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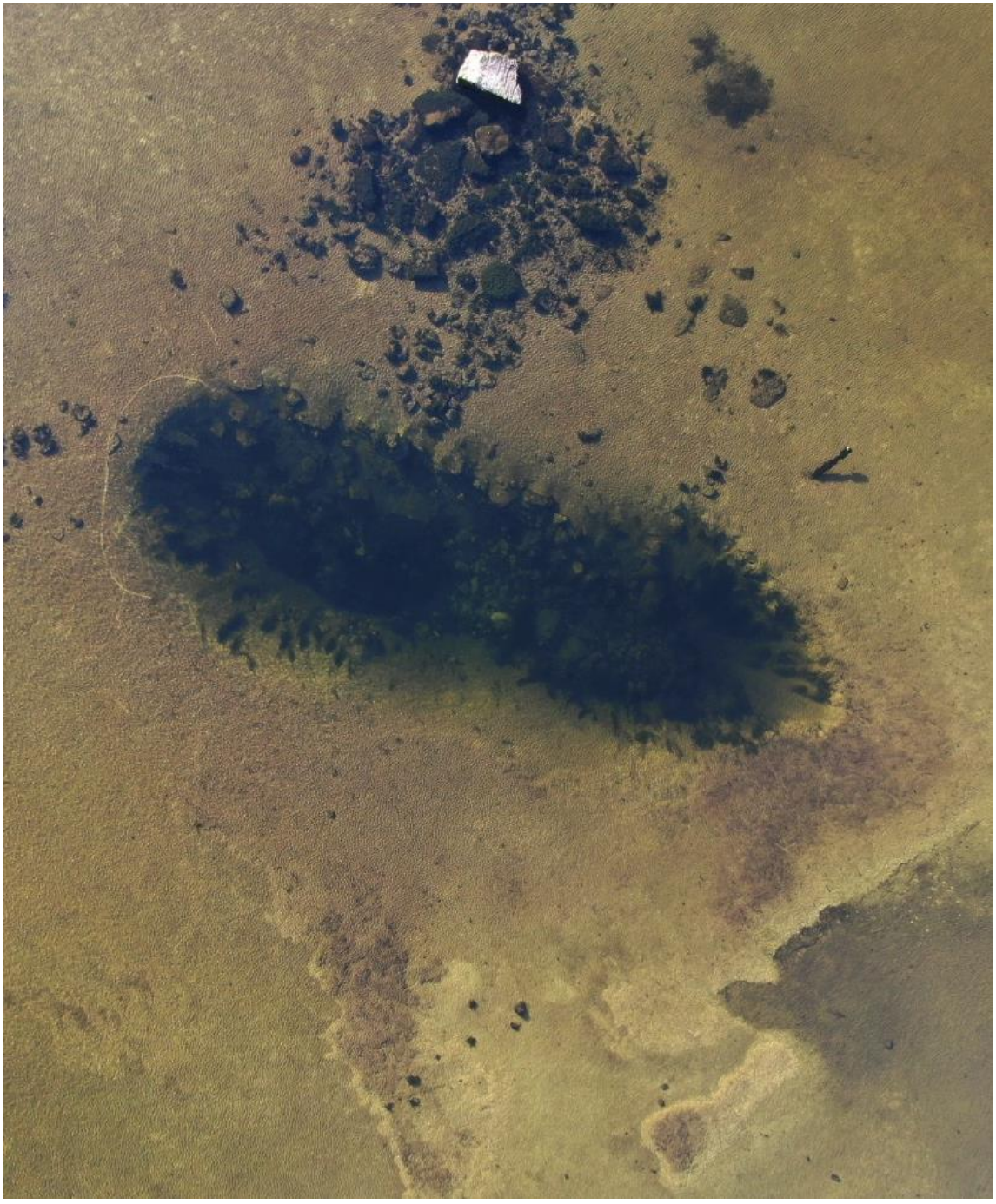
Lough Carra LIFE Groundwater Catchment Study
D2.0 Initial conceptual model



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Cover photograph: Aerial image of Moorehall Spring and sinkhole in Lough Carra (GSI 2022)

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1. Introduction

Lough Carra is a marl lake circa 16 km^2 in area, located in the lowlands of southeast County Mayo (Figure 1). It is Ireland's best example of a hard-water/marl lake (National Parks and Wildlife Service habitat 3140) and comes under the protection of the Lough Carra/ Mask Complex SAC/pNHA. Its status as a protected area is intrinsically linked to its geology and hydrogeology, as it has a significant groundwater input (NPWS, 2015).

Geological Survey Ireland will undertake a hydrogeological investigation of Lough Carra as part of the EU-financed LIFE Project, Lough Carra LIFE. The aim of this project is to improve water quality in Lough Carra to favourable condition, improving the national status and trends of this habitat, and to improve the conservation status of the Orchid-Rich Grasslands, Limestone Pavement, Common Gulls, Otters and Lesser Horseshoe Bats in the Special Area of Conservation and Special Protection Areas.

Action A.2 (Groundwater Catchment Study) of Lough Carra LIFE will define groundwater-surface water connectivity in the catchment to confirm the catchment boundary more exactly and help target nutrient-reduction actions. This report is a deliverable of Sub-action A2.1 (Desk Study & Survey Design). The report represents the initial hydrogeological conceptual model after the completion of the desk study. It is informed by the data outlined in deliverable 2.0 (data register). This initial conceptual model will be updated as the hydrogeological investigation progresses.

1.1. Physical Setting

1.1.1. Topography

Lough Carra is situated in Ireland's Western Lowlands, in the southeast of County Mayo. It is located at the western end of a large area of low-lying, gently undulating topography, rarely rising above 60 m OD (Figure 1). To the east there are slightly elevated areas (80 – 100 mOD) found around the town of Claremorris, some 14 km east of Lough Carra.

There is a continuation of this gently undulating low-lying topography to the west of Lough Carra for about 4 km. Approximately 4 km west of the northern basin of Lough Carra the land rises steeply to form the Party Mountains. The highest point of these mountains, called Drumcrogg Mountain, rises to a peak of 381 m OD and is located over 9 km to the west of Lough Carra (Figure 1).

1.1.2. Hydrology

The east of this large expanse of limestone lowlands is drained by the River Shannon and the River Suck and to the west by the Rivers Robe, Clare and Moy. Arterial drainage has considerably modified many of the river courses and other drainage features in this area. The current river courses now follow somewhat convoluted courses to Lough Mask, Lough Corrib and the coast. Lough Carra lies to the northeast of Lough Mask and the outflow of Lough Carra, the Keel River, flows into Lough Mask (Figure 1).

There are a number of rivers in the vicinity of Lough Carra (Figure 1). The Meander River is located approximately 6.5 km east of the northern basin of Lough Carra and flows in a northerly direction away from Lough Carra, towards Lough Cullin and Lough Conn and eventually flows out to the

Atlantic at Killala Bay via the River Moy. The River Robe flows in a westerly direction, south and southeast of Lough Carra and into Lough Mask. It rises in the limestone lowlands area to the east of Lough Carra, between Claremorris and Ballyhaunis, and drains much of this area.

The Aille and Camoge River drain the western slopes of the Partry Mountains. The Aille River rises on the western slopes of the Partry Mountains and flows north before sinking underground when it meets a strip of limestone. It flows underground as the Aille Cave and remerges at a large spring 2.8 km to the east and then flows southeast to meet the Camoge River. The Claureen River joins the Aille River further downstream and then flows in a southerly direction 1-2 km west of Lough Carra, eventually flowing into the northern shore of Lough Mask. The eastern slopes of the Partry Mountains are drained by several rivers and streams, such as the Glensaul River, which flows into the western shores of Lough Mask.

