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Author(s): L. Ragneborn-Tough, M. J. Pybus and C. Pybus
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A HYDROGRAPHIC STUDY OF LOUGH BUNNY, CO. CLARE

L. Ragneborn-Tough, M.J. Pybus and C. Pybus

ABSTRACT

Lough Bunny is a permanent lake in a karstic limestone area of County Clare in the west of Ireland. A survey of the lake was carried out from November 1992 to October 1993. The maximum depth recorded was 14m and the mean depth was 2.7m. The lake has no riverine inflow or outflow but is fed from springs and drains through sinkholes at the northern end of the lake. Studies by other workers have shown that this water discharges into the Rockvale river. Accordingly, Lough Bunny should be considered as part of Hydrometric Area number 29, the Galway Bay South East catchment. Pronounced seasonal variations in lake level, conductivity, alkalinity and pH were noted during 1992 and 1993. Median values for conductivity, alkalinity and pH were 324μS cm^{-1}, 2.85meq dm^{-3} and 8.06, respectively. Highest values were recorded during the winter months, suggesting flushing of karst aquifers into the lake, and lowest values were recorded during the summer months. Hardness ranged from 195mg $CaCO_3$ dm^{-3} to 250mg $CaCO_3$ dm^{-3}. An estimate of the heat budget (3.2kcal cm^{-2}) was similar to values found for lakes in the same area, but unlike the other lakes, Lough Bunny was always well mixed and did not develop any thermal stratification during the study period. Oxygen saturation was generally close to 100% throughout the lake.

L. Ragneborn-Tough, M.J. Pybus and C. Pybus (corresponding author), Department of Life Sciences, Galway-Mayo Institute of Technology, Dublin Road, Galway

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INTRODUCTION

The Burren is a Carboniferous limestone region in north-west County Clare. In the north and west it rises from the marine waters of Galway Bay and the Atlantic Ocean to the Burren plateau, which reaches heights in excess of 300m. The southern boundary may be considered to lie where the Carboniferous limestone dips beneath the younger Namurian shales (Drew 1990, 1997). The eastern boundary of the Burren is less easily defined. From a hydrological point of view Drew (1990) considers the foot of an escarpment at an elevation of 60m to be the boundary. Beneath this escarpment the limestone gradually shelves eastwards towards the bare pavement karst of the Gort lowlands. Some authors (e.g. Watts 1984 and D'Arcy 1992) include parts of these lowland areas within the eastern boundary of the Burren. For descriptive convenience, the term 'high' Burren is used here to include all those areas higher than, and bounded by, the 60m contour, and the 'low' Burren is used to refer to the predominantly limestone pavement that lies below, and mainly to the east of, the 60m contour. Lough Bunny is located on this eastern extension of the 'low' Burren and lies just within the boundary of the Burren National Park.

The proximity to the Atlantic Ocean produces a relatively warm climate and high rainfall, 1400mm–1600mm $year^{-1}$ (Jordan 1997). Despite this high rainfall there are few rivers or permanent bodies of standing water, although turloughs, or temporary lakes, are quite common especially in the 'high' Burren (Coxon 1987a, b). The hydrology, as in any karstic area, is complicated and not well understood as most of the drainage is underground (Drew 1990). Only towards the eastern boundary are there any permanent lakes, and Lough Bunny is the most northerly lake of what may be called the 'east Burren wetlands' (D'Arcy 1992). This system of freshwater wetlands, including lakes, fens and turloughs, extends approximately 15km along the south-eastern boundary of the 'low' Burren. They form one of the most extensive systems of calcareous wetlands in Ireland and act as a catchment for much of the uplands of the eastern Burren (D'Arcy 1992). Most of the lakes to the south of Lough Bunny are connected to the River Fergus by small streams, but Lough Bunny has no permanent overground inflows or outflows.

