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THE USE OF MULTIPLE TECHNIQUES FOR CONCEPTUALISATION OF LOWLAND KARST, A CASE STUDY FROM COUNTY ROSCOMMON, IRELAND

UPORABA VEČ METOD ZA KONCEPTUALIZACIJO NIZKO LEŽEČEGA KRASA, PRIMER IZ OKROŽJA ROSCOMMON, IRSKA

Caoimhe HICKEY[1]

Abstract UDC 528.9:551.44(417)

Caoimhe Hickey: The Use of Multiple Techniques for Conceptualisation of Lowland Karst, a case study from County Roscommon, Ireland

This paper summarises research carried out in county Roscommon, Ireland to characterise the workings of low-lying karst, of which little is known. The research employed a combination of five main investigative techniques, in conjunction: geomorphological mapping, spring chemistry and discharge analyses, dye-tracing, microgravity geophysical investigations and bedrock core drilling. The results enabled the production of a detailed conceptual model for the area. Surface and subsurface karst landform mapping revealed a high level of karstification. Clustering and alignment of recharge landforms is found to be a significant aspect of the karst. Analyses of spring chemistry and discharge data revealed characteristics of the aquifer systems in operation. It was found that a significant percentage of flow is via enlarged conduits but that the smaller fractures are important for providing base flow. Water tracing experiments proved that water moved from highly karstified, elevated recharge zones to springs at the periphery. Microgravity geophysical investigations, detected and located solutionally enlarged voids in the bedrock and demonstrated the importance of the shallow epikarst system as well as a deeper conduit network. Bedrock core drilling detailed the nature of the bedrock underneath karst landforms and showed the successes and failings of the geophysical investigations. Spring catchment boundaries were then delineated using water balance equations and a combination of the information retrieved from the other methods. Using these results in combination large amounts of information were gathered leading to the production of the first conceptual model for the karst of Roscommon, which can be adapted and applied to Irish Lowlands in general. The use of multiple, complimentary, investigative techniques in conjunction greatly enhanced the accuracy and success of this project. The aim of this paper, therefore is to highlight the benefits of using many analytical techniques together.

Keywords: karst landform mapping, analyses of spring data, dye-tracing, geophysics, drilling, conceptual model.

Povzetek UDK 528.9:551.44(417)

Caoimhe Hickey: Uporaba več metod za konceptualizacijo nizko ležečega krasa, primer iz okrožja Roscommon, Irska

Pričujoči članek povzema izsledke raziskav, ki so bile opravljene v irskem okrožju Roscommon z namenom, da bi bolje označili delovanje nizko ležečega krasa, o katerem je malo znanega. V raziskavah je bilo uporabljenih pet poglavitnih raziskovalnih tehnik: geomorfološko kartiranje, analiza kemičnih in pretočnih podatkov z izvirov, sledilni poizkusi, mikrogravitacijske geofizikalne raziskave ter vrtanje na jedro. Izdelan je bil natančen konceptualni model preučevanega območja. Kartiranje površinskih in podzemnih geomorfnih oblik je pokazalo na visoko stopnjo zakraselosti. Določevanje in razvrščanje območij koncentriranega napajanja se je izkazalo za pomembno v krasu. Analize kemičnih lastnosti izvirov in pretočnih vrednosti so pokazale značilnosti delovanja vodonosnih sistemov. Ugotovljeno je bilo, da je pomemben delež pretoka skozi razširjene kanale in da so manjše razpoke pomembne predvsem za bazni odtok. Sledilni poizkusi so dokazali pretok voda z višje ležečih, bolj zakraselih napajalnih območij k izvirom na obrobju vodonosnikov. Mikrogravitacijske geofizikalne raziskave so odkrile in določile lege korozijsko povečane praznine v kamnini ter pokazale na pomen plitvega epikraškega sistema in globlje mreže kanalov. Vrtanje na jedro je določilo naravo kamnine pod površinskimi oblikami ter potrdilo uspešnost geofizikalnih raziskav. S pomočjo enačb vodne bilance in strnitve informacij, pridobljenih z uporabljenimi metodami, so bila začrtana prispevna območja izvirov. Z združitvijo rezultatov je bila zbrana velika količina informacij, ki je bila uporabljena za izdelavo konceptualnega modela krasa v Roscommonu. Ta model je lahko prilagojen in uporabljen na splošno za irski nizko ležeči kras. Uporaba več dopolnilnih raziskovalnih metod hkrati je zelo povečala natančnost in uspešnost tega projekta. Namen članka je torej poudariti prednosti uporabe več analitičnih metod skupaj.

Ključne besede: geomorfološko kartiranje, analize z izvira, sledilni poizkus, geofizika, vrtanje, konceptualni model.

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INTRODUCTION

Almost half the Republic of Ireland is underlain by Carboniferous limestone and consequently karst is a significant characteristic of its landscape and hydrology. In fact, Ireland possesses the largest continuous area of limestone in north-western Europe, covering approximately 30,000 km^2 (Williams 1970; Simms 2004). Three-quarters of this limestone lies in a lowland central plain, which rarely rises above 100 m in elevation (Fig. 1). The upland outcrops (rising between 300 and 650 m above sea level) are largely confined to plateaux in the west and northwest such as the Burren, Leitrim-Fermanagh and Sligo. The workings of upland karst in Ireland are relatively well understood. These karsts are typified by steep hydraulic gradients, significant allogenic point recharge, conduit-dominated hierarchical flow, low storage and concentrated discharge points (Drew 2008). The extent to which the conceptual models of karst, developed in upland karst areas worldwide, apply to low-lying karst regions is uncertain.