Surface water input to Lough Carra comes from the Aghinish River, Annies River, Cloondaver Stream, and other small streams, with all of these inputs located along the northern and eastern shorelines. Further north, a number of smaller rivers and streams all flow south, west and southwest to Lough Carra. The lake is 15.6 km² in area, and mostly shallow, with three distinct but connected basins.

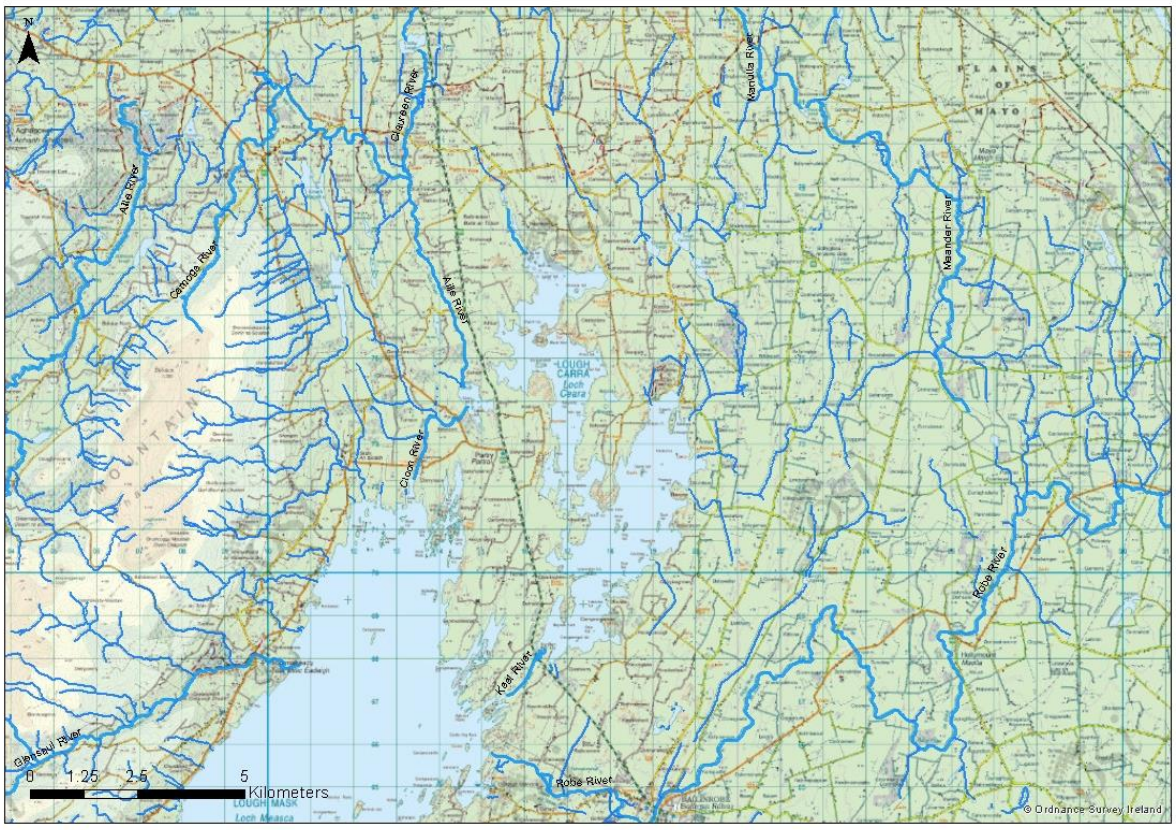

Figure 1 Physical setting of Lough Carra, showing topography and drainage (the larger rivers are named)

1.2. Geological Setting

1.2.1 Geology

Lough Carra, Lough Mask and Lough Corrib (the Great Western Lakes) all lie at the western edge of a very large continuous block of low-lying Carboniferous limestone that stretches across much of the midlands and west of Ireland (Figure 2).

The bedrock to the west of the Great Western Lakes is older, of Ordovician age (488-444 Mya), and is characterised by dramatic upland peaks and glacial valleys. These hard rocks are mainly composed of sandstone, shale, greywackes and igneous rock such as granites that are resistant to erosion, thus forming the present-day uplands (Figure 2).

The bedrock underlying Lough Carra and perhaps its entire catchment area is made up of several different limestone units of the Dinantian Pure Bedded Limestone rock unit group. There is also a strip of Dinantian Lower Impure Limestones and younger Dinantian Sandstones immediately west of Lough Carra.

Faulting occurs through the central portion of the southwest of the catchment and a major fault (the Erriff Fault) bypasses the catchment circa 1 km northwest of the northern lake boundary, close to the village of Ballyhean.

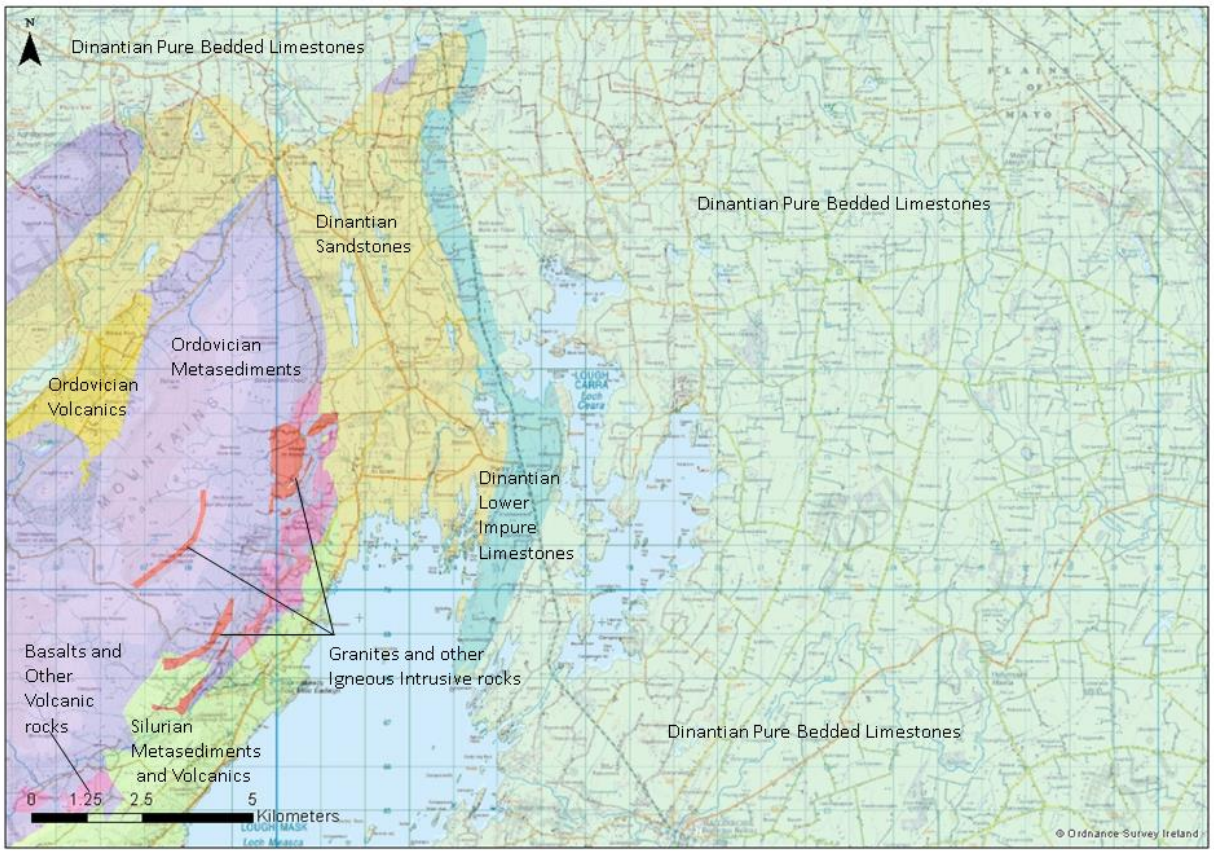

Figure 2 Simplified Bedrock Geology of the Lough Carra Region

Bare rock or rock near the surface is widespread around Lough Carra, most notably along the lakeshore, but large expanses of limestone pavement are also observed from satellite imagery in the region between Lough Carra and Lough Mask, and in the area east of Ballintubber. The subsoils within the surface water catchment of Lough Carra are dominated by tills derived from limestones,