Few scientific studies on the hydrology or biology of these lakes have been published. Allott (1986) examined the temperature, oxygen and heat budgets of six of the wetland lakes, and Flanagan and Toner (1975) and Toner *et al.* (1986) have presented results from routine sampling of Lough Inchiquin. The survey presented here was carried out in 1992 and 1993 to examine the bathymetry of the lake and seasonal variation in some hydrophysical and chemical variables.

Following an exceptionally wet winter in 1994/95 widespread flooding occurred in the south Galway area, including the immediate environs of Lough Bunny and the lake itself. The flooding caused serious social and economic problems and led to the commissioning of a survey by the Office of Public Works. The resulting report (Office of Public Works 1998) contains extensive and intensive data, much of which is relevant to any scientific understanding of Lough Bunny and especially to its importance in the hydrology of the area.

SITE DESCRIPTION

Lough Bunny (R 37 96) lies within a closed depression, bounded by a 20m contour, in the upper Carboniferous limestone near the village of Boston. The area is thinly populated. In parts, the limestone pavement is covered by thin soils that are used mainly for pasture. The major axis is orientated SW to NE (Figs. 1 and 2a).

The south-eastern shore is mainly composed of limestone pavement, which gradually shelves down into the water. One road runs parallel to this shore and another runs close to the north-east shore. There are small islands along the north-western shoreline. The surface of the lake is 17m above chart datum (Ordnance Survey of Ireland 1998), and the surface area is approximately 102ha including the islands. Its greatest length is 2.4km and the greatest breadth is 740m. The direction of the prevailing winds in the area is west to south-west, but the 'high' Burren to the west and Mullagh More to the south-west may provide some protection from these winds.

A series of smaller lakes, including Castle Lough, Skaghard Lough and Travaun Lough, lie to the west of Lough Bunny. These lakes are connected hydraulically by overground streams and may also have underground connections with each other, but they have no observable connection with Lough Bunny. Neither the six-inch Ordnance Survey map produced in 1840 and revised in 1913 nor the most recent OS map (Ordnance Survey of Ireland 1998) show any surface waters flowing into the lake. Extensive areas around the lake are liable to flood and there are several small springs in the area but none provide a permanent inflow.

According to D'Arcy (1992), Lough Bunny was formed originally by the localised collapse of the bedrock. Likewise, Lough Gealain, which is just south of Mullagh More and has a 'broad central shaft with vertical rock walls' (Watts 1984), is believed to be formed from a collapsed cave, or doline (Byrne and Reynolds 1982). The series of

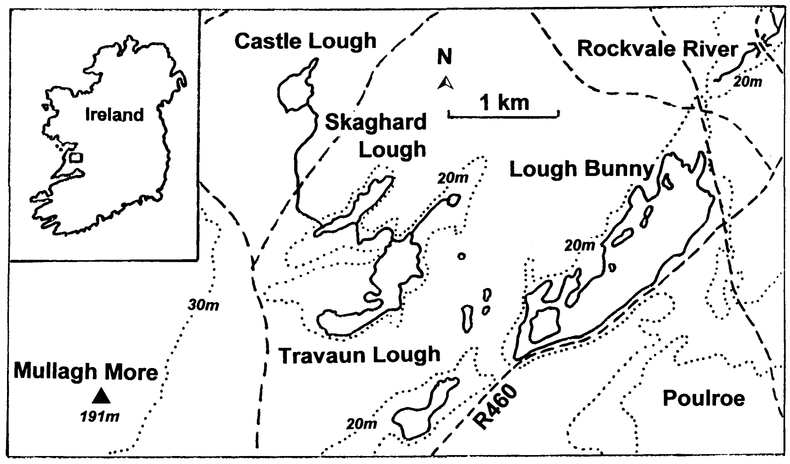

Fig. 1—The main map shows Lough Bunny and some of the other topographical features mentioned in the text. Dashed lines are road. Dotted lines are contours. The inset shows a map of Ireland and the approximate location of the main map.