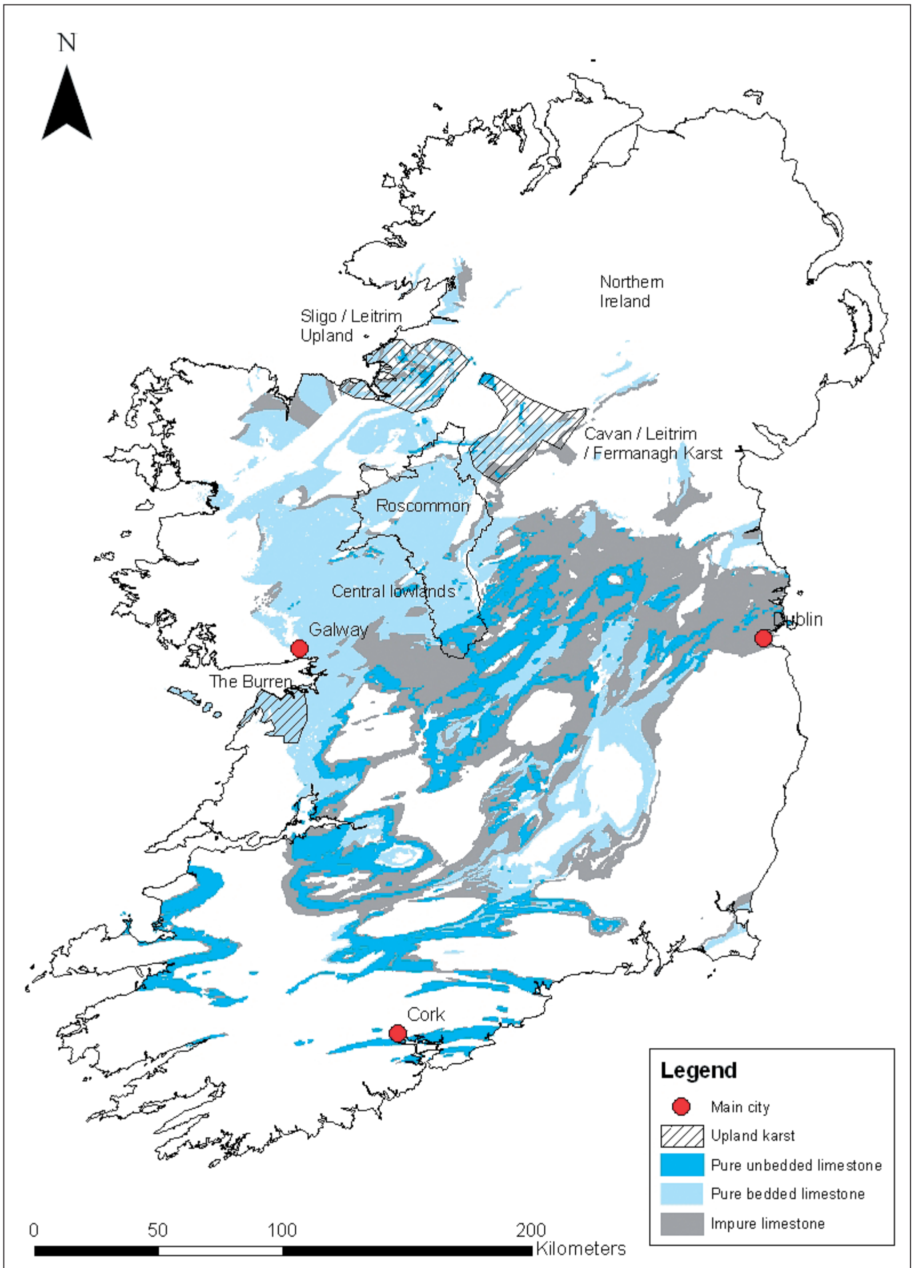


Fig. 1: The Carboniferous limestone areas of the Republic of Ireland, showing Roscommon. The limestone areas not marked as upland are considered lowland karst.

The limestone lowlands of Ireland are the principal source of groundwater for the country. Moreover, the low-lying limestones underlie the most productive agricultural land and all the large towns and cities (Drew 2008). However, the lowlands are not obviously karstic. Glacial sediments, principally till and peat deposits, overlie the limestones in varying thicknesses. This mantle of Quaternary deposits allows a surface drainage system to exist in places. The lowlands are often characterised by high water levels and severe flooding in winter. In some areas artificial drainage systems have been constructed to alleviate flooding. By contrast, some rivers and springs become dry in summer months. The lack of knowledge of lowland karst systems can result in poor management of both these economic aquifers and surface water systems linked to them. As karst aquifers are particularly vulnerable to pollution (due to the nature of the flowpaths in operation within) proper understanding and management is vital.

Roscommon is a karstified, western Irish, low-lying county (Fig. 1). There is a great paucity of knowledge of the karst of Roscommon. Information from technical reports has shown the karstified nature of the bedrock in certain parts. However, previous to this research no large-scale investigations of the karst hydrology or its associated landforms have been carried out. The only research into the karst of Roscommon, prior to this research, was a study of five karst springs (Doak 1995). An understanding of these systems would greatly reduce problems with water supply and water quality issues, which are a county-wide cause for concern.

The objective of this investigation is to improve the understanding of low relief karst in Ireland by studying the karst of Roscommon. This is done by the production of a conceptual model showing the functioning of the karst systems in operation. The conceptual model summarises and displays the main characteristics of the three main aspects of a hydrogeological system; recharge, through-put and discharge. Karst aquifers have many characteristics that differ from other karst aquifers and, therefore, require specific investigation techniques (Goldscheider *et al.* 2007). Information for the conceptual model was gathered using a combination of specific investigative techniques. The aim of this paper is to conceptualise the karst of Roscommon and to demonstrate how a combination of investigative techniques are not only favourable, but necessary, in order to fully understand and conceptualise the karst processes operating in an area.

Most authors agree that the way forward is modelling karst aquifers in order to understand them in real practical terms (White 1999; Bakalowicz 2005). Conceptual models are important, as they are usually the first step in the development of a mathematical groundwater flow model.

THE PHYSIOGRAPHY OF COUNTY ROSCOMMON

Much of Roscommon's 2,500 km^2 (Fig. 1) lies between 60 and 100 m asl and hence the topography is one of a flat to undulating plain, separated by isolated areas of higher ground. These upland areas can be divided into higher hills and mountains, underlain by non-carbonate rock, and low plateau areas underlain by limestone (Fig. 2). Mean annual rainfall varies from 900 to 1,000 mm/yr in the lower lying southern and eastern areas of the county, and from 1,000 to 1,200 mm/yr in the higher northern and western regions. Average evapotranspiration values range from 400 to 450 mm/yr.

The geology underlying Roscommon ranges in age from the schists of Precambrian age to the sediments of the present day. Almost 90% of Roscommon is underlain by Carboniferous limestones of different degrees of purity, 75% of which are considered pure-bedded limestones, susceptible to karstification.

Almost two-thirds of the bedrock is overlain by glacial till, and peat accounts for most of the remaining third. The glacial deposits are unevenly distributed being generally thin or absent on the higher areas and thicker in the low-lying areas in between. The glacial deposits found in northern Roscommon are generally stream-lined, parallel ridges aligned northwest to southeast. In the south the glacial landscape is dominated by eskers, kames and moraines.

There is an abundance of surface streams, lakes and rivers in Roscommon (Fig. 2). The River Shannon and its associated lakes, streams and tributaries form the eastern boundary of Roscommon and drain the region. Most of western Roscommon drains towards the River Suck, which defines the county's south-western border. The low-lying areas between drumlins are marshy, and artificial drainage and lakes are common. However, the surface drainage is unevenly distributed with the elevated limestone plateaux characterised by very low drainage densities.

Dependency on groundwater is extremely high at almost 90% (compared to national average of 25%) and due to the karstified nature of the aquifers, many groundwater abstractions are via large karstic springs, as opposed to boreholes.

The presence of a complex surface water system and glacial deposits gives the impression of a non-karst landscape. There are generally low hydraulic gradients between recharge areas and discharge areas and very little allogenic recharge.