deposited as drumlins; these subsoils are generally less than 10 m thick. Lacustrine sediments and cut over raised peat overlie the tills and/or bedrock in a few places. The subsoils are thicker towards Claremorris in the east, and most of the area is underlain by glacial deposits that are generally greater than 10 m thick. This is interspersed with some areas of shallower rock. Where the subsoils exist the permeability is generally described as moderate over much of the area. Pockets of low permeability exist.

Groundwater vulnerability, described as the ease by which contaminants can pollute groundwater, is generally a function of the nature and permeability of the overlying protective sediments above the aquifer. Where there are large thicknesses of low permeability subsoil, the groundwater is described as having a low vulnerability (surface water will likely be at risk here) and where there are little or no sediments overlying the aquifer then the aquifer is considered extremely vulnerable. The role of karst features, enabling these overlying protective layers to be bypassed is also considered ((DHLG/EPA/GSI, 1999). The groundwater vulnerability classification for the Lough Carra area is shown in Figure 3.

Most of the area immediately around the lake is classified as extremely vulnerable to pollution as there is little or no subsoil to filter out any potential contaminants. Over much of the area to the east of lough Carra the groundwater vulnerability is considered high with pockets of low and moderate vulnerability interspersed. There are large areas of low groundwater vulnerability further east. Most of the upland area to the west of Lough Carra has extreme vulnerability as rock is at the surface.

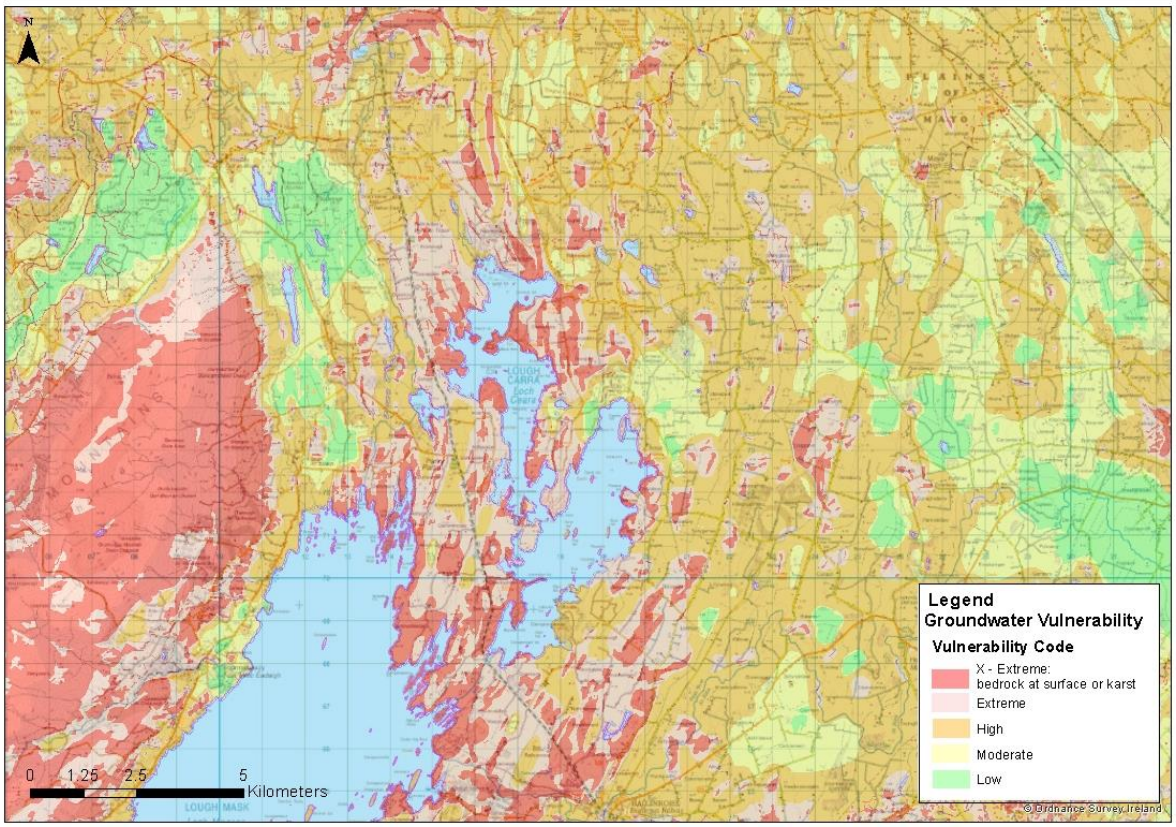

Figure 3 Groundwater Vulnerability of the Lough Carra Region

1.2.2 Hydrogeology

The limestones around and to the east of Lough Carra are considered to be highly karstified. This means they have been dissolved by moving water creating preferential underground pathways for

water flow. Karstic landscapes have distinct characteristics landforms such as turloughs, swallow holes, sinking streams, sparse or intermittent streams, limestone pavement, dry valleys and large springs. All of these features can be found in the Lough Carra catchment.

Within the Lough Carra region, all of the limestones within the Dinantian Pure Bedded Limestone group are classified as a Regionally Important karstified bedrock aquifer that is dominated by conduit flow systems *(Rkc)* (Figure 4). The purity of the limestones here and the degree of bedding and other openings means that these limestones are high susceptible to karstification. The muddier limestones of the Kilbryan Limestone Formation, found to the west of Lough Carra, are less susceptible to karstification and are classified as Locally Important bedrock aquifer which is moderately productive only in local zones *(Ll*).

The Dinantian sandstones are relatively permeable due to interconnected openings, such as faults and fissures, and are classified as Locally Important bedrock aquifers which are generally Moderately Productive (*Lm*). Much of the harder, older rocks to the west are classified as Poor bedrock aquifers, which are generally Unproductive expect for Local zones *(Pl*).