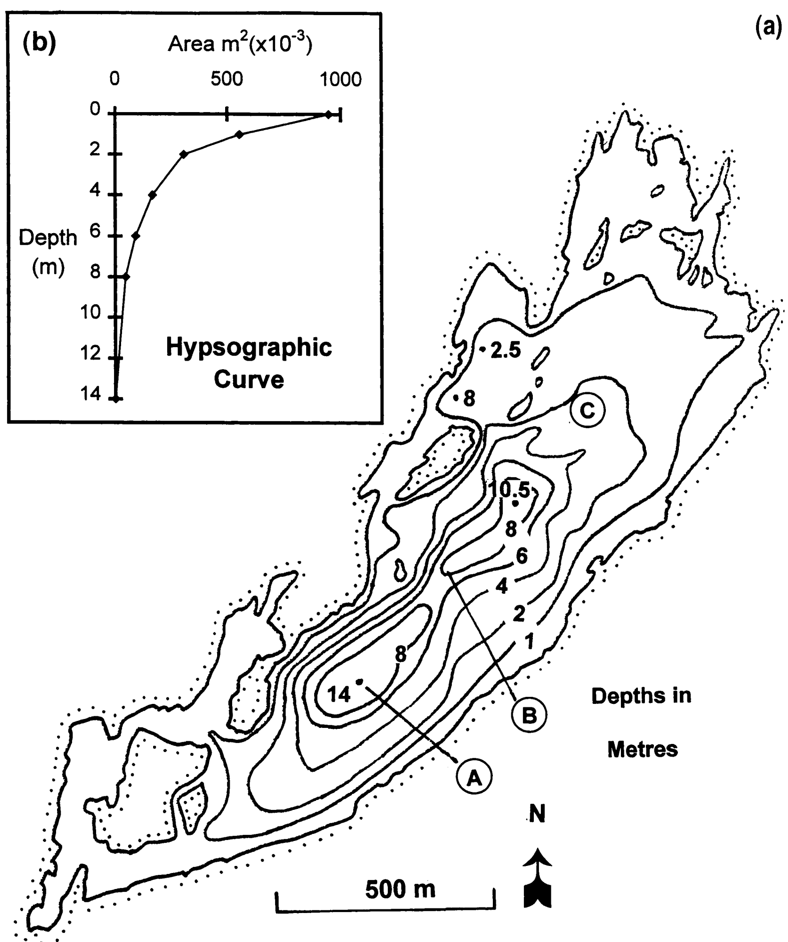

Fig. 2a—Map of Lough Bunny showing the metric isobaths. A, B and C mark the sampling stations referred to in the text. Fig. 2b—An area/depth hypsographic curve for the lough.

lakes to the south of Lough Bunny occupy solution hollows in the limestone and may receive substantial quantities of ground water in addition to overland flow (Allott 1986). These lakes form part of the Fergus River catchment

The chart 'Rivers and their Catchments' prepared by the Ordnance Survey of Ireland in 1958 shows Lough Bunny to be the most northerly lake in the catchment of the River Fergus Drew *et al* (1977), however, place the lake within the Kinvarra drainage basin Therefore, water from Lough Bunny, unlike the other lakes of the east Burren wetlands, which are in direct hydrological contact with the River Fergus, could flow in a northerly direction and ultimately pass into Galway Bay via the emergent springs or 'risings' at Kinvarra Maps associated with Bowman *et al* (1996) and Lucey *et al* (1999) show Lough Bunny within Hydrometric Area 27, which is essentially the catchment of the River Fergus However, it has now been demonstrated (Office of Public Works 1998) that water draining from the sinkholes at the northern end of Lough Bunny re-emerges at the springs that form the source of the Rockvale River (Fig 1). This river flows in a northerly direction into Lough Mannagh, via Lough Skeardeen and Lough Avatia, and is part of the Cloonteen River catchment; this, in turn, is part of the Kinvarra catchment. Lough Bunny therefore discharges water into Hydrometric Area number 29—the Galway Bay South East catchment

METHODS

Depths were determined using a calibrated, weighted line. Substratum type was observed from the surface, where possible, and from material raised by dredging The lake level was measured daily from a marked stake driven through the sediment to the bedrock at the northern part of the lake. Daily rainfall data was obtained from collections made at Kinvarra Garda Station, approximately 15km north of Lough Bunny.