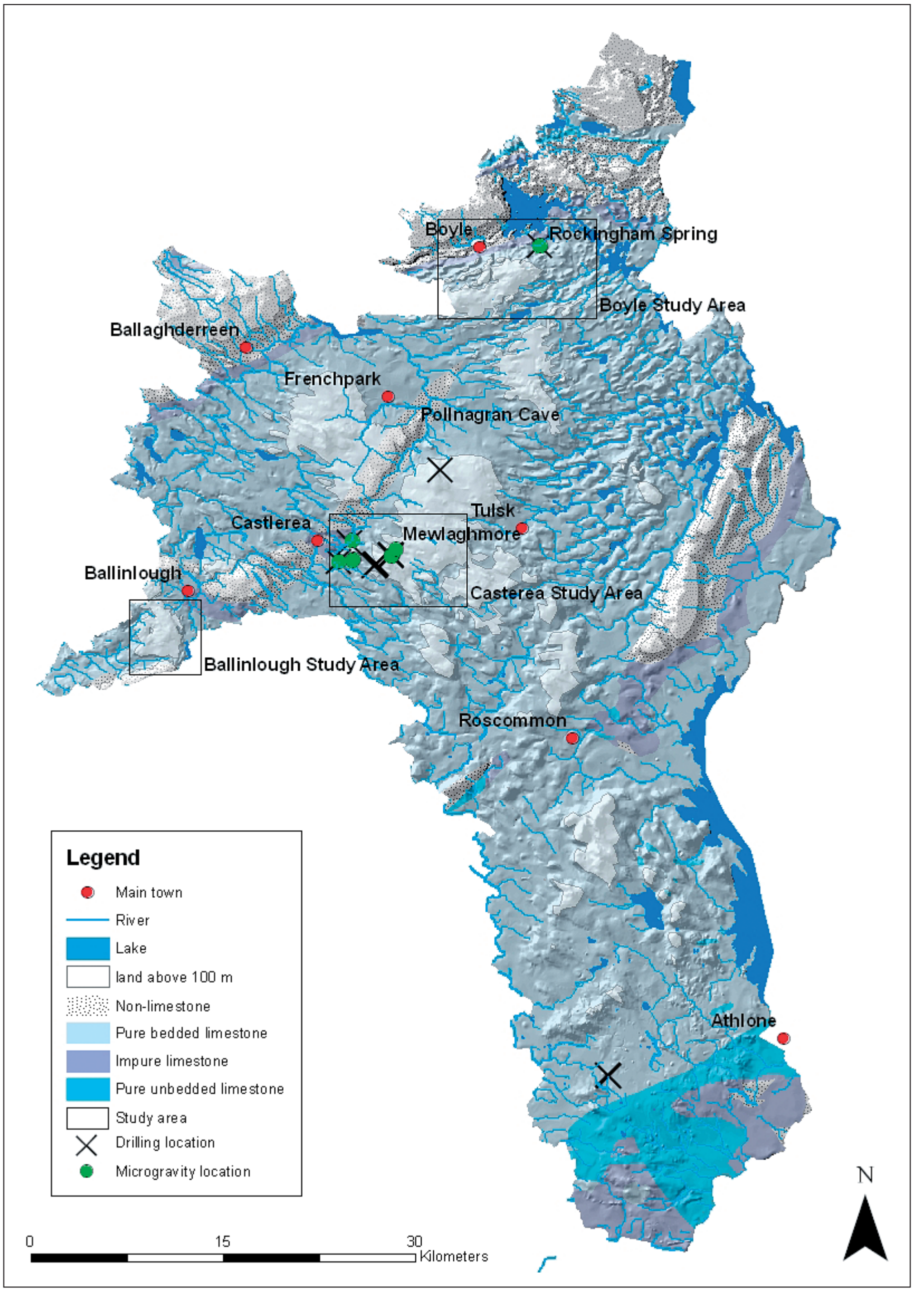


Fig. 2: The physiography and bedrock geology of County Roscommon and location of the study areas and site-specific techniques of investigation.

METHODOLOGY

Five main different investigative techniques were employed to characterise and understand the functioning of this lowland karst environment. These were karst landform mapping, spring chemistry and discharge analyses, dye-tracing, geophysical investigations, bedrock core drilling. The techniques were intended to be complimentary and to obtain the maximum accurate data on karst hydrogeological conditions. Karst geomorphological mapping and karst spring monitoring occurred throughout the county. Three study areas were then chosen (based mainly on the results of the karst mapping and spring survey) for more intensive investigation (Fig. 2). All water balance calculations and spring catchment delineation took place within the study areas. The majority of the water tracing experiments were conducted, during the course of this research, in the study areas, with two smaller single tracing experiments conducted in caves, outside of the study areas. All microgravity investigations and most of the bedrock core drilling were made in two of the three study areas. Three boreholes were drilled outside of the study areas to investigate sub-surface conditions underneath closed depressions.

KARST GEOMORPHOLOGICAL MAPPING

Previous studies in Roscommon had indicated that karst landforms were present (Coxon 1986; Burke 1998; Doak 1995; Drew & Burke 1996; Devoy & Gilhuys 1969; Fenwick & Parkes 1997). However, the degree of knowledge of this karst varied greatly, with the majority unmapped. In order to get a better understanding of karst in Roscommon, a county-wide karst geomorphological investigation was undertaken. This consisted of surface karst landform mapping in the main, with some endokarst landform (cave) mapping. The geomorphological investigation was performed by field examination, using the 1:10,560 (six-inch to one mile) maps, in conjunction with topographical maps, aerial photos and the Geological Survey of Ireland's (GSI's) karst database. Attributes, specific to each landform, were recorded on site such as dimensions and seasonal variability. For endokarst landforms, detailed cave surveying was carried out.

SPRING MONITORING

In order to gain an insight to the workings of the aquifers, 270 springs were occasionally sampled for discharge, pH, temperature and electrical conductivity using a current meter and a hand-held temperature and electrical conductivity meter (Multi 340i/SET WTW, corrected to 20°C). Based on low flow and high flow reading for the springs, 55 (20%) were chosen for further study. These springs were visited and monitored as often as possible (each monitored approximately every month for 2 years). The variability of discharge of each spring was examined as it is considered important in examining the level of karstification of the aquifer (Shuster & White 1971; Bakalowicz & Mangin 1980; Atkinson 1977). Spring hydrographs were analysed, where available, as they can yield important information about complex internal structure and storage of karst systems (Milanovic 1981; Mangin 1975; Bonacci 1993; Shuster & White 1971).

WATER TRACING EXPERIMENTS

Water tracing experiments were undertaken to yield information about the catchment areas of the springs, to trace cave passages and to aid understanding of groundwater flow. Six dye traces were carried out, four of which were multi-dye traces, involving up to five different fluorescent dyes. One tracing experiment was repeated in the same area under different conditions to see how this affected groundwater movement. Both qualitative and quantitative analysis of tracing was carried out. The details of the methodology of water tracing experiments are summarised in Tab. 1. In some cases water was artificially injected to ensure the dye was adequately washed away (Fig. 3). Monitoring points were sampled manually using 100 ml dark glass bottles and charcoal bags. The presence of dye was determined from the charcoal bags by elutriating the charcoal in an alcohol elutant. The water samples were analysed using both a Turner TD-700 filter fluorometer and Perkin Elmer LS 55 spectrofluorometer.

Fig. 3: Injection in a small swallow hole with the aid of an artificial injection of water (Photo: R. Meehan).

MICROGRAVITY SURVEYING

Geophysical investigations provide non-intrusive, tools that characterise and map variations in the physical properties of what lies beneath the ground surface (Stierman 2004) and have been used in karstic terrains in Ireland with a high degree of success (McGrath & Drew 2002; Gibson *et al.* 2004; Styles *et al.* 2005). As cavities usually present a significant density contrast with their surroundings, microgravity geophysics was chosen to reveal

Tab. 1: Summary details of dye tracing experiments.