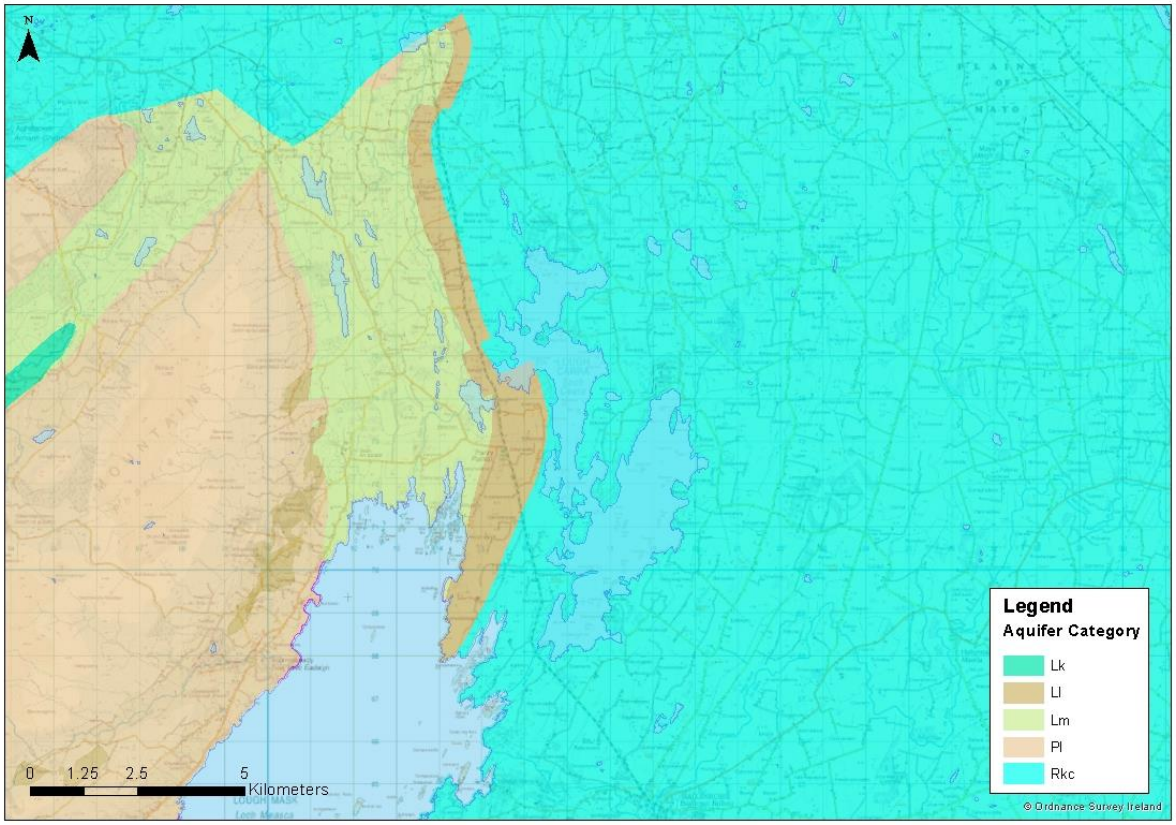

Figure 4 Aquifer Classification of the bedrock in the Lough Carra Region

This configuration of aquifer types means that the majority of groundwater movement in the area is through the karstified limestones underneath and to the east of Lough Carra (and Lough Mask). Lough Carra is classified as being a marl lake, which means it is characterised by the presence of marl, a calcium carbonate deposit, on its lakebed, which comes from the limestone geology.

There are a large number of karst landforms recorded in Geological Survey Ireland's National Karst Database for the area (Figure 5). However, as can be seen on Figure 5, the karst landform mapping coverage is patchy, with many areas yet to be mapped. In 2019 Geological Survey Ireland's 'Groundwater 3D' programme undertook an extensive karst feature mapping programme in Lough

Carra. The overall aim of the research was to help develop a greater conceptual understanding of groundwater movement within the Lough Carra catchment and surrounding area, by characterising the karst landforms.

In total, **693** potential karst features were identified within and around the Lough Carra surface water catchments as a result of field mapping; **119** excluding enclosed depressions. The area covered in the field survey was *c.* **200 km^2** (the area of the surface water catchment is *c.* 110 km^2). All of these features have been added to the GSI karst database.

Figure 5 shows the results of this karst mapping, combined with more recent karst landform mapping as part of the Lough Carra LIFE project as well as some pre-existing landforms in the national databases. It also shows the results of some previous groundwater tracing experiments in the wider area.

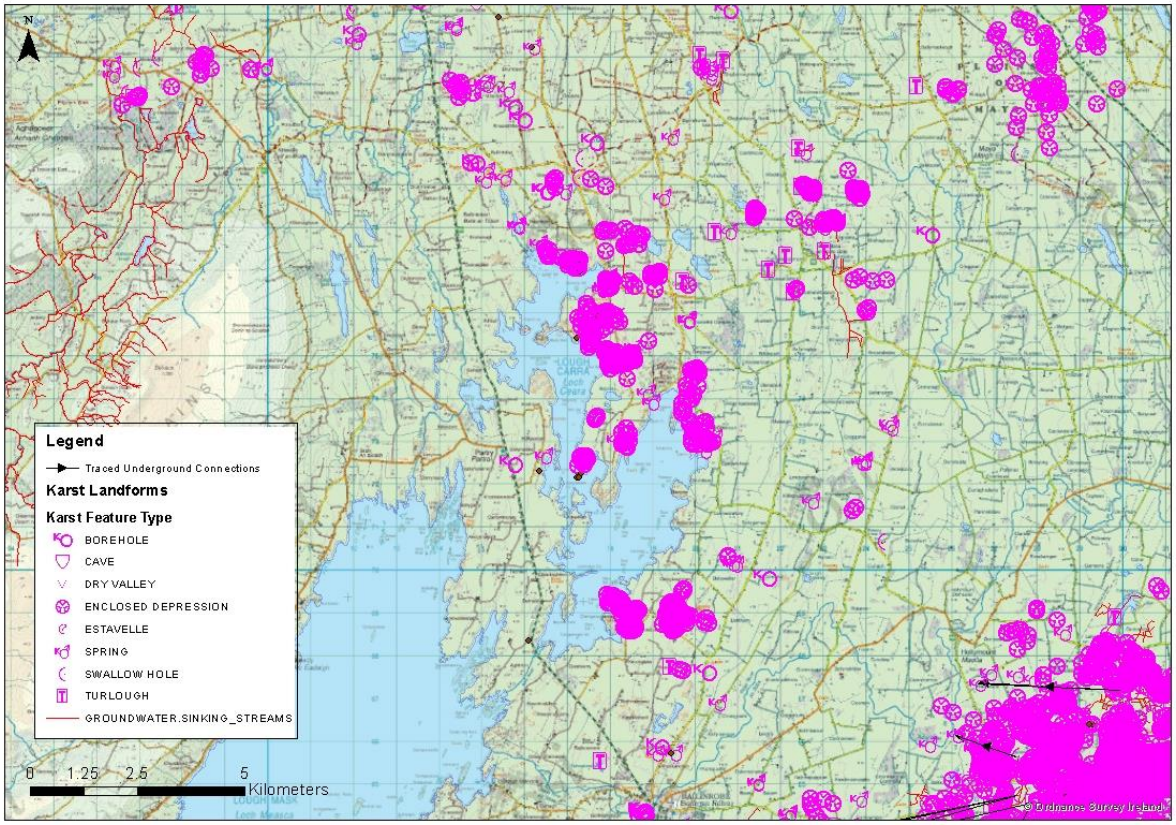

Figure 5 Karst landforms and water tracing results in the Lough Carra Region

2. Conceptual Model

2.1. Introduction

Lough Carra is fed by small surface water rivers and by groundwater. The surface water catchment is relatively easy to understand and define. The groundwater catchment is much more complex and harder to define.

The aim of Lough Carra LIFE is to improve water quality in the lake to favourable condition through a series of measures across the catchment to reduce losses of nutrients. However, the groundwater catchment and groundwater pathways to the lake need to be understood in order to effectively help target nutrient-reduction actions. The aim of the groundwater team is to define groundwater-surface water connectivity in the catchment through a groundwater study, to define the total catchment boundary to the lake and, therefore, help effectively target nutrient-reduction actions.

