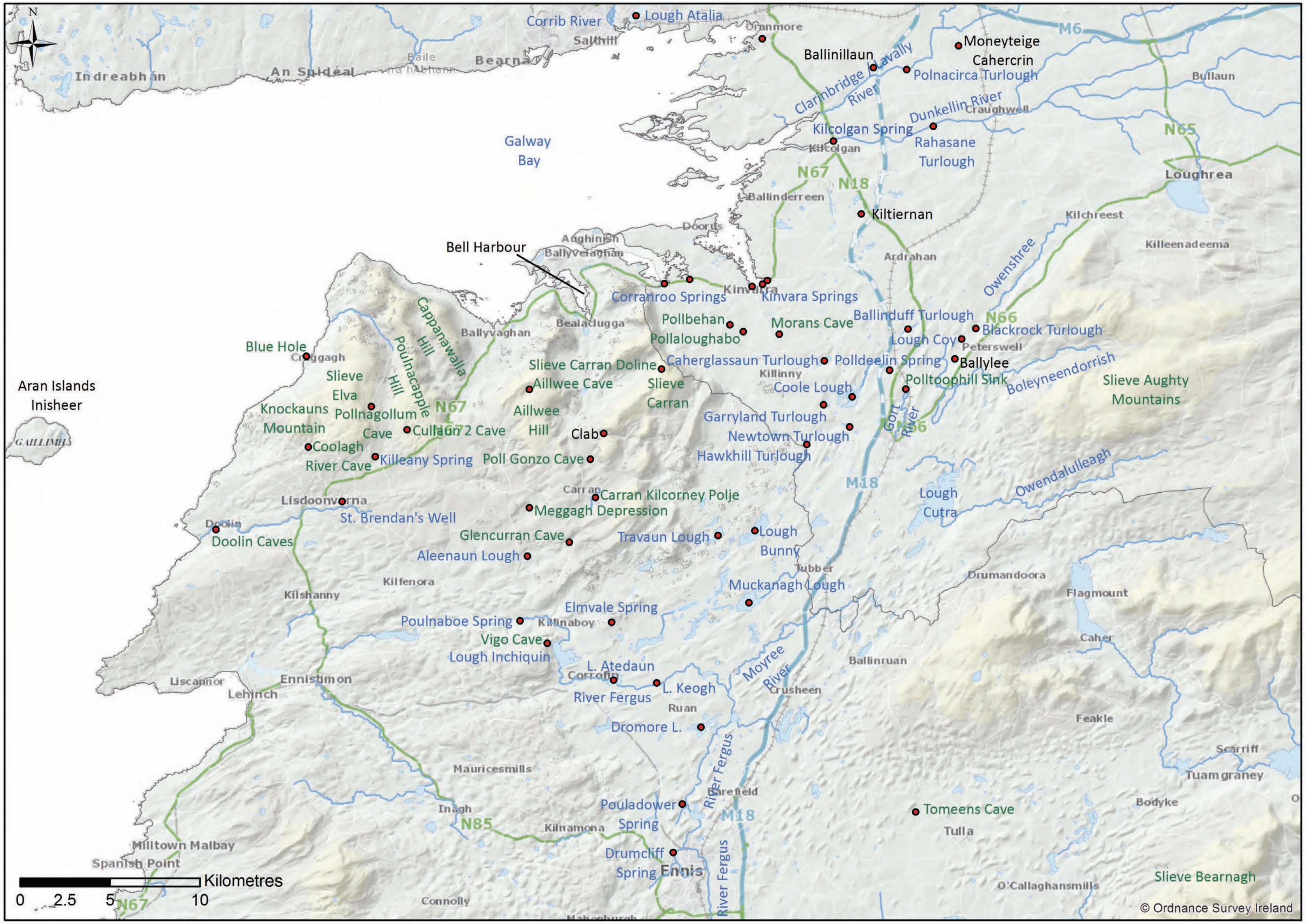
Map 2 Southwest Ireland



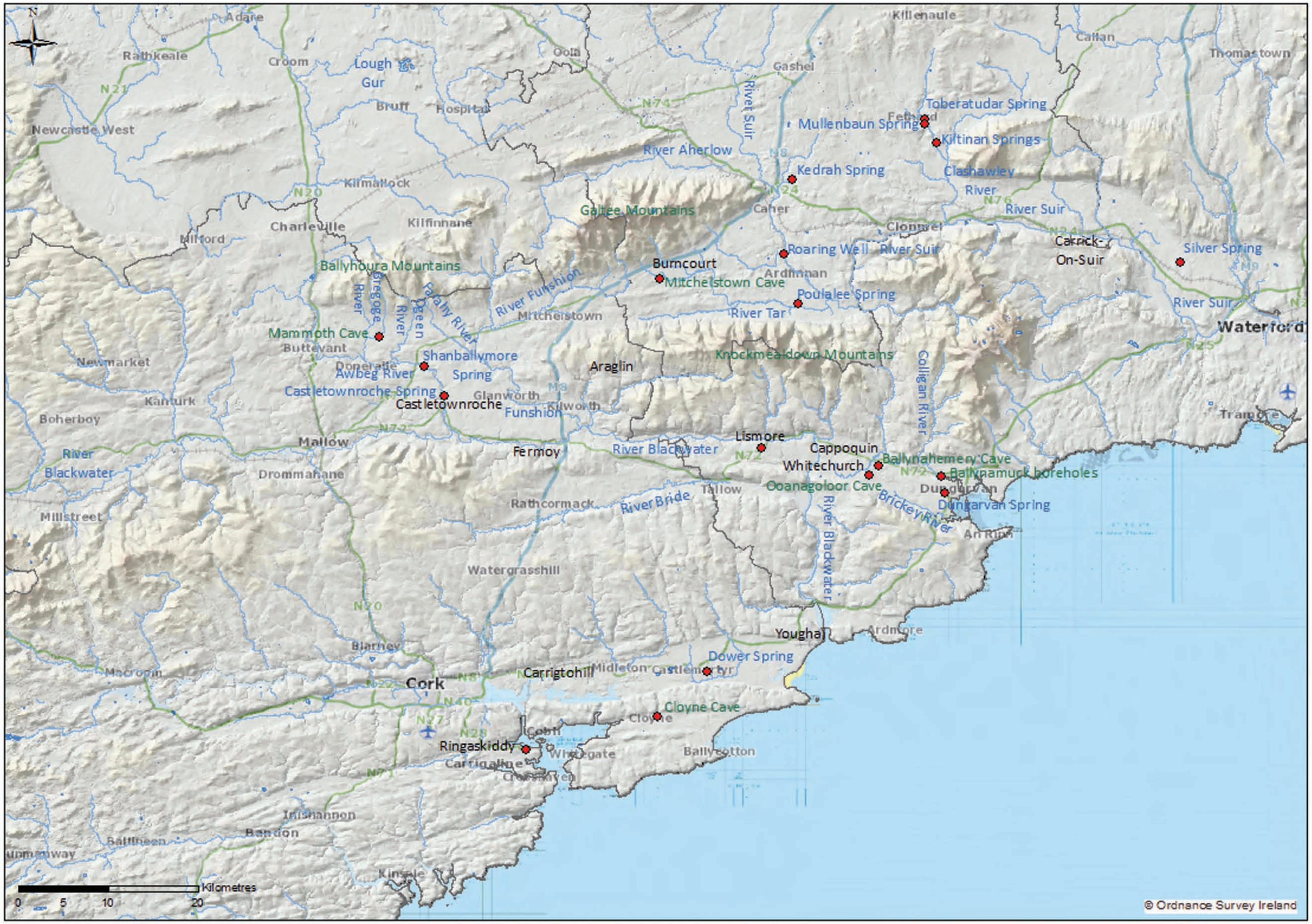
Map 3 Northwest Ireland



Map 4 The western lowlands of Ireland



Map 5 The Burren and the Galway Bay – Shannon estuary karst corridor.



Map 6 The south of Ireland

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