Study area	Tracer Used	Injection Details	Monitoring Details	Hydrological Conditions
Boyle	Uranine (1.5 kg), liquid form. Funnel and pipe used.	Solution pipe in large doline. Artificial injection of 11,820 L via tanker.	7 springs, 3 streams and 1 river were monitored and sampled manually for a period of 64 days after the injection. Samples were taken twice daily for the first 5 days, then every day for 2 weeks and then every second day. After a month sampling was reduced to once a week and then every two weeks.	Mid-November: During period of normal to high flow conditions.. 2 days of heavy rain occurred 5 days after injection.
	Eosine (1.5 kg), liquid form. Funnel and pipe used.	Small swallow hole with inflow of 3 L/s. Artificial injection of 11,820 L via tanker.		
	Rhodamine WT (7.5 L or 1.5 kg).	Dye poured directly into large sinking stream. Colour had gone after 20 mins.		
	Naptionate (2.7 kg), crystal form.	Two swallow holes located on pavement draining surrounding fields.		
	Pyranine (1.5 kg), liquid form.	Intermittent flow during light rain. No tanker needed.		
Castlerea	Eosine (1.5 kg), powder form.	Small sinking stream in large doline. Dye added directly to sinking water.	12 springs and 2 rivers were monitored manually for a period of 3 months. Samples were taken twice daily for the first 5 days, then every day for 2 weeks and then every second day. After a month sampling was reduced to once a week and then every two weeks. Charcoal detectors were also used and changed regularly.	Early November. Very wet conditions prior to trace. Little rain after injection.
	Sulphorhodamine B (1.5 kg), powder form.	Permanent swallow hole. Dye added directly to sinking water.		
	Uranine (1.5 kg), powder form.	Permanent pothole through till. Dye added directly to sinking water.		
	Naptionate (1.5 kg), crystal form.	Large permanent swallow hole. Dye added directly to sinking water. Colour gone after an hour.		
Ballinlough Tracer Test 1	Rhodamine WT (6 L or 1.2 kg), liquid form. Funnel and pipe used.	Small intermittent swallow hole. Sufficient water was sinking during injection. Dye poured directly into sinking stream.	9 springs were monitored and sampled manually for a period of 35 days. Charcoal detectors were also used.	The trace was carried out in April during dry conditions.
	Uranine (1.5 kg), liquid form.	Permanent swallow hole. Dye poured directly into sinking water.		
Ballinlough Tracer Test 2	Uranine (1.5 kg), liquid form.	Large flooded swallow hole. Dye stayed in ponded water for 24 hours.	15 springs were monitored and sampled manually for a period of 19 days. Charcoal detectors were also used.	Trace was carried out in dry conditions but this time water was artificially injected using a tanker.
	Eosine (1.5 kg), liquid form.	Dye injected into small sinkhole with fast flow.		
	Pyranine (1.5 kg), liquid form.	Small swallow hole. Sufficient water sinking to wash dye away.		
	Rhodamine WT (3 L or 0.6 kg).	Tanker used to wash dye into small sinkhole plug. 6,820 L of water flushed in artificially.		
Pollnagran 1	Uranine (500 g).	Dye added to sinking stream at the cave entrance.	The connection was proven using a visual test at the cave resurgence.	The trace was carried out in September during dry conditions
Pollnagran 2	Rhodamine WT (1 L or 200 g).	Dye added to allogenic sink near Pollnagran main entrance.	The connection was proven using a visual confirmation inside the cave and at the resurgence.	The trace was carried out in September during dry conditions but this time water was artifically injected using a tanker.

the location of subsurface pathways and the approximate dimensions of the cavities and their depth below the surface. The information gathered from the previous investigative techniques greatly aided in choosing favourable location for geophysical surveying. The equipment used was a Lacoste and Romberg D gravimeter. Six line profiles and two subsequent detailed grid profiles were carried out in total. In both the line surveys and the detailed grids microgravity readings were taken every 5 m (Fig. 4). All stations were topographically surveyed using the total station accurate to 1 mm. Other important surface features were also accurately surveyed, such as springs, swallow holes, dolines or field boundaries. Quality control data was performed on all the sites to assess the effects of bad weather and unstable ground. In bad weather the survey was postponed. All the processing of the microgravity field data was conducted by members of Keele University.

BEDROCK CORE-DRILLING

A Bedrock core-drilling programme was carried out in order to investigate the underground conduits in more detail and to 'ground-truth' the geophysics. The boreholes were drilled using a diamond core drill rig using 'wireline' drilling techniques, giving a hole diameter of 75.7 mm and a core diameter of 54.7 mm (Fig. 5). Eleven boreholes, including controls, were drilled in total in

Fig. 4: Microgravity surveying being conducted at 5 m intervals in a grid system (marked out by coloured flags) (Photo: C. Hickey).

Fig. 5: Bedrock core drill rig in a dry valley, Mewlaghmore, Castlerea. Note small closed depressions (Photo: C. Hickey).

both the north and south of the County and for various different reasons (Fig. 2). Seven boreholes were drilled to investigate what is happening to the surface of the rock beneath different types of dolines. A control borehole was drilled adjacent to each doline for comparison. Five boreholes were drilled to ground-truth the microgravity surveying results. The bedrock core was also geologically logged to increase geological knowledge in the areas classified as 'undifferentiated limestones' by the GSI (Morris *et al.* 2003).

RESULTS

KARST LANDFORM MAPPING

Before this project began, there were approximately 150 karst landforms recorded in the GSI's karst database for county Roscommon. Presently, there are over 1,300 karst landforms entered for the same area and almost 90% of these landforms were field checked for this research.

The study is a first large-scale regional assessment of the attributes of karst landforms in the Irish Lowlands. The factors affecting the distribution of the landforms in general, and for each type of landform were then ascertained. The results demonstrated that karst landforms are abundant in Roscommon with an especially large number of recharge landforms (dolines and swallow holes; Fig. 6). Although the overall density is quite high, it is unevenly distributed and clustering and alignment of landforms is evident. In some areas karst landform densities of 80-90 per km^2 were found which is on a par with areas such as the Mitchell Plain in Indiana (Palmer & Palmer 1975). A noticeable feature is that of recharge landforms aligned along the bottom of parallel dry valleys, which are oriented northwest to southeast. The closed depressions are generally small dropout dolines with simple circular plan forms (Fig. 7). The dolines have not had time to enlarge and coalesce and indicate a young karst. Even though allogenic recharge is rare, small sinking streams that originate on areas of thicker subsoil are common, demonstrating the efficiency of the karst system to channel surface water underground. There are also many medium sized ('intermediate sized springs' defined by the GSI as a spring with an average discharge of 5 – 25 L/s) and a few large ('high springs' average discharge of greater than 25 L/s) karst springs in each drainage basin. Five previously unrecorded caves were explored and surveyed including Pollnagran cave (> 750 m long; Fig. 8), which is located where four allogenic streams sink underground (Hickey & Drew 2003).