2.2. Surface water catchment

The surface water catchment at the start of the project was defined by the Environmental Protection Agency (EPA) for the River Basin Districts as part of the Water Framework Directive. River Waterbodies (RWB) are the management and reporting units for the WFD. The RWB polygons are associated watershed areas delineated using ArcHydro and the EPA 20 m hydrologically corrected DTM. The catchment boundary generally used is a combination of 3 river sub-catchments: Aghinish_010, Annies_010 and Cloondaver_Stream_(North)-010 which are the sub-catchments for the three main streams that flow into Lough Carra. The Aghinish catchment is the largest at 67 km^2, Annies catchment is the next largest with 27.7 km^2 and the smallest catchment is the Cloondaver catchment with an area of 12.5 km^2. This gives a total surface water catchment area of 107 km^2. Surface water exits the lake at the south, via the Keel River, to Lough Mask. Figure 6 shows the surface water catchment as defined by EPA WFD RBD catchments.

From an initial appraisal of the surface water catchment it is clear that there are some issues with it. The boundary seems to cut across streams and other water features, such as turloughs. This boundary will need to be redefined based on all available information. Figure 7 shows an example of the issues with the surface water boundary.

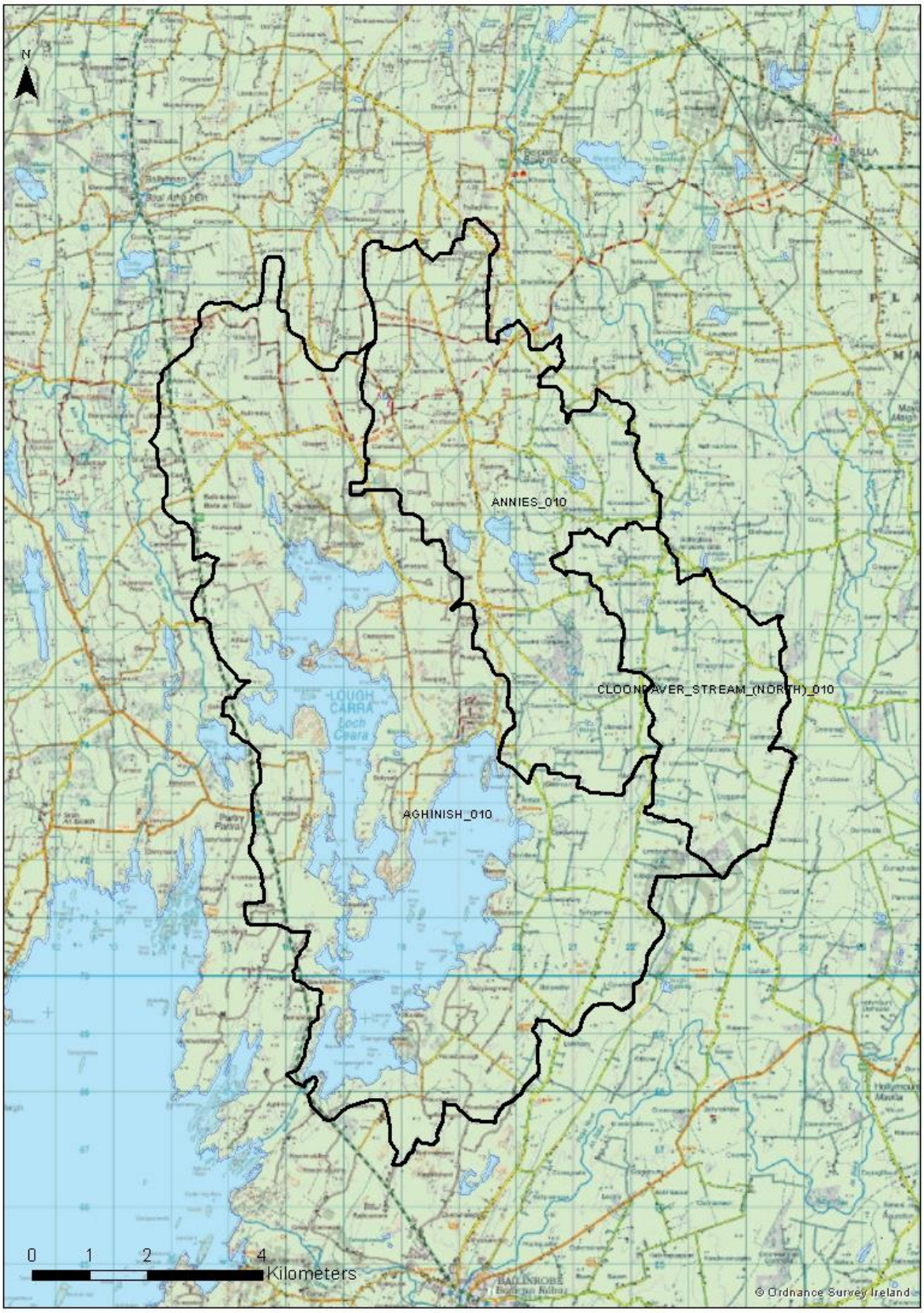

Figure 6 Surface Water Catchment to Lough Carra as per WFD RBDs

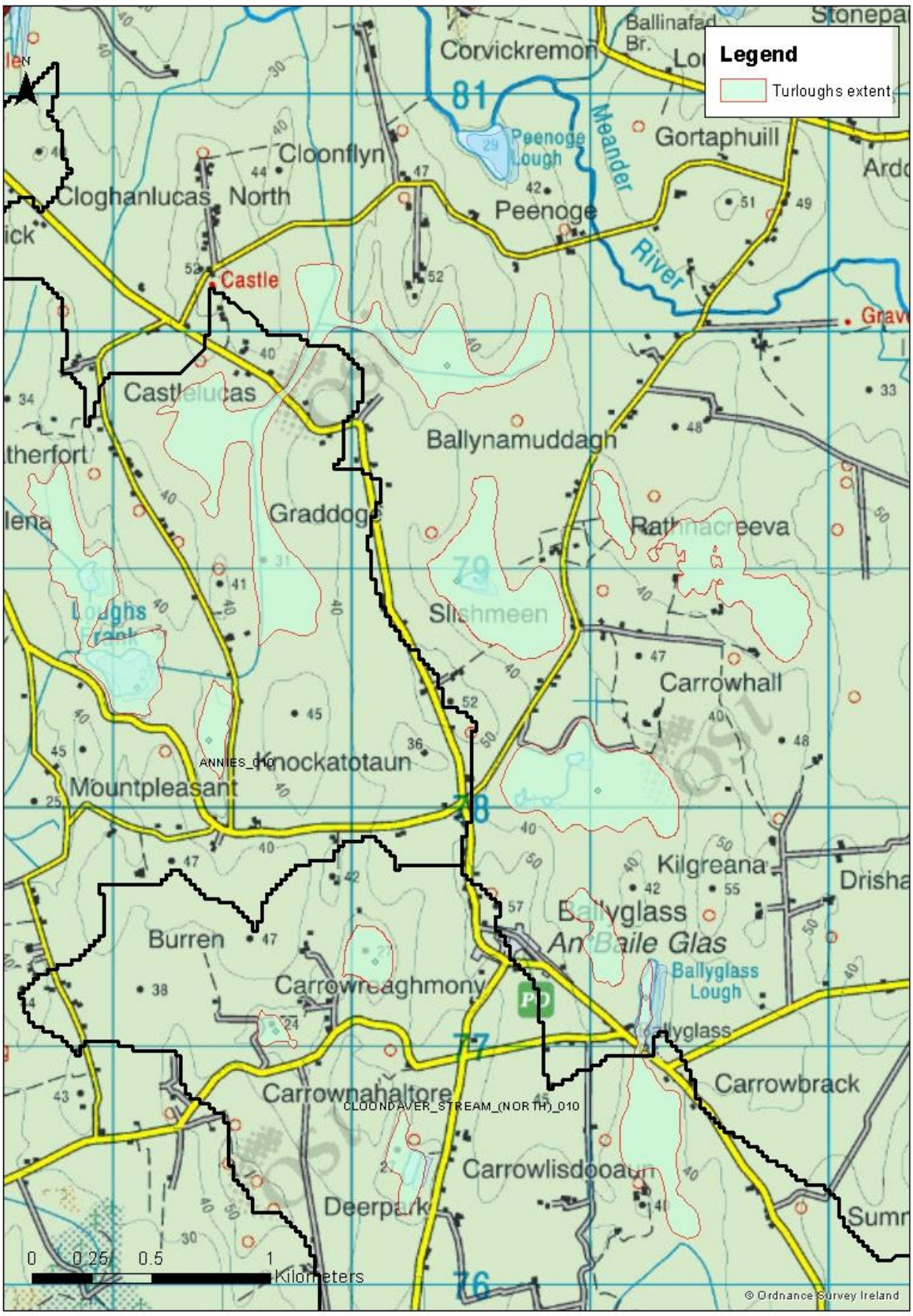

Figure 7 Catchment boundary cutting across surface water features such as turloughs

2.3. Groundwater Catchment

2.3.1 Introduction

Lough Carra owes it unique character to its underlying bedrock. Lough Carra's status as a protected area is intrinsically linked to its underlying geology and hydrogeology, as it is located within karstified bedrock with significant groundwater input (NPWS, 2015). Lough Carra, famous for its marl deposits, is highly alkaline and carbonate rich. This gives rise to a distinct macrophyte community and a distinct naturally translucent blue-green colour. Marl is formed by precipitation of calcium carbonate into the lake by groundwater.