Water samples were collected each month, from November 1992 to October 1993, from three locations on the lake identified as A, B and C on Fig. 2a. A 'Hydrobios' sample bottle was used to take sub-surface samples Conductivity and temperature profiles, with 0 5m depth intervals, were determined at each position using a WTW Conduktometer LF191 The heat budget was calculated using the method given by Wetzel and Likens (1991) Measurement of the *in situ* surface pH was made with a portable pH meter (Delta OHM HD 8602). Dissolved oxygen was measured with a portable polarographic oxygen meter (WTW OXI 191) Alkalinity was determined by acid titration (Golterman *et al.* 1978) usually within a half-hour of sampling. Hardness was estimated from calcium and magnesium concentrations obtained by atomic absorption spectrophotometer, Perkin-Elmer model 280 (Stirling 1985)

RESULTS

Depths were recorded at 77 points along a series of transects across the lake Isobaths were interpolated from these depths and are shown in Fig. 2a The isobaths indicate the depth (in metres) from the water surface to the bedrock, where exposed, or to the sediment/water interface The lake is relatively shallow, as shown by the hypsographic curve (Fig 2b) On the day of the survey (7 April 1993) the lake had an average depth of 2 7m In some parts the depth varies greatly over short distances, for example to the west of the islands, where there is an area with large limestone blocks interspersed with deep holes A maximum depth of 14m was found during the survey. Along the eastern margin and between the islands and the western shoreline the substratum is bare limestone, but along the other sides and in the central areas there are deposits of mud and marl Mud with peaty outcrops was found at the northern end of the lake and by the islands

Following periods of rain the lake level would rise by about 1–2cm per day On reaching a temporary maximum height, the level would fall at a similar rate until the next period of rain, when the level would rise again These fluctuations in lake level continued throughout the year, but the lake level progressively fell by 1.2m, from the maximum level, recorded in December 1992, to the minimum level, recorded in September 1993

The temperature–depth–time diagram at position B (Fig 3) indicates a well-mixed water column throughout the survey, except in July and August where the beginning of a weak thermal stratification could be observed The temperature difference from surface to bottom was never greater than 1°C. Table 1 summarises the chemical variables measured during the survey. Maximum, minimum and median values are presented. Marked seasonal cycles were shown by each variable

DISCUSSION

Lough Bunny is shallow (less than 2m in depth) for much of its area. The bare limestone pavement of the south-eastern shore shelves gradually to the deepest areas in the central parts of the lake Other deep areas are found between the islands and the north-west shoreline. In this part of the lake large limestone blocks form the bottom.

Their arrangement is very irregular and it is possible that areas deeper than the 8m recorded here may exist. The arrangement of these blocks, and the localised deep areas found between them, supports the suggestion of D'Arcy (1992) that some of the deeper parts of the lake may have been formed by the collapse of submerged chambers. This has also been suggested for the deep parts of Lough Gealain (Byrne and Reynolds 1982; and Watts 1984), which is another karst lake to the south of Lough Bunny. However, the length/width and depth/width ratios of the deeper parts of Lough Bunny both exceed unity. These dimensions indicate that a more linear feature, for example a solution corridor (as defined by White 1988), and not a doline, may have collapsed in Lough Bunny.

In comparison with those lakes studied by Allott (1986), Lough Bunny, while having a large surface area (101ha), is of intermediate maximum depth (14m). It has one of the smallest average depths (2.7m) and the lowest mean depth to area ratio (0.03m ha^{-1}). This value will fluctuate many times during the year because the water level changes rapidly following periods of rainfall. From the highest water level recorded in December to the lowest in September there was a height difference of 1.2m. This results in a substantial reduction in the lake surface area due to its shallow margins, especially along the south-eastern coastline.