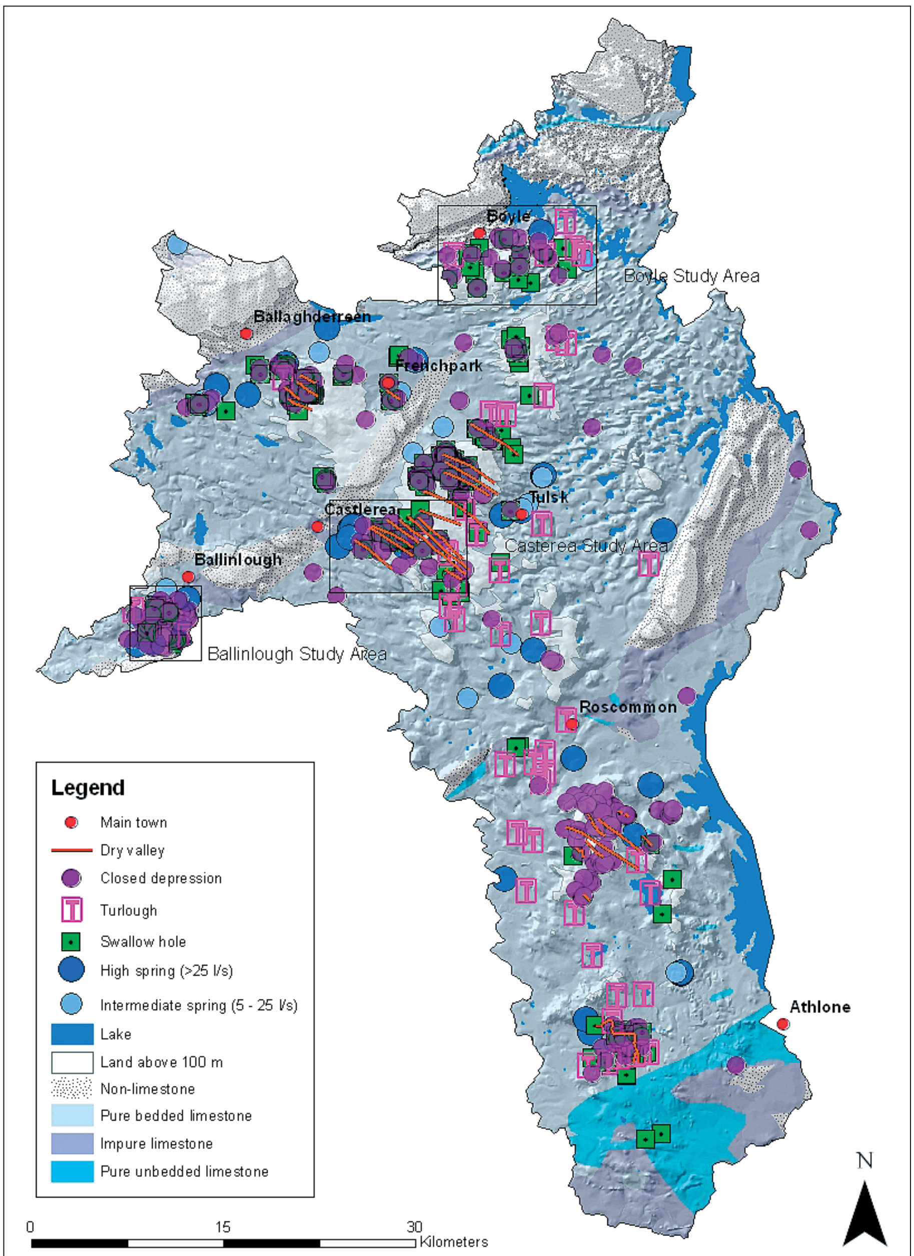


Fig. 6: Distribution of karst landforms in Roscommon.

Fig. 7: Clustering of closed depressions, Mewlaghmore, Castlerea (Photo: C. Hickey).

Fig. 8: Pollnagran Cave, Frenchpark, County Roscommon (Photo: C. Hickey).

SPRING DISCHARGE AND CHEMISTRY ANALYSES

There are five main clusters of springs in Roscommon, three of which were chosen for more detailed hydrological investigation. Assessment of the water quality provided some initial indication to the origin and transport of recharging water and aided in catchment delineation for the springs. Specific conductivity data enabled the coefficient of variation (CV) and frequency distribution of electrical conductivity (EC) to be calculated for each spring (Fig. 9). CV of EC (based on 24 readings taken every two weeks over a period of a year) range from 8.4 to 20.5 and average 14.6. This shows dominance of conduits for flow but importance of small fissures for storage (Shuster & White 1971). Spring hydrograph recession analysis yielded information on the triple porosity functioning of the karst. For example, the recession analysis showing 're-covery' after a storm event of Rockingham spring, near Boyle, shows three stages. The first stage represents the outflow for caves and large conduits and is shown to take approximately 12 days.

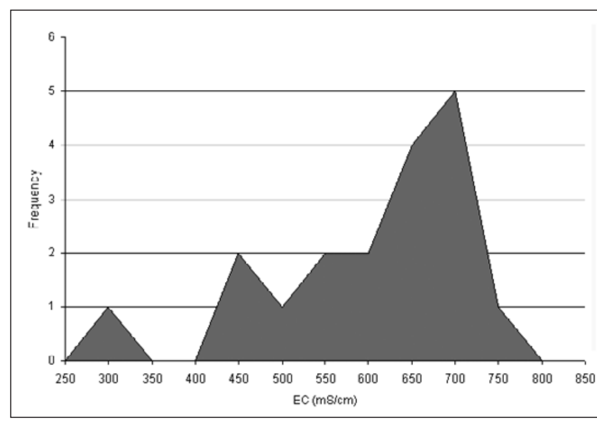


Fig. 9: An example of a frequency distribution graph of electrical conductivity, Rockingham Spring, Boyle.

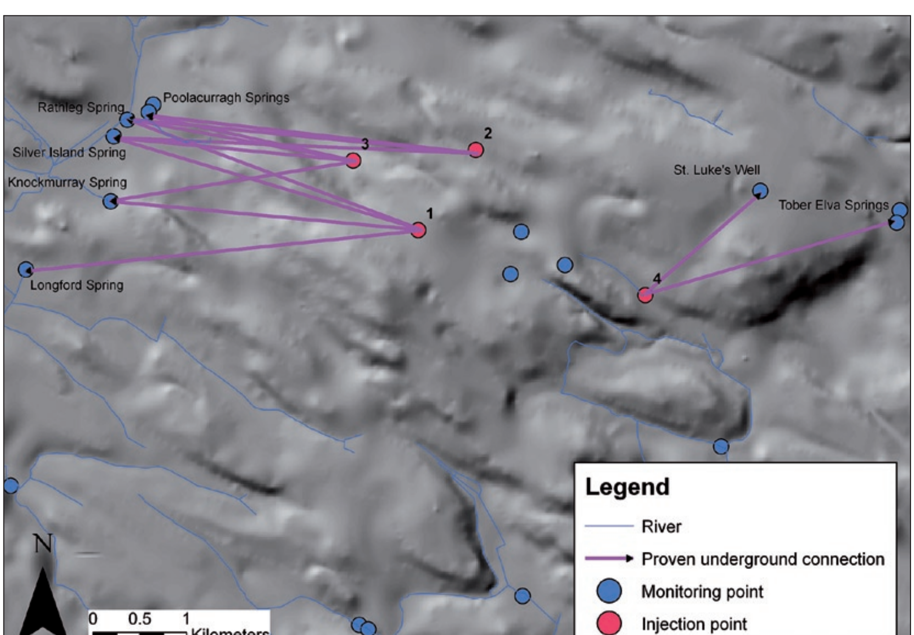


Fig. 10: Results of dye tracing experiment in the Castlerea study area.

The outflow from a system of enlarged fissures is shown to take 23 days and the outflow from a system of narrow fissures and fractures is shown to be still on-going after 40 days.

The study of outflow from springs gave an insight into the degree of karst development in the aquifers and allowed comparisons between drainage basins. This technique showed a high level of drainage basins dominated by conduit flow, with 'flashy' hydrographs and highly variable springs (in terms of discharge and EC). However, all drainage basins studied had elements of triple porosity with a conduit network operating in conjunction with a system of smaller fractures and openings. The technique also demonstrated that highly variable overflow springs are a common feature, suggesting some limitations on the conduit development.