Groundwater enters Lough Carra through direct and indirect means. There are known karst springs that directly feed the lake, for example a subaqueous spring located close to Moore Hall (see cover photo) and Bull's Well located in Burriscarra. Figure 8 shows two images taken with a thermal imaging camera which shows the contrast between the cold groundwater (usually around 10-11 °C) and the warmer surrounding landscape.

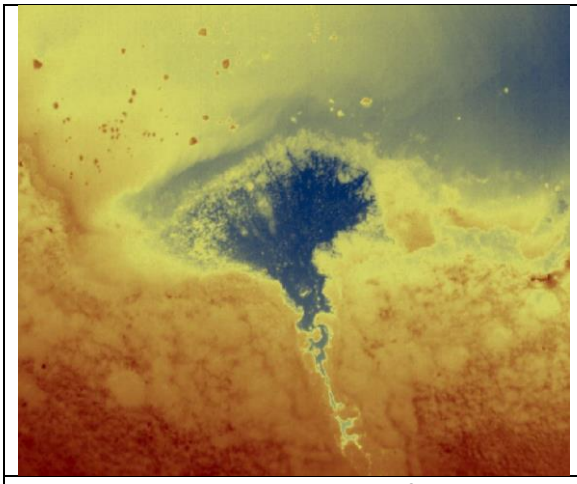

Figure 8a Thermal image of Bulls Well

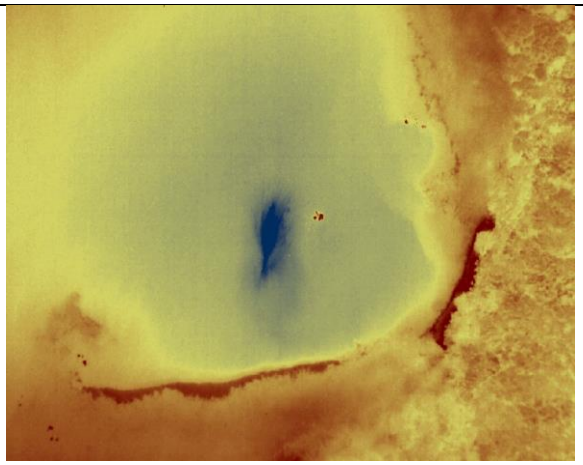

Figure 8b Thermal image of Moorehall Spring

It is likely that there are more subaqueous springs located within Lough Carra. There are numerous deeper basins within Lough Carra, similar to the one found at Moorehall spring. Figure 9 is the EPA's 2012 bathymetric map of Lough Carra, showing similar basins to that at Moorehall spring. Further work is needed to determine the locations of these springs. It is also likely that groundwater is entering the lake via smaller springs and seeps, which will be difficult to locate with any certainty.

In addition, it is considered that a proportion of the surface water input is derived from karst springs and seeps, and from turloughs. The surface water streams flowing into the lake have a significant input from groundwater and many have their source as karst springs. For example, Ballintober stream, which flows into the northern shore of Lough Carra, originates in several karst springs including those around Ballintober Abbey. Figure 10 shows the location of known springs in the vicinity of Lough Carra. The eastern shores of Lough Carra have a significant number of karst springs, providing groundwater input to the lake from the land to the east of the lake. Turloughs are also abundant in this area especially east of the northern basin of Lough Carra.