At the time of the survey, the relationship between Lough Bunny and the other water bodies in the area was uncertain. However, there was serious flooding in the south-Galway area during the winter of 1994/95. A subsequent investigation (Office of Public Works 1998), during which tracer dyes were used, demonstrated that the spring (located at M3898), which gives rise to the Rockvale River, is in direct hydraulic contact with Lough Bunny. Accordingly, water from Lough Bunny is now known to flow in a northerly direction via the Rockvale River into Loughs Skeardeen, Avatia and Mannagh. It is therefore situated in the Kinvarra catchment and should be considered as part of Hydrometric Area number 29, Galway Bay South East. It is unlikely to have

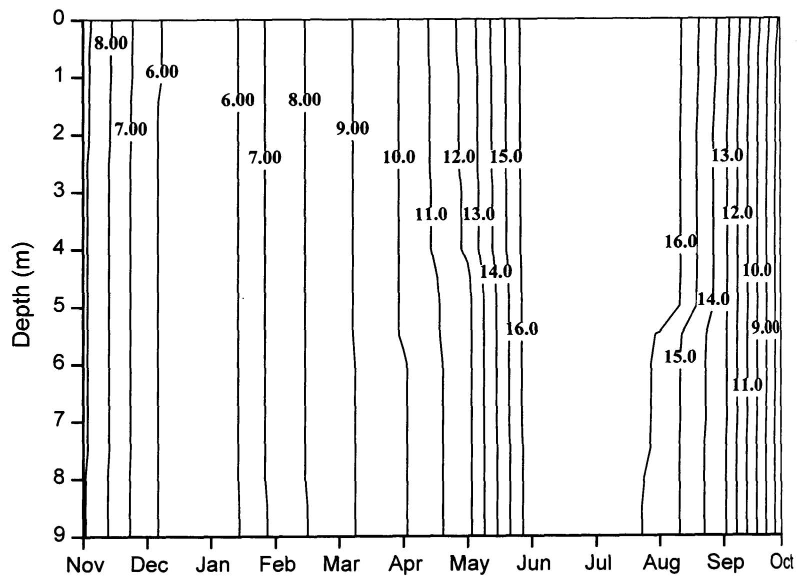

Fig. 3—Temperature–depth–time diagram for Lough Bunny, November 1992 to October 1993.

direct hydraulic connections with the other lakes of the east Burren wetlands, which are part of the Fergus River catchment and are located in Hydrometric Area number 27, Shannon Estuary North.

The temperature–depth–time diagram (Fig. 3) indicated a well-mixed body of water for most of the survey period. The temperature difference between the surface and the bottom was never greater than 1°C even during the late summer months. Allott (1986) found that the two shallow lakes, Ballycullinan South and Lake Black (4.1m and 2.7m mean depth respectively), were too shallow to exhibit an annual cycle of stable stratification, but both lakes stratified temporarily in periods of warm, calm weather. In both lakes, surface water temperatures in excess of 20°C were recorded by Allott (1986). Lough Bunny, although deeper than the lakes surveyed by Allott (1986), has a smaller depth/area ratio (Table 2). It is also vulnerable to mixing by winds from the south-west as its axis runs SW to NE. Therefore, thermal stratification will probably only develop in this lake

Table 1—Summary of chemical variables measured during the survey. Variables were measured at monthly intervals from November 1992 to October 1993 with the exception of hardness, which was only measured from May 1993 to October 1993.

Variable	*Maximum (month)*	*Minimum (month)*	*Median*
Conductivity (µS cm^{-1})	368 (Feb)	265 (Sep)	324
Alkalinity (meq dm^{-3})	3.42 (Dec)	2.25 (Aug)	2.85
pH	8.54 (Nov)	7.64 (May)	8.06
Hardness (mg $CaCO_3$ dm^{-3})	250 (Aug)	195 (Jun)	220
Dissolved Oxygen (% saturation)	120 (Aug)	92 (Feb)	101

when water temperatures approach or exceed those recorded by Allott (1986), thus permitting a greater temperature differential between the surface and subsurface water to develop. A heat budget for Lough Bunny, between the winter minimum temperature in January and the summer maximum temperature in July, was estimated as 3 2kcal cm^{-2} This value is close to that predicted from the relationship established by Allott (1986) between heat budget and mean depth for those lakes listed in Table 2, which reinforces his suggestion that mean depth rather than surface area determines the heat budget of the lakes in this area