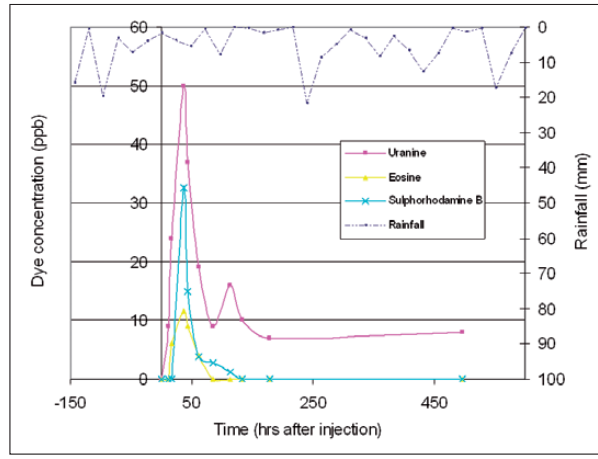


Fig. 11: Tracers' breakthrough curves observed at Rathleg Spring, Castlerea study area (the rhodamine dye used was Sulphorhodamine B) and daily rainfall values.

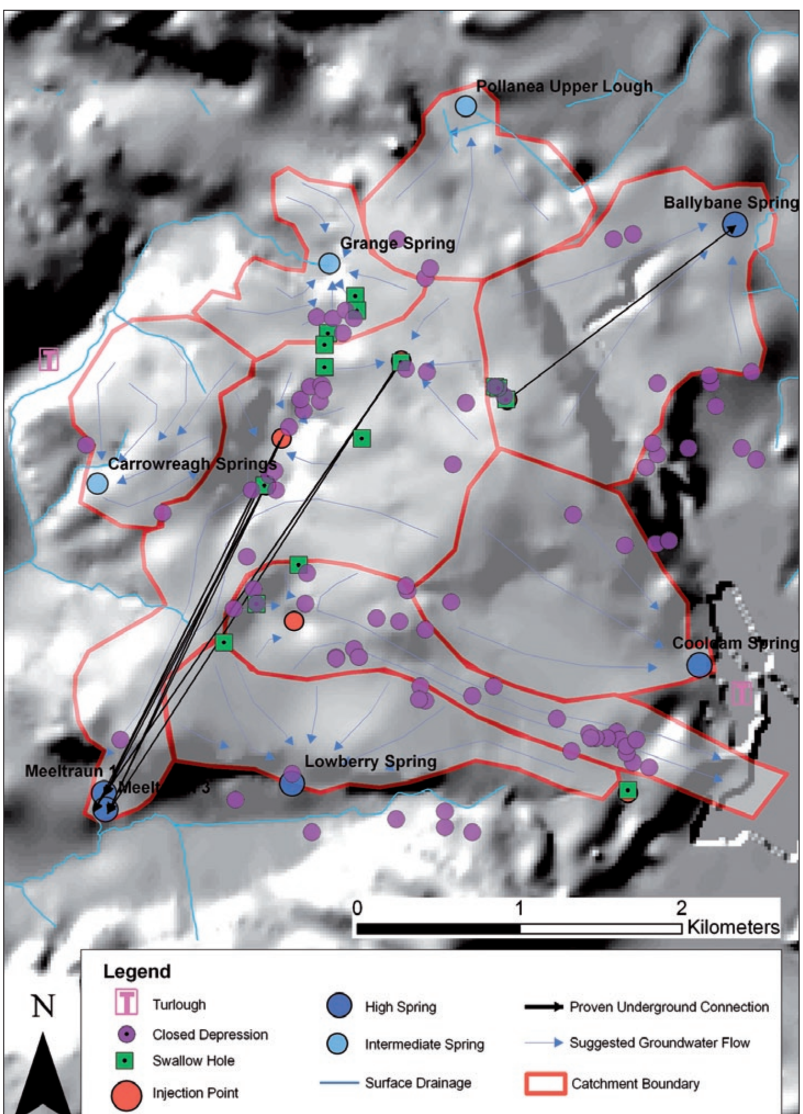


Fig. 12: Catchment delineation for the springs in the Ballinlough study area.

GROUNDWATER TRACING

A feature common to all of the study areas is an elevated limestone plateau dominated by recharge landforms, that is surrounded by springs at the periphery. Linear assemblages of collapse features (or dolines) and swallow holes located at the bottom of dry valleys were especially prevalent on these plateaux.

The dye-tracing experiments proved successful, providing connections from the sinkholes in the upland areas to the springs. They not only demonstrate the direction of groundwater flow, but diverging flow directions illustrate catchment divides (Fig. 10). Water tracing techniques also reveal that Roscommon's karst aquifers are also characterised by heterogeneous, anisotropic groundwater flow.

Spring catchment boundaries were delineated using a combination of techniques including water balance calculations, geological and topographical information, spring chemistry and discharge analysis, karst landform mapping but most importantly, water tracing experiments. Water tracing enabled 'zone of contributions' of different springs to be delineated with high confidence (Fig. 12). An interesting feature of overlapping catchments was also highlighted due to the water tracing experiments as the same dye went to neighbouring springs. The experiments showed unusually rapid flow rates for such a low gradient environment and peaked dye breakthrough curves, which range from 28 m/h to 279 m/h and averaged 80 m/h (Fig. 11). Interestingly, traces of dyes were still being detected at the springs months after the injection indicating the importance of smaller openings for providing base flow to the perennial springs. Recession analyses of the dye breakthrough curves were also an important source of information on the functioning of different systems within and between different groundwater basins.

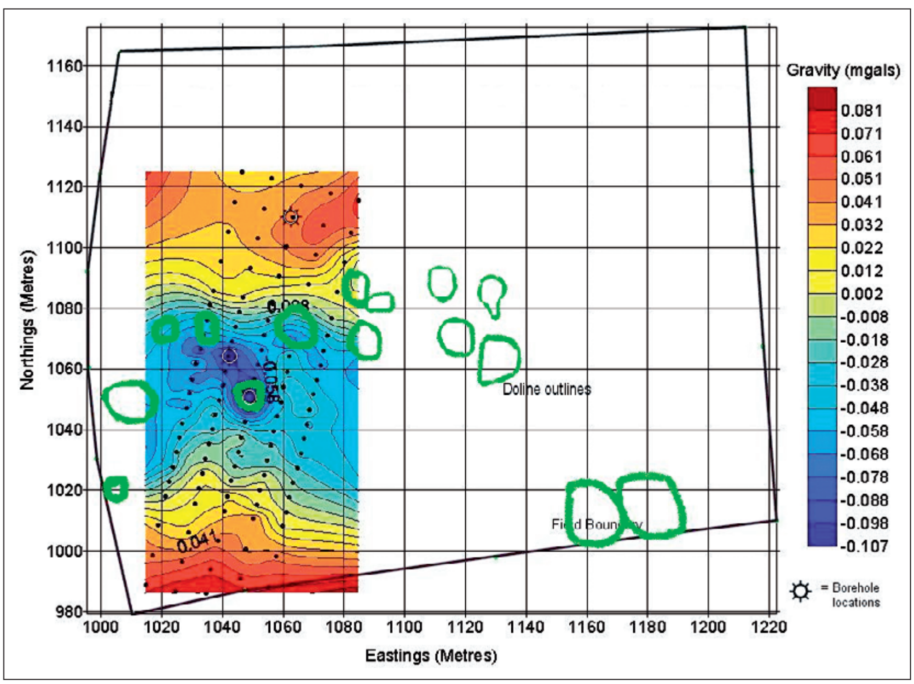


Fig. 13: Bouguer contour map of Mewlaghmore, Castlerea, showing doline outlines (Source: McGrath 2003).