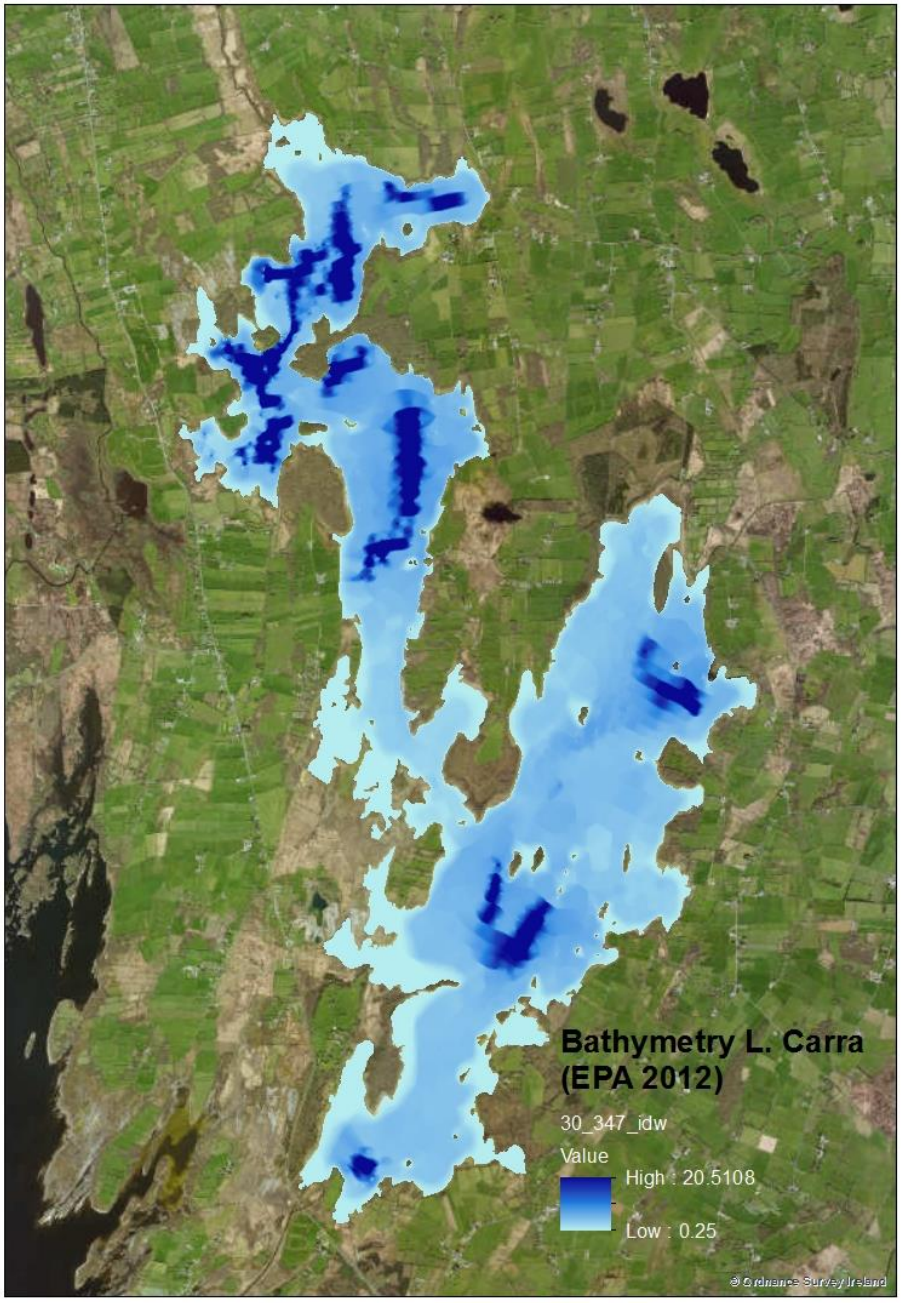

Figure 9 Bathymetric Map of Lough Carra (EPA 2012) showing marked basins

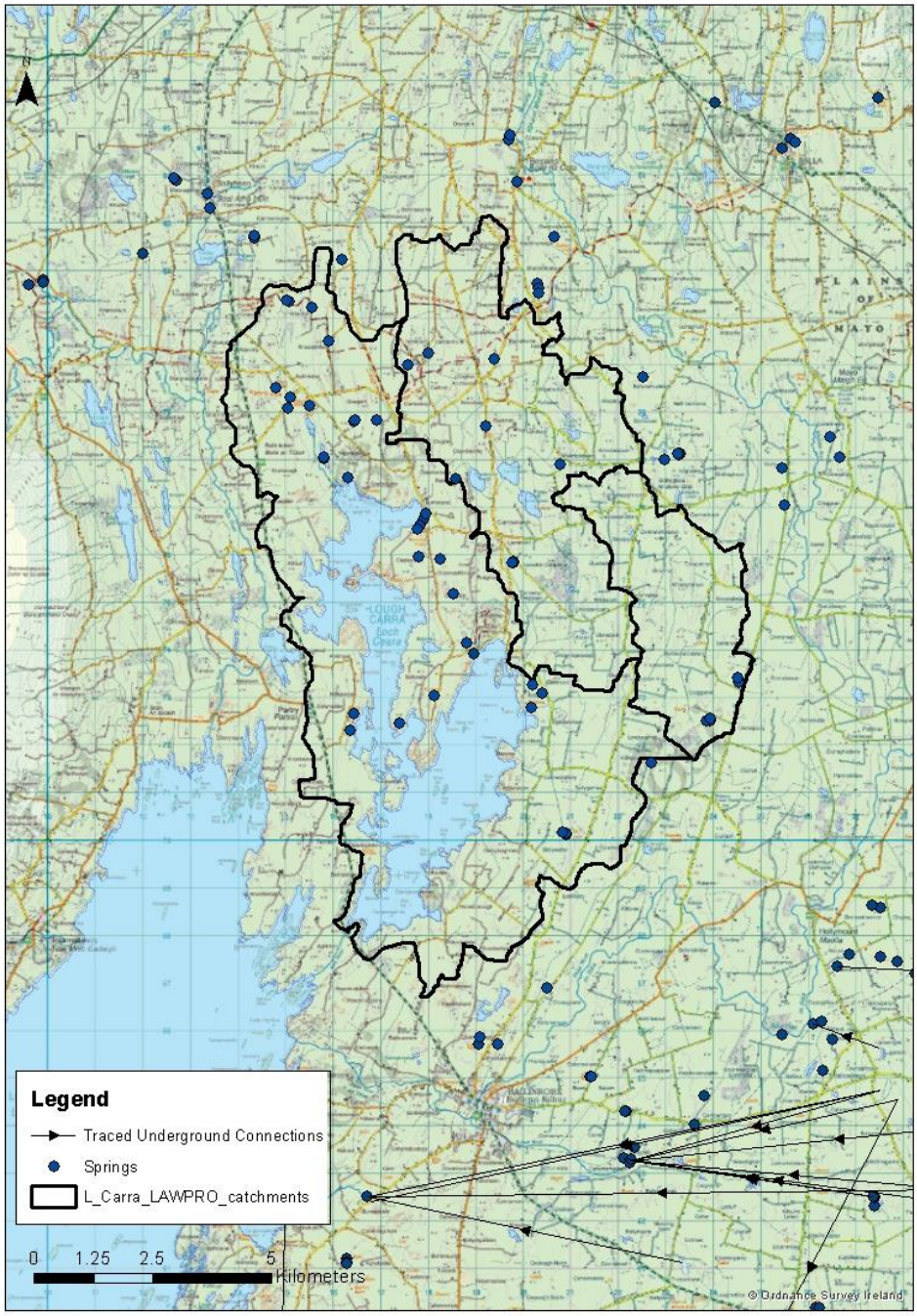

Figure 10 Known springs and proven underground connections in the Lough Carra region

2.3.1 Regional Groundwater Flow

Defining the groundwater catchment is one of the main aims of Action A2 of the Lough Carra LIFE project. As is usual in karst systems, the groundwater catchment is rarely the same as the surface water catchment and in this case is expected to be significantly larger. Flow paths in a karst aquifer are usually long and water can move at a relatively fast speed through conduits and enlarged openings within the aquifer.

It is unknown what proportion of the lake is groundwater fed, but initial water balance estimates suggest that it may be as high as 58 %. This figure is based on a preliminary desk study and more data will be required to get a better understanding.

Regional groundwater flow in the area is from east to west towards the lakes and the coast. The Great Western Lakes mark the western limits of the karstic lowland of Ireland. The lakes are located on the boundary between the limestone and the non-limestone rocks of western Connaught and the lakes function as base levels for the karstic drainage to the east. A series of large springs, east of the lakes, such as Bunatober (mean discharge 5000 m^3/d), Fountainhill (1500 m^3/d) and Cross (12,000 m^3/d) are known to drain the limestone lowlands to the east (Drew and Daly 1993).

Figure 11 shows the results of water tracing experiments in the wider region, clearly showing the dominance of this westerly and south-westerly flow. The longest traced underground connection in the region has a minimum distance of 13.5 km with the average for the region being circa 5 km in length. Flow velocities are high and range from 120 m/d to over 7,200 m/d, with the average being 1,680 m/d. These velocities are akin to surface water velocities and indicate the high level of karstification in the region. However, these tracing experiments are likely to be along zones of higher permeability and may represent the maximum rates (Coxon and Drew, 1986; Coxon, 1986).