Flanagan and Toner (1975) state that the conductivity values measured in the lakes of the central limestone plain of Ireland are generally in excess of 250µS cm^{-1}. Both Lough Bunny and Lough Inchiquin exceed this value. Conductivity, being a reflection of the total ionic concentration of the water, is highest in water that has been in contact with limestone bedrock for long periods (White 1988). Therefore, high winter values may reflect the flushing of high conductivity water from storage aquifers into the lake. This flushing would also cause an increase in hardness and other variables related to the dissolved constituents, such as pH and alkalinity

The pH and total alkalinity both fall within similar ranges (Table 2) to those obtained in the lakes surveyed by Allott (1986) and Flanagan and Toner (1975). Similar values were also recorded in Lough Bunny during 1995 and 1996 (Table 3). In karst lakes the predominant ions are calcium and bicarbonate and it is the concentrations of one or both of these ions that, to a great extent, determine the pH, alkalinity, hardness and conductivity Like conductivity, both pH and alkalinity showed marked seasonal, cyclic variations, with highest values recorded in the winter months and lowest values in the late summer at times that coincided with maximum and minimum water levels respectively

The water of Lough Bunny is hard. Total hardness (median value of 220mg $CaCO_3$ dm^{-3}) was higher than the values, 165mg $CaCO_3$ dm^{-3} and 170mg $CaCO_3$ dm^{-3}, recorded in Lough Inchiquin by Flanagan and Toner (1975) This can be explained by the differences in the catchment geology Most of the water entering Lough Bunny is in contact with the limestone bedrock of the area and would be expected to be hard as a result of the high calcium content. Lough Inchiquin, on the other hand, receives some softer waters draining the Namurian shales and flagstones. Hardness values for Lough Bunny in 1995/96, calculated from the data in Table 3, were 247mg $CaCO_3$ dm^{-3}, 172mg $CaCO_3$ dm^{-3} and 131mg $CaCO_3$ dm^{-3} for October, December and June

Table 2—Physical features and chemical characteristics of some lakes referred to in the text.

Lake	*Area (ha)*	*Z_{max} (m)*	*$\bar{Z}$ (m)*	*pH*	*Alkalinity (meq dm^{-3})*
Bunny (June 93)	101	14	2.7	8.1	2 7
Ballycullinan North*	2.3	10	5.6	8.0	3 4
Ballycullinan South*	3.9	8	4.1	7 9	2 5
Black*	2.3	6	2.7	8.3	3.1
Cullaun*	37.8	23	10.2	8.2	3.0
Dromore*	35 5	19	9.0	8.3	3.2
Inchiquin*	110	28	10.8	8.1	3 0

*Data (June 1985) from Allott (1986)

Table 3—Some chemical variables measured in Lough Bunny during the Gort Flood Study (1995/96) (data from Office of Public Works 1998).

	Field pH	*Field conductivity (µS cm^{-1})*	*Ca total (mg l^{-1})*	*Mg total (mg l^{-1})*	**Field alkalinity (meq dm^{-3})*
12 Oct 95	8.00	200	89.10	5.90	4 0
16 Dec 95	8.00	n/a	63.00	3 67	3.0
05 Jun 96	8.58	296	47.10	3.27	2.2

*Results presented here are converted from original data that was presented as mg l^{-1} $CaCO_3$

respectively These data also indicate marked seasonal variations and, with the exception of the low final value, are similar to concentrations recorded two years previously in Lough Bunny (Table 1)

Lough Bunny is an unusual lake It has some chemical similarities with the other lakes of the east Burren wetlands, but it is quite different in other respects—for example, its unusual hydrological situation and its relationship with other temporary water bodies in the areas

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