MICROGRAVITY GEOPHYSICS

Three line surveys were conducted adjacent to large karst springs, perpendicular to the direction of groundwater movement as indicated by the dye tracing experiments and karst landforms alignment. The profiles were carried out on the upstream side of the springs. Two line profiles were located by and perpendicular to the linear arrangement of the swallow holes and dolines located along the bottom of parallel dry valleys. One profile was conducted in the middle of the drainage basin between the recharge area and discharge area but with no real constraints from previous investigations.

All of the areas surveyed, except the profile carried out in the middle of the drainage basin, showed conclusive evidence of large cavities or voids in the rock. The surveys carried out adjacent to springs and swallow holes, which had been successfully traced showed very clear gravity anomalies and void depths and dimensions were modelled with conviction. The results indicate that there is a conduit system, with one or two main conduits overlain by many smaller, shallower conduits.

Two of these areas, one by a large karst spring (Silver Island Spring) and another in a dry valley at Mewlaghmore, in the Castlerea study area (Fig. 10) were chosen for a more intensive microgravity study which produced very detailed microgravity maps. When the karst landforms were overlain on these maps it became clear that the area of large gravity anomalies coincided with the karst landforms and dry valleys (Fig. 13) (Hickey & McGrath 2004).

BEDROCK CORE DRILLING

In all cases the bedrock was extremely fractured and a well developed epikarst layer was found. Both shallow and deeper conduits were found at each site. In each case, the control borehole was significantly less karstified, with only a few minute openings. The holes were drilled to varying depths ranging from 7 to 37 m below ground level (bgl).

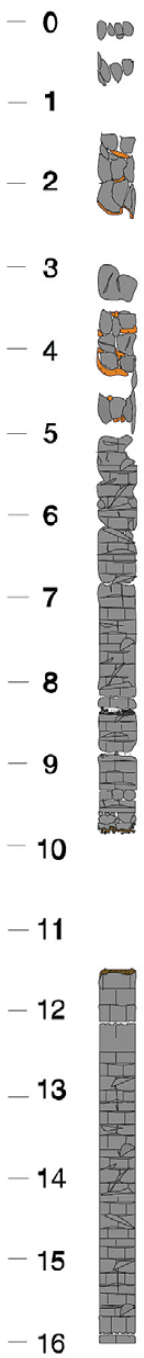
One hole was drilled beside Rockingham Spring, a large karst spring (Fig. 14). where the geophysics had indicated a large anomaly at 10 m bgl. At exactly 10 m bgl a large air filled cavity was encountered, the drill bit dropping some 1.5 m. In some cases, the dimensions estimated from the microgravity were an overestimation but this is thought to be due to the epikarst zone in the first 5 m of rock where the average core recovery was less than 50%.

Four boreholes were drilled using the detailed microgravity maps as a guide. One was drilled adjacent to Silver Island Spring, Castlerea (Fig. 10) where conduits

Hole number:6 **GSI number:**D/H229/02 **Drilled date:** 28/10/01 **Townland:** Rockingham
Elevation:48m **Grid Reference:** 184880 302780 **Depth to Bedrock:** 0 **Depth of Hole:** 27.5m

Reason for drilling: Along line between swallow holes and Rockingham spring. Microgravity profile modelled an air-filled conduit at a depth of 10 m at this point so to validate the geophysical

Depth (m) **Graphic Log**



TCR (%)	Fossils	Description	Unit	Drilling comments
70		No overburden, rock at surface.	Epikarst	
0		Air-filled cavities.	Conduits	Bit jumped many times
50		Recovered pebbles and bits or rock. Very broken up and shattered.	Epikarst	Bit got stuck
0		Conduit of 50cm 2.4m of the first 3m was air filled.	Conduit in epikarst	Bit jumped 50cm through air
50	Bioclasts and shell fragments	Mostly just small stones and crumbly rock in fine-grained matrix.	Epikarst – minor argillaceous, fine grained Limestone (Oakport?)	Bit got stuck a few times
80		At 6.5m get first real core. Still have cracks and fractures but only small. Have gravely layers in fractures.	Oakport Limestone bedrock with many fractures	
20		Example of one of the fractures with rounded pebbles and gravel.	Small conduit	
60		Bitty broken core with rounded pebbles and gravel and clay layers.	Fractured area. Start of large conduit	
0		Bit dropped 1.5m through air.	Large air filled conduit	Bit jumped
100		Start of bedrock again at 11.5. One fine layer and then good, clean core with some small fissures.	Other side of cavity. Limestone bedrock	
90		Broken core with numerous fissures, cracks and numerous solutionally widened fractures.	Fractured and dissolved Oakport limestone	Bit got stuck
0		Enlarged fracture 20cm wide	Small conduit	

Fig. 14: Graphic log of the core taken from drilling near Rockingham Spring, Boyle study area.

were modelled from the microgravity surveying. Three were drilled in Mewlaghmore dry valley area (Fig. 13). One was drilled in the dry valley where the geophysics indicated the greatest gravity anomaly, one was drilled at the bottom of a doline in one of these dry valleys also where the geophysics showed the greatest anomaly. The third was drilled at the other end of the field where the microgravity map showed no gravity anomaly.

All the boreholes drilled into the areas of gravity anomalies encountered large conduits and a significant epikarst zone. The borehole drilled beside Silver Island Spring encountered a network of conduits with many air-filled openings in the top 15 m of the rock. Larger conduits were encountered at around 20 m bgl with two main openings in the rock, 1.5 and 1.7 m in thickness.

In the Mewlaghmore area, drilling again proved the existence of significant underground openings. Firstly, 4 m of overburden were encountered in the dry valley before reaching the bedrock. In the control borehole bedrock is reached straight away. This demonstrates large amounts of rock removed by karst processes. Both boreholes revealed an intensive amount of karstification with average core recovery being less than 40% in the first 25 m of rock. Many large cavities were encountered, some air filled and some filled with fine material. At 11 m bgl a cavity of 1.5 m thick was encountered and this was underlain by a sediment filled cavity some 6.5 m deep. The control borehole, only metres away, showed clean, fissured limestone with almost 100% total core recovery.

CONCEPTUAL MODEL

A regional conceptual model was developed, based on the results of this investigation to reflect the aspects, landforms and hydrology of karst found in Roscommon (Fig. 15). The model summarises the main findings of the research. Recharge zones are located on the plateaux, which is largely devoid of surface drainage. This