2.3.2 Groundwater flow in the vicinity of Lough Carra

Although the area to the east of Lough Carra appears to be a fluvial landscape, drainage densities are low, reflecting the dominance of groundwater. As with the limestone east of the River Shannon, thick subsoils mask much of the bedrock topography, with only isolated exposures of bedrock protruding above the undulating or flat terrain. The River Robe is the only natural surface stream of any magnitude and there is considerable interchange between river flow and groundwater (Drew and Daly 1993).

There is a high density of karst features to the east of the surface water catchment, including several turloughs, some of which are shown in figure 7. As these turloughs drain underground, usually at the start of the summer, large volumes of water are channelled underground. It is thought that this water may flow west and contribute to the water in Lough Carra. This may be in the lake itself or via springs. Dye tracing experiments are needed to test this hypothesis. The area further east again is littered with karst landforms and small sinking streams. A comprehensive karst mapping programme and more dye tracing experiments will be needed to understand the connection between this area and Lough Carra.

2.4 Conceptual Model

Lough Carra is fed by a mixture of both surface water and groundwater. An annual average of 1,294 mm/yr (Met Éireann 1981-2010 annual average rainfall grid) of rain lands of the land surface around and to the east of the lake. Some of this (about 30 % on average) is lost to evapotranspiration. This leaves about 800 – 900 mm/yr of effective rainfall (ER). Some of this effective rainfall will run off and flow into drains, streams and rivers on the surface. On average in the catchment this is about 40 %. This will be much higher in areas underlain by impermeable subsoils such as peat, where the percentage runoff will be much higher (as high as 96 % of ER) and much lower in areas of bare rock or limestone pavement (as low as 15 %). Some of this runoff will eventually run off the impermeable subsoil areas and may subsequently sink underground at some of the smaller sinking streams to the east. Any surface water that does not sink underground will make its way into the surface streams previously described in this report. Some of these streams flow away and out of the Lough Carra catchment and some of these flow to Lough Carra.

As most of the catchment is underlain by moderately permeable subsoils of varying thickness, it is estimated that an average of 570 mm/yr of rainfall makes its way down in to the underlying aquifer. In karst aquifers such as those in the West of Ireland, the flow is usually quite localised in a network

of interconnected conduits. Once the groundwater reaches a large conduit it can move quite fast, as demonstrated by dye tracing experiments in the area. The assumption is that this water will then follow the regional groundwater flow direction and travel west towards the lakes and the coast. Some of this groundwater will resurface again at springs and seeps in the Lough Carra surface water catchment, and at springs by and in the lake. The proportions of re-emerging water are thought to be seasonally dependent with more water thought to contribute to the lake and surface streams during high flow periods, when the water table is higher.

However, some of this groundwater will continue on further west. As it reaches the contact between the Carboniferous limestones and the much older, harder rock further west it will be forced upwards. This is because the older rocks to the west are much less permeable and essentially will act as a barrier to flow, forcing the water up into Lough Mask.

Figure 11 shows a simplified conceptual model of the hydrology and hydrogeology of Lough Carra (not to scale). As can be seen from this schematic model groundwater flow mostly occurs in the karstified limestone aquifer found underneath Lough Carra and to the east. The regional groundwater flow direction is to the west towards the older Ordovician rocks. When the groundwater meets this geological contact it will be forced upwards into the lake and nearby springs. Smaller springs also occur east of Lough Carra and give rise to small streams. Some of these flow into lough Carra. There are turloughs in the east of the surface water catchment that may contribute to Lough Carra and springs within the catchment. There are some question marks over some of the features of the model, such as groundwater flow coming from the area east of Meander River and the turloughs. Further hydrogeological investigation will establish whether there are more subaqueous springs in Lough Carra and the location of the water table.

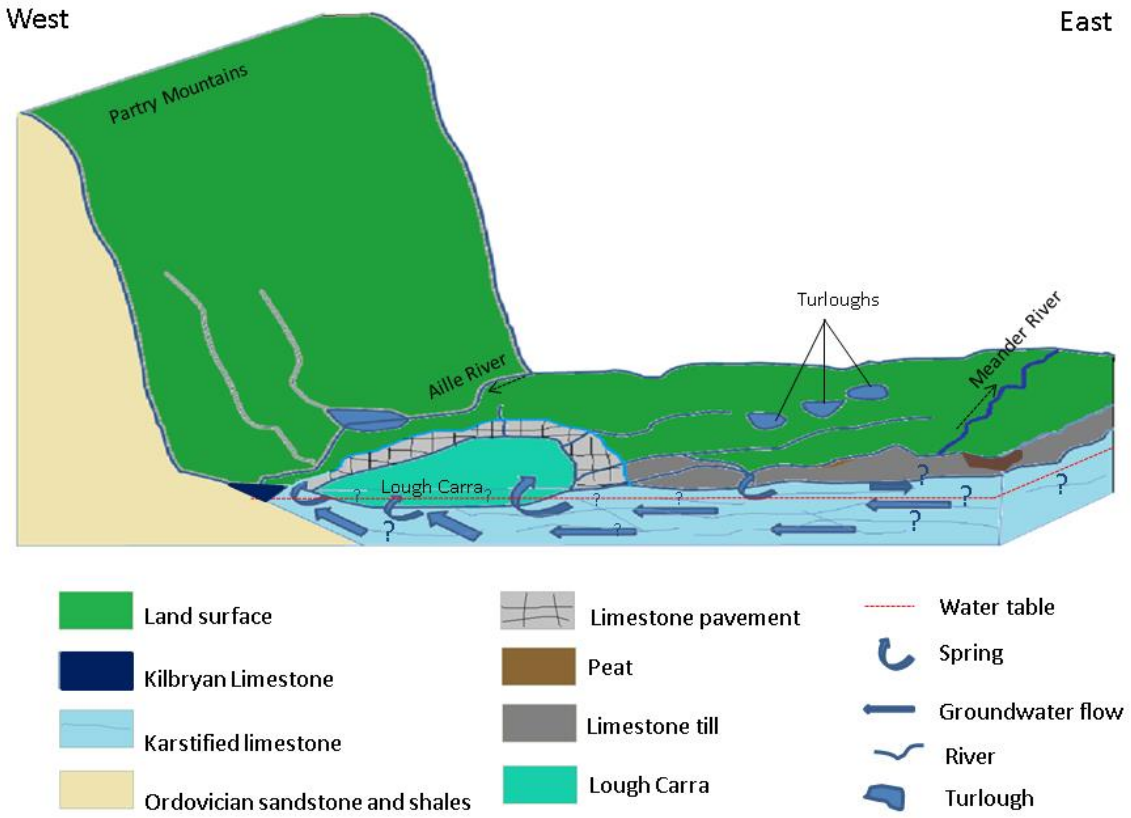

Figure 11 Conceptual model of hydrology and hydrogeology of Lough Carra (not to scale)

3. Next Steps

Geological Survey Ireland will carry out a groundwater catchment study (Action A2 of Lough Carra LIFE), focusing on groundwater-surface water connectivity in the catchment, including karst feature mapping, hydrological investigation and tracer testing. This will use existing and new data to improve this initial conceptual model. The conceptual model is a starting point for a detailed investigative programme and will be improved iteratively throughout the project as more knowledge of the hydrogeological system is obtained. The development of the conceptual model will allow the programme of field investigations to be optimised.

The planned work stream for Geological Survey Ireland will include:

- *Sub-action A2.2*: Monitoring of Groundwater Levels and Updating Groundwater Databases
- *Sub-action A2.3*: Mapping, including karst features, LiDAR and bathymetric surveys
- *Sub-action A2.4:* Hydrogeological investigations including tracer testing, piezometer installation and thermal mapping

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