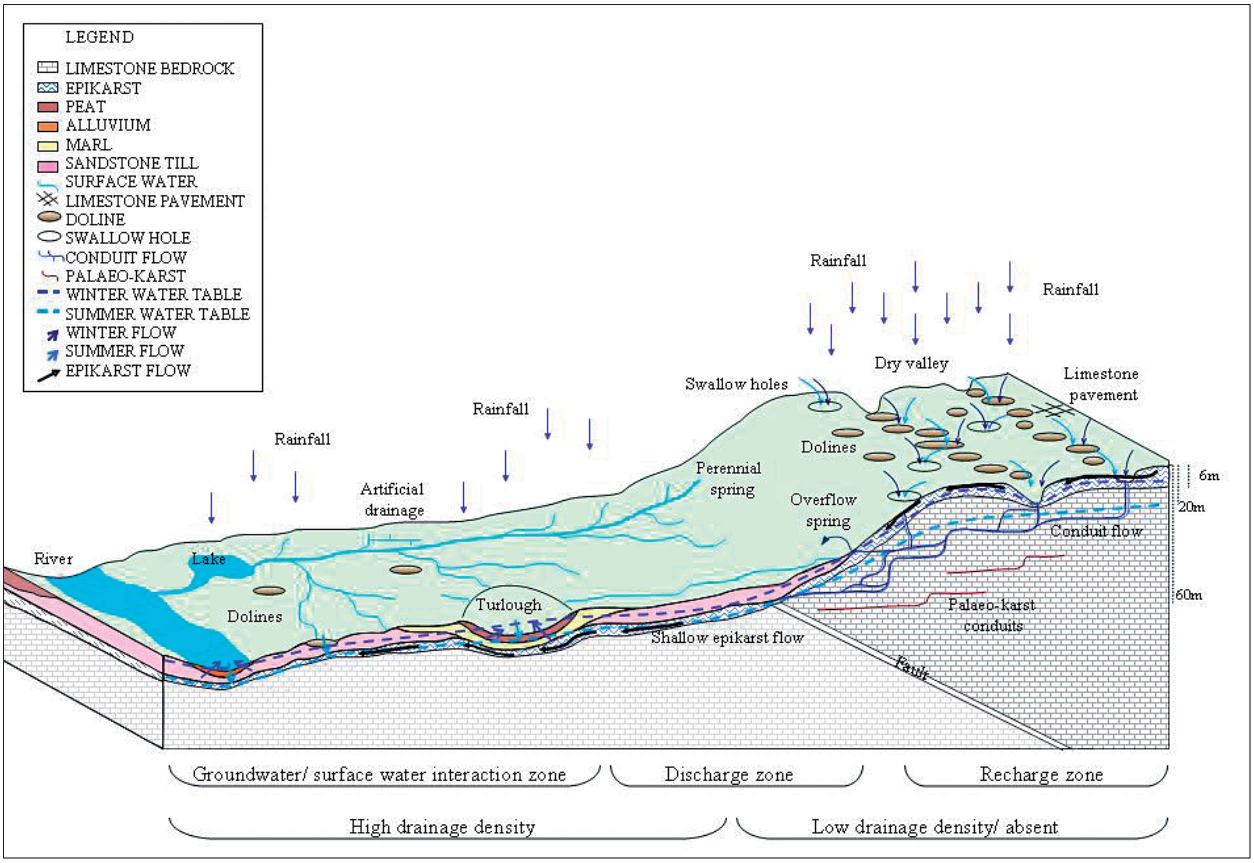


Fig. 15: Conceptual model of the karst of Roscommon.

plateau is characterised by a high density of recharge landforms some of which are aligned at the bottom of the dry valleys. There is also a well-developed epikarst zone, which is thought to laterally transmit large amounts of flow. Some recharge also penetrates deeper into a shallow conduit zone. The flow moves from this plateau area to the periphery, where it emerges at springs, in a discharge zone. Both perennial and overflow springs exist (note winter and summer flow lines). These springs give rise to surface drainage, such as streams, lakes, rivers and turloughs, which are common in the lower lying areas. Artificial drainage networks are also widespread in low permeability subsoil such as peat. The river shown in this model is considered influent during low flow conditions and effluent during high flow conditions, which may lead to flooding. The turlough shown in this model is an epikarst turlough with a very shallow flow system, though some turloughs may connect with deeper (< 20 m bgl) channels. This shallow epikarst flow is thought to dominate the groundwater movement in the lower regions, although some deeper conduits may exist. The subsoils are thin or absent on the plateau and thicker on the plains (Hickey 2010).

CONCLUSIONS

Many new techniques and investigative equipment have evolved during the latter part of the twentieth century that can describe more precisely the characteristics of karst systems (La Moreaux & La Moreaux 2007). These significant advances in hydrological investigations and techniques have enabled a much deeper understanding of karst hydrology. Present conceptual models have been shaped and built by the way in which the karst aquifer has been analysed and investigated. There are many problems posed to the karst hyrdogeologist when trying to understand the processes operating in an area. Ford and Williams (2007, p. 145) suggest a 'grey box' whereby as much information as possible is gathered and used in any conceptualisation of a karst area.

The identification and characterisation of specific flow pathways at a given site is probably the most sought after yet difficult outcome in studying a karst aquifer. Future advances in analytical techniques of karst aquifers, and in particular advances in remote sensing and modelling will bring the science closer to achieving such complex aims (Sasowsky 2000). Many studies in the past have concentrated on one or of these analytical tools for investigation, e.g., dye-tracing, computer modelling. However, it is now seen that these aims can only be achieved when a combination of as many analytical tools as possible are employed (Bakalowicz 2005). A combination of techniques (geomorphological mapping, structural and lithological mapping, and electrical resistivity imaging) was found to greatly enhance the success of characterisation of karst area in SW Slovenia, which was later used for vulnerability and risk mapping (Ravbar & Kovačič 2010).

Large amounts of information were gathered in this study from using the different investigative techniques in conjunction (karst landform mapping, spring chemistry and discharge analyses, dye-tracing, geophysical investigations, bedrock core drilling). The information from the techniques enabled a comprehensive conceptual model, outlined above, of the karst of Roscommon and the Irish karstic lowlands to be developed.

The karst landform mapping programme provided a comprehensive study into the extent and distribution of the karstification of the aquifers in the county. However, it did not provide any real detail of the hydrological functioning of the aquifers. This was revealed by analyses of karst springs in different drainage basins. This technique provided information on the triple porosity functioning of the systems and allowed for comparisons between areas. These two methods alone, however, provided no information about groundwater flow directions or velocities. Water tracing techniques were then employed to prove connections between recharge landforms and the springs, establish flow directions and velocities and enable delineation of groundwater catchments. Analyses of the dye breakthrough curves revealed further information of the inner workings of the karst drainage systems. These three methods did indicate a hierarchical system of conduits but did not provide any details of this. Microgravity geophysics was then used to characterise the conduit system and reveal the nature of the bedrock. Lastly, bedrock core drilling was undertaken to actually prove or demonstrate the accuracy of all the other methods.

By employing a combination of methods there was much greater confidence in the results, as each technique greatly enhanced the success, accuracy and reliability of the next one. This is clearly shown by the success at finding large karst conduits at every site. As larger conduits only occupy a tiny percentage of karst aquifers, the likelihood of intersecting one is slight. Not only were conduits found, but they closely resembled what was modelled from the geophysical investigations for each site. Again, part of the success of the geophysical surveying was due to the wealth information available for each site. This was gathered from previous investigative techniques - such as the karst landform mapping and dye tracing. The success of the water tracing was due to the detailed field reconnaissance and karst mapping that occurred in each area prior to the trace.

Drew and Goldscheider (2007) state that any complete groundwater investigation, whether in karst or not, requires the application of more than one investigative method and unfortunately, for us all there is "no magic single hydrogeological method" that is going to give all the answers (Bakalowicz 2005, p. 156). Unfortunately, for us there is also no magic combination of methods that will give all the answers. There are uncertainties associated with every investigation and this study is no different. The accuracy of the catchment boundaries, for example, remains uncertain and would require further investigation in every possible weather condition. Continual spring monitoring is also necessary on every spring in a drainage basin to really understand the processes occurring in the aquifer. There are uncertainties associated with any geophysical method, as the results are only an interpretation. However, this paper demonstrates how the use of orthodox groundwater investigative methods in conjunction with those specific or adapted to karst environments can greatly enhance both the resultant data and the understanding and interpretation of those results